NASA/CP—2009-215797

Airframe Icing Workshop

July 2009

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Airframe Icing Workshop

Proceedings of a conference held at and sponsored by
NASA Glenn Research Center
Cleveland, Ohio
June 9, 2009

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

July 2009

Level of Review: This material has been technically reviewed by technical management.

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Abstract

The NASA Glenn Research Center (GRC) has a long history of working with its partners towards the understanding of ice accretion formation and its associated degradation of aerodynamic performance. The June 9, 2009, Airframe Icing Workshop held at GRC provided an opportunity to examine the current NASA airframe icing research program and to dialogue on remaining and emerging airframe icing issues and research with the external community. Some of the airframe icing gaps identified included, but are not limited to, ice accretion simulation enhancements, three-dimensional benchmark icing database development, three-dimensional iced aerodynamics modeling, and technology development for a smart icing system.

Contents

*Not for public distribution.

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National Aeronautics and Space Administration

NASA Airframe Icing Research Overview Past and Current

Airframe Icing Workshop
NASA Glenn Research Center

Cleveland, Ohio *June 9, 2009*

www.nasa.gov

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NASA Airframe Icing Research

Objective

The objective of fundamental research in airframe icing has been to provide the aviation community with the design and analysis tools needed to accomplish better and safer designs of aircraft and aircraft sub-systems, with respect to operations in icing conditions.

Approach

- Development of new experimental methods and advanced icing simulation software
- Highly integrated, multi-disciplinary effort
  - examination of the underlying physics of icing
  - analytical model development
  - software development and maintenance
  - experimental methods development
  - creation of experimental databases related to ice formation and its effects

The tools developed in the NASA Glenn Icing Branch are used for a variety of purposes including but not limited to, ice accretion shape prediction, ice protection system performance evaluation, and examination of the effects of ice accretion on aircraft aerodynamics.

These tools have an impact in design, testing, construction, and certification and qualification of aircraft and aircraft sub-systems.

NASA Airframe Icing Research Overview
Past and Current

Outline

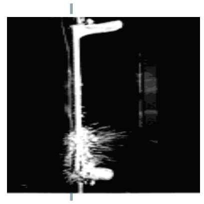
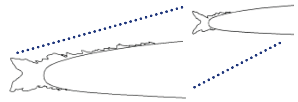
- Experimental Methods
- Computational Methods
- Flight Dynamics
- Experimental Databases

- Historical timeline
- Highlights
- Development of major products

Historical Progress in Technology

Experimental Methods




1980s

- **Ice shape tracing methods**
- **Development of accurate ice shape casting technique**
- **Scaling laws identified and tested**
- **De-icing fluid aerodynamic tests conducted in IRT**
- **Aircraft performance testing with artificial ice shapes using Twin Otter**
- **Icing cloud droplet size and liquid water content probes tested in IRT and in flight**
- **Development of methods for measurement of collection efficiency on clean airfoils**

1990s

- **3D laser scanner for ice shape measurement**
- **Significant progress in extension of scaling laws to greater range of sizes and conditions**
- **Investigations of Reynolds number effects on iced airfoil performance using cast ice shapes**
- **Tailplane Icing Project develops methods for evaluation of stability and control parameters for iced aircraft**
- **Shed ice particle tracking with high speed cameras**

2000s

- **Development of SLD simulation capability in IRT**
- **Extension of scaling laws to SLD icing conditions**
- **Investigations of SLD droplet splashing, break-up and associated mass loss**
- **Development of methods for sub-scale aero testing of complete aircraft with artificial ice shapes**
- **Full scale iced airfoil performance testing at flight Reynolds numbers in ONERA F1 pressurized wind tunnel**
- **Swept wing ice shape generation and performance testing on representative business jet model**
- **Extension of collection efficiency measurement methods to iced airfoil geometries**

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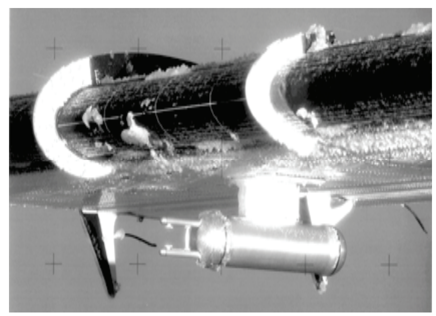
Experimental Methods

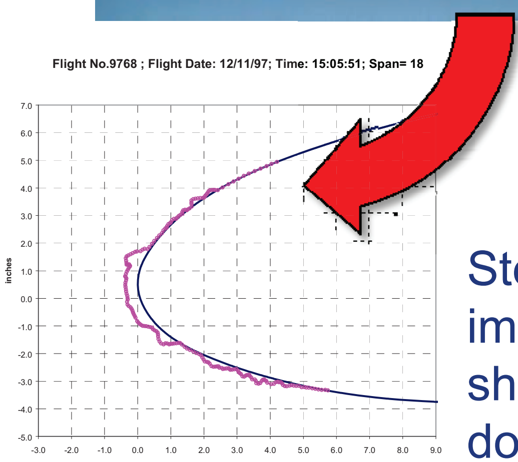
In-Flight Testing Projects

– Icing cloud characterization
– Ice shape measurements
– Instrumentation development
– Aircraft performance measurements with simulated ice shapes
– Aircraft handling and stability & control characteristics with simulated ice shapes

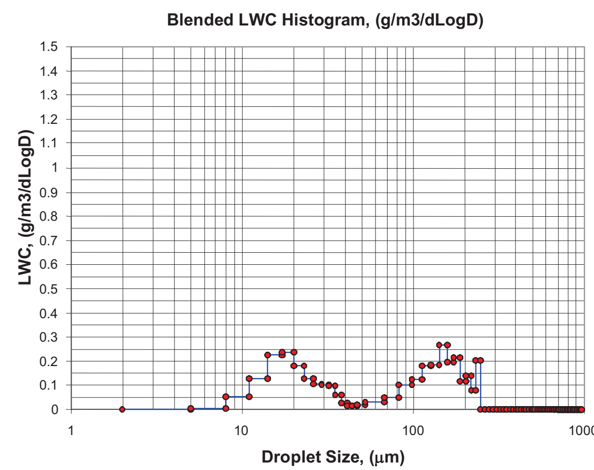


Particle sizing probe mounted on Twin Otter

LWC histogram for Twin-Otter flight in SLD



Stereoscopic imaging for ice shape documentation



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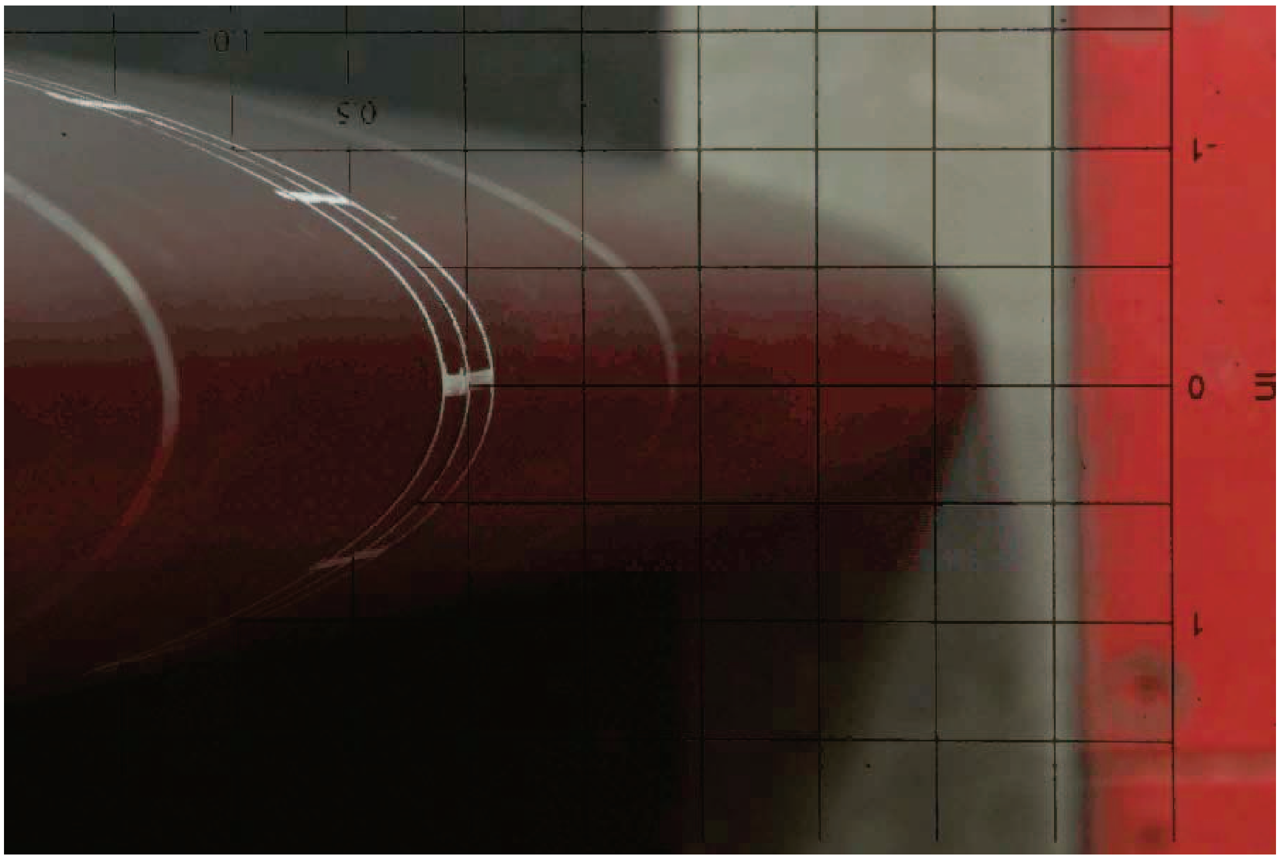
Experimental Methods

Ice Accretion Studies

Research needed to de-construct ice growth stages into micro-physical phenomena from roughness to ice feathers to ice shape → new physical models & improved CFD tools

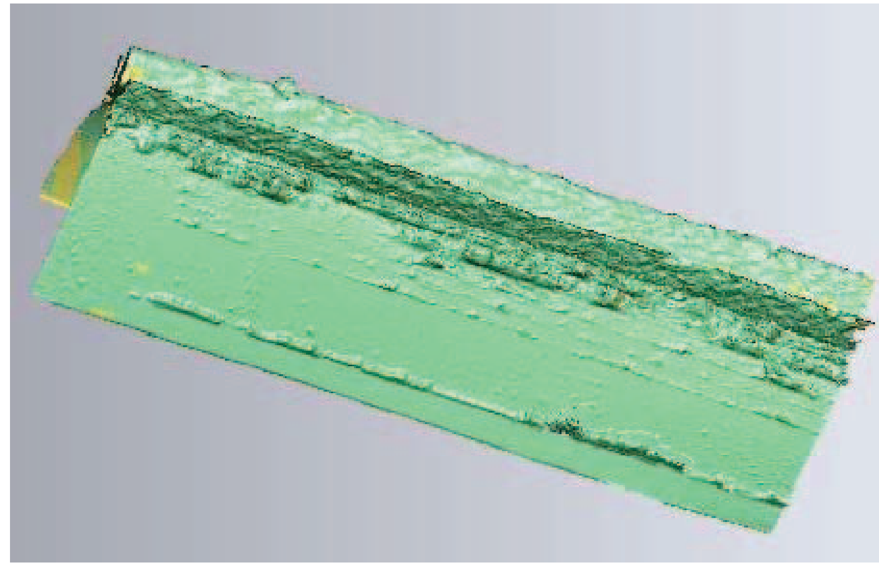


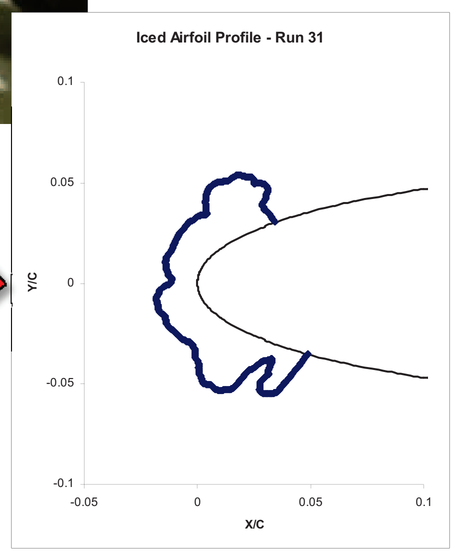
IRT Test - ice shape growth **Click to play movie**

Experimental Methods

Ice shape Measurement Methods

- Ice shape tracing
- Ice shape molds and castings
- Utilization of 3D scanner technology





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Experimental Methods

Ice shape Measurement Methods

– Ice shape tracing
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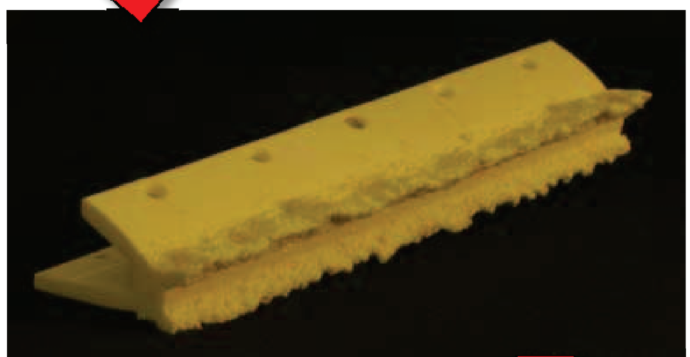

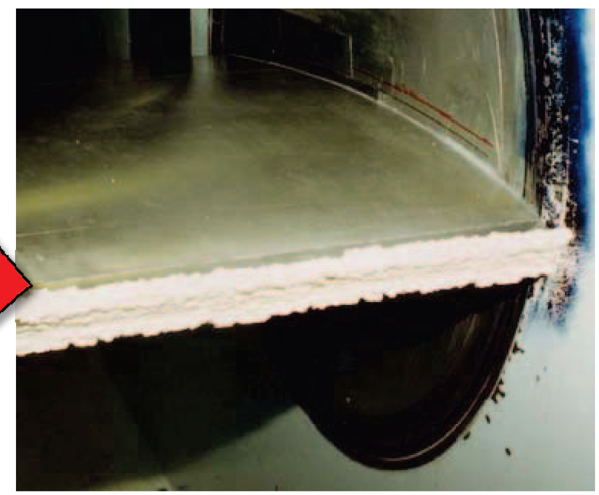

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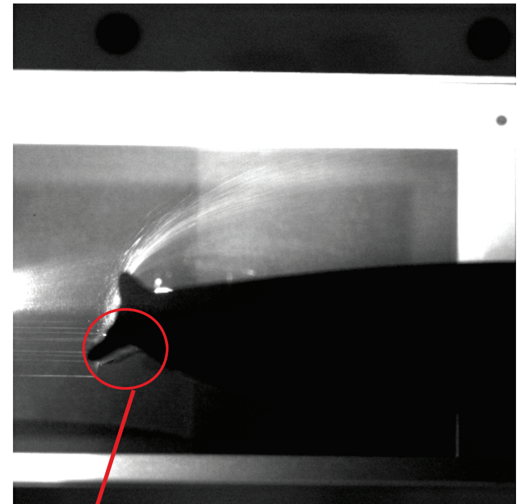
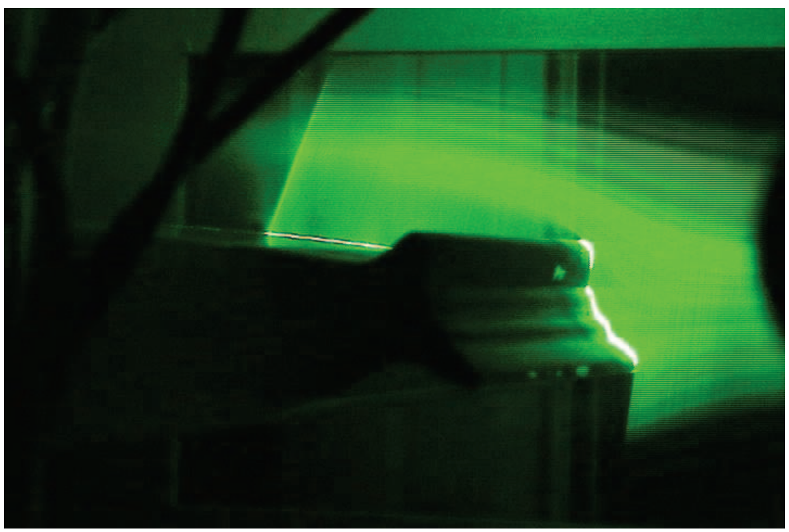
Experimental Methods

Advanced Measurement Techniques

- Fluid-thermal measurements in the region near the ice/water/air interface
- Non-intrusive liquid water and droplet diameter measurement methods for regions upstream and surrounding test targets
- Unsteady, high-speed velocity measurements in the entire flow surrounding the iced geometry
- Automated ice shape measurement techniques

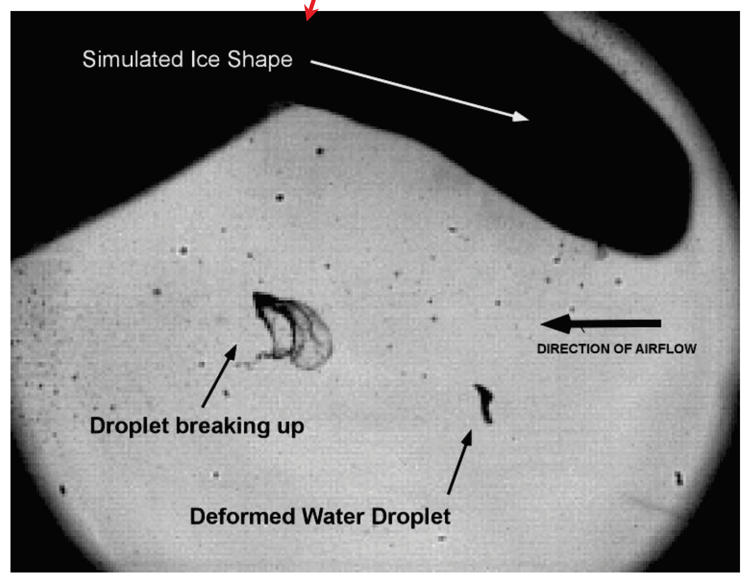




Images

From

DrIFT



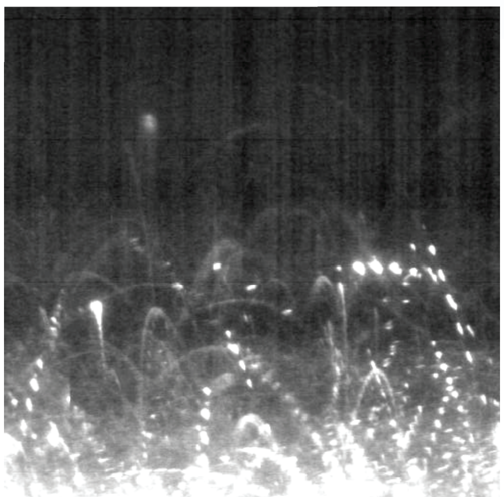
Click to play movie

Experimental Methods

Microphysical Studies

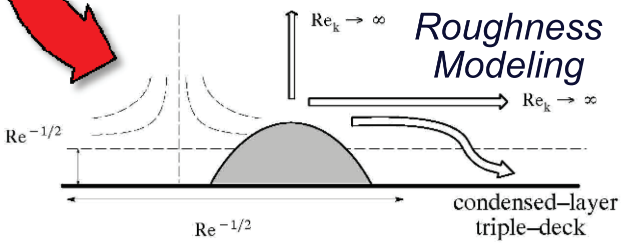
– Multi-phase region at the ice surface: water film thickness and velocity, the ice surface topology, detailed airflow temperatures and velocities

Scalloped Ice Shape Studies



Droplet Splashing Imaging

Vertical Icing Studies Tunnel



Roughness Modeling

Experimental Methods

Aerodynamic Performance Measurements

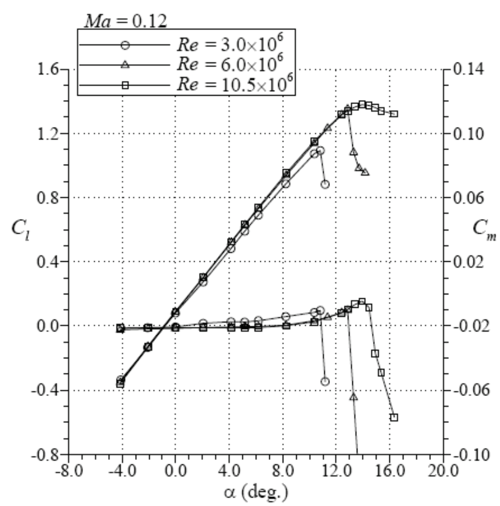
- Pressure and force measurements on airfoils and wings with leading edge artificial ice shapes
- Ice shapes can be 3D castings, extrusions from 2D ice shape tracings, or geometric shapes representing ice shapes (e.g. spoiler shapes used to simulate ice horns)
- Most testing has been at moderate Reynolds numbers using 2D ice shapes on airfoil models; some 3D testing and high Reynolds number

Two-Minute Glaze Ice Shape 202

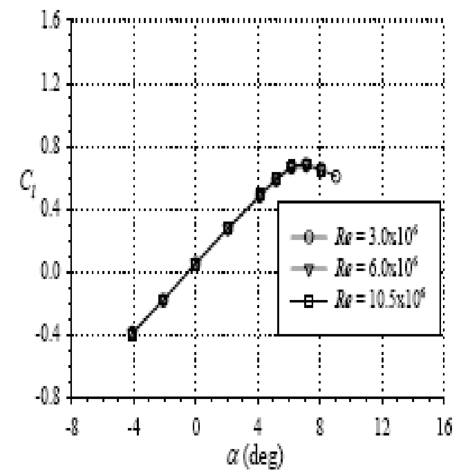
16.7-Minute Rime Ice Shape 212

22.5-Minute Glaze Ice Shape 904

22.5-Minute Glaze Ice Shape 944



Effect of Reynolds number at constant Mach number on performance for the clean GLC-305 airfoil.



Reynolds Number Effects on 22.5-minute Glaze Ice Shape (944 casting) at *Ma = 0.12*

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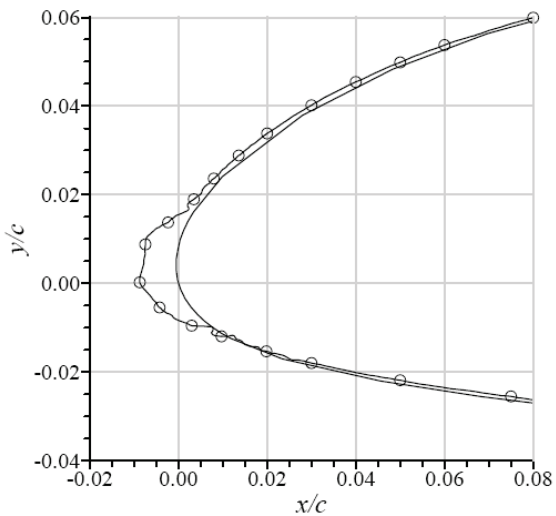
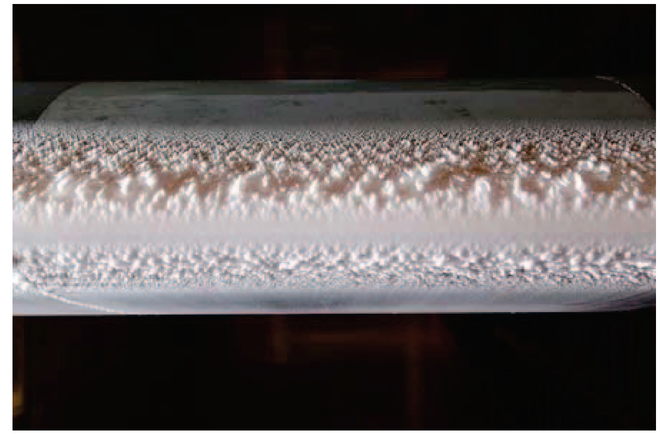
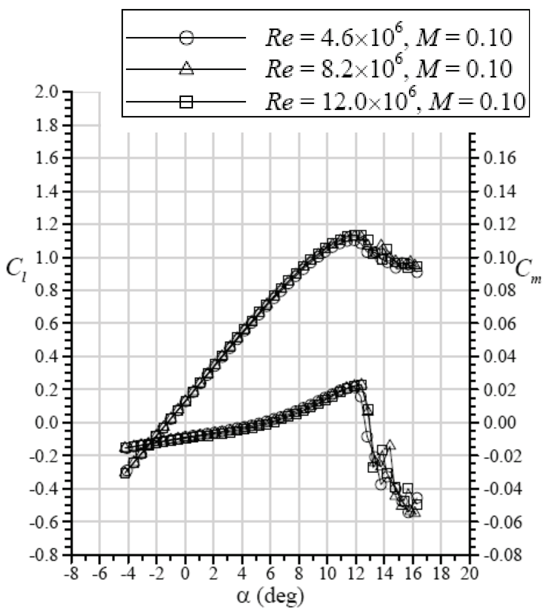
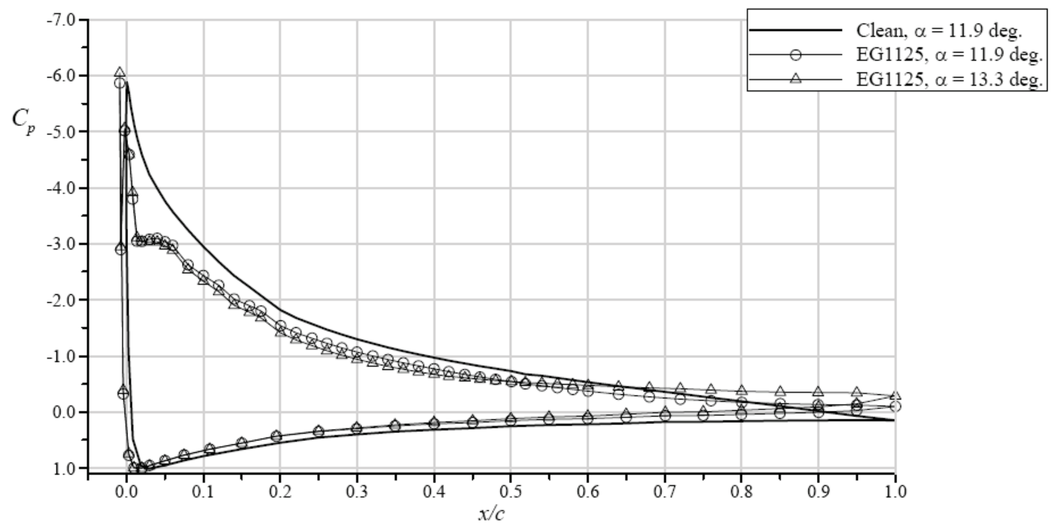
Experimental Methods

High Re Aerodynamic Performance Measurements at ONERA F1 Facility









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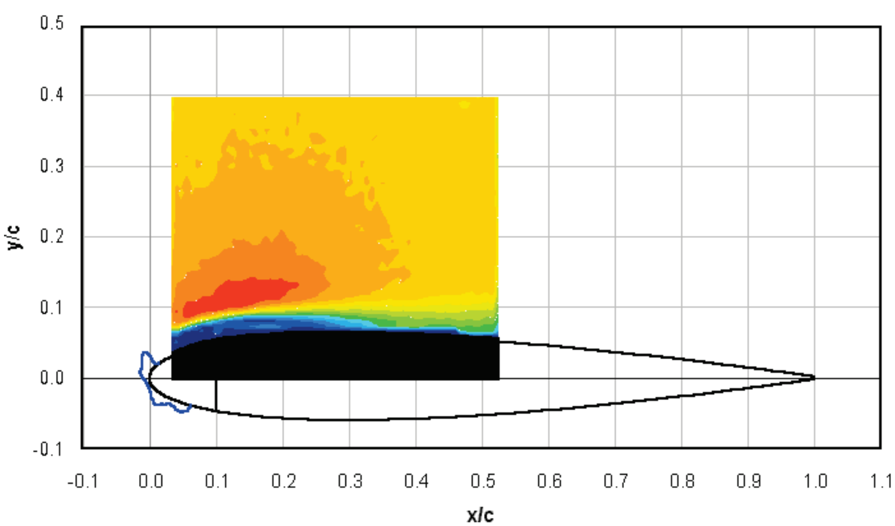
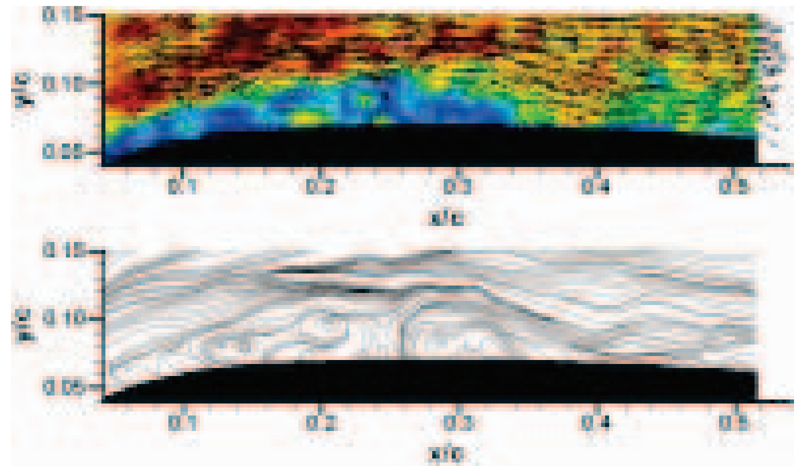
Experimental Methods

Iced Aircraft CFD Modeling Validation - near-stall condition flow field research

- Regions containing vortex shedding, vortex interaction from several regions of interest, flow separation and reattachment, separation bubble reattachment unsteadiness, and extended regions of boundary layer transition



Contour plot of the average velocity field at mid-span for the NACA 0012 airfoil with 2D glaze ice simulation at *Re* = *1x10*^{6} *and α = 2.7º*



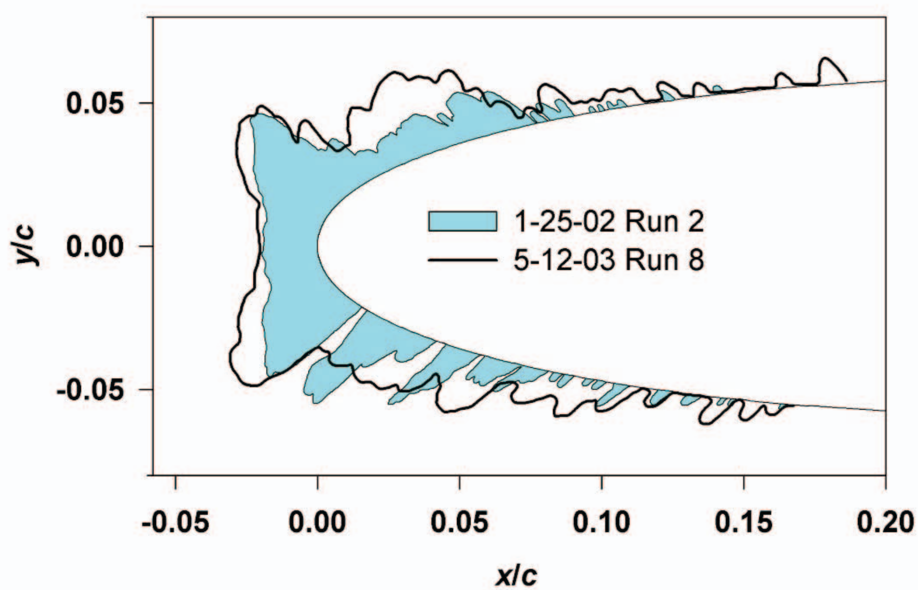
Contour vector and streamline plots of an instantaneous velocity field at mid-span for the NACA0012 airfoil with 2D glaze ice simulation at *Re* = *1x10*^{6} and α = 2.7º

Experimental Methods

Scaling Methods

– Geometric and physical parameter scaling methods have been developed and used when models are too large for the experimental facility or the icing conditions of interest cannot be obtained in the facility

	c, in	t_{st}, °F	V, kt	MVD, μm	LWC, g/m^3	τ, min	β_0, %	$\beta_0 A_c$	n_0	We_L, 10^6
(shaded)	36.0	5	100	160	1.50	9.7	95	1.6	0.43	1.2
(line)	10.5	11	200	40	1.00	2.4	93	1.8	0.40	1.4



Scaling to App C for MVD's up to 160μm has been demonstrated

Historical Progress in Technology

Experimental Methods – In-flight Testing

1983-1992	Natural ice cloud characterization, icing instrumentation development, ice detection & protection systems evaluations
1994-1997	NASA/FAA Tailplane Icing Program: explored factors that lead to ice contaminated tailplane stall; developed and evaluated flight test methods and recovery procedures
1997-1999	NASA/FAA/NCAR SLD Icing Flight program: cloud characterization, ice shape & performance measurements. Data used to develop SLD icing certification envelope.
2000	Alliance Icing Research Study: Icing remote sensing validation
2001	Piloted Icing Flight Simulator: flight data used to validate an ice contamination effects flight training simulator
2001-2002	Smart Icing Systems Flight Tests: flight data to develop and evaluate systems identification methods for isolating icing effects on airplane performance, stability & control

Historical Progress in Technology

Experimental Methods – Ground-based Testing

1989	Developed methods for testing aerodynamic penalties resulting from application of de-icing fluids
1985-1990	Developed ice casting methods for creation of realistic ice shape models to be used in dry-air wind tunnel performance testing
1985-Present	Developed methodology for collection efficiency measurements on airfoils, wings, engine inlets and other aircraft surfaces
1990-1995	Developed visualization methods for shed ice particle tracking
1995	Adapted laser sheet flow visualization methods for use in icing cloud; examined effects of ice growth on delta wing leading edge vortices
1990-Present	Developed procedures for aero-testing of ice shape geometries ranging from castings to simplified representations of ice shape features; examination of Reynolds and Mach number effects
2003-2006	Development of methods for simulation of SLD icing conditions

Historical Progress in Technology

Experimental Methods – Icing Scaling

1982 – 1989	Preliminary tests of methods to scale model size or test conditions using combinations of matched similarity parameters
1990 – 1993	Experimental evaluation of early scaling methods; scaling for rime ice demonstrated; ability to scale LWC shown using Olsen method
1993 – 1999	Importance of surface phenomena demonstrated; demonstrated significant improvement by including Weber number in scaling methodology
2000 – present	Preliminary study of scaling for intercycle ice accretion performed; scaling methods incorporating water-film thickness proposed and evaluated; scaling for SLD conditions begun; effect of drop MVD on ice shape being mapped
2003	Release of Icing Scaling Manual
2006	Addendum to Icing Scaling Manual to include SLD scaling

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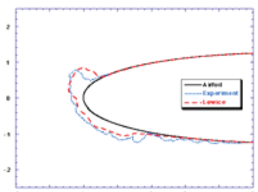
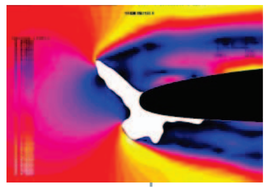
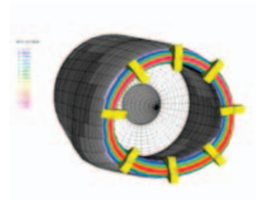
Historical Progress in Technology

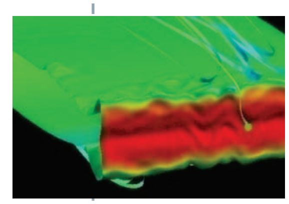
Computational Methods

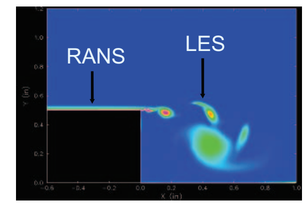
1980s	1990s	2000s











1980s

- **LEWICE development**
- **Early 2D performance analysis studies**

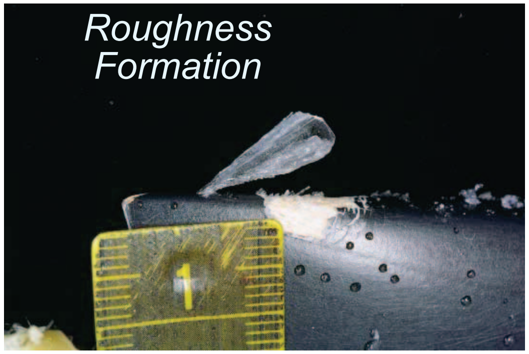
1990s

- **LEWICE3D development**
- **Release of LEWICE 2.0**
- **2D grid sensitivity and turbulence model evaluations**
- **Early 3D performance analysis studies**
- **Development of stand alone thermal IPS simulation methods**

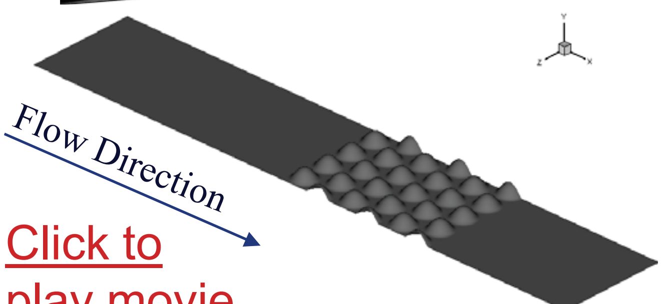
2000s

- **Release of LEWICE3D version 2**
- **Collaboration with Boeing on use of LEWICE3D for 787 analysis**
- **Release of LEWICE 3.2.2; includes initial modifications for SLD**
- **International release of LEWICE**
- **Automated grid generation for LEWICE**
- **Release of SmaggICE 2.0**
- **Unsteady DES methods for iced performance analysis**
- **Thermal IPS model in LEWICE 2.2**

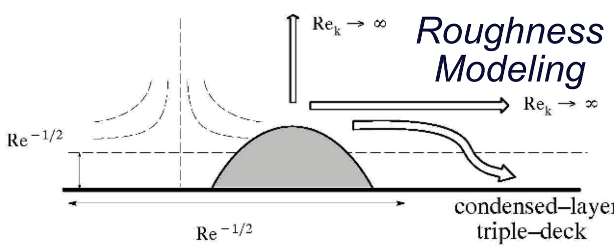
Ice Accretion Modeling



Feather growth



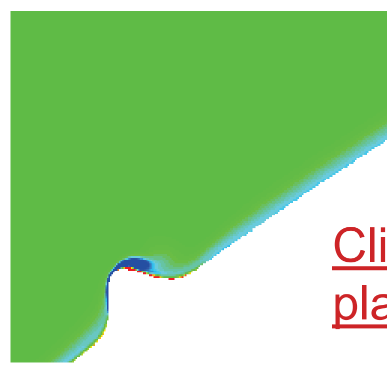
Click to play movie



Roughness Modeling

Examine the physics of ice accretion to understand:

- Droplet impact dynamics (splashing, break-up, re-impingement)
- Surface water transport
- Heat transfer
- Roughness formation
- Phase change kinetics
- Scallop ice (swept wing) shape formation



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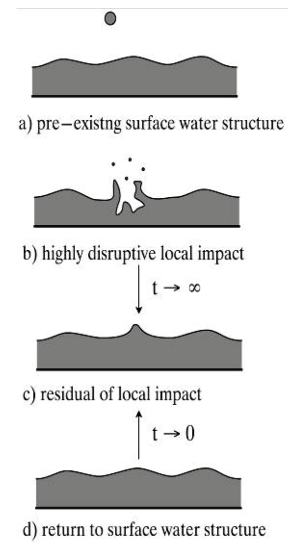
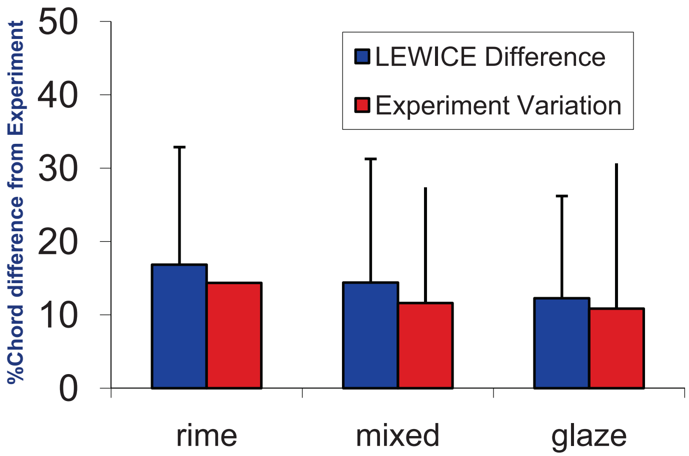


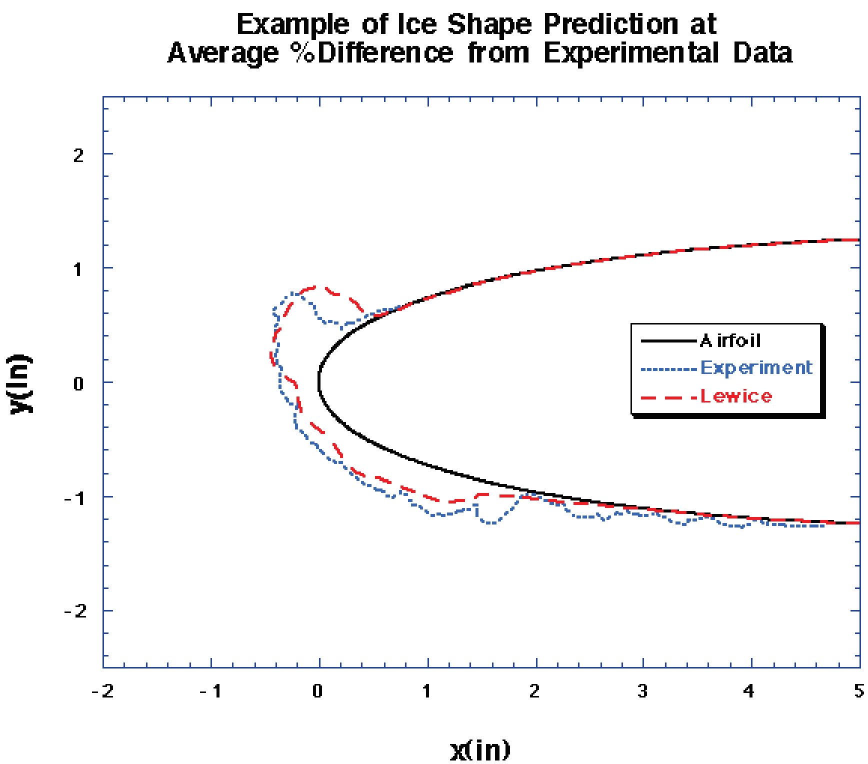
Ice Accretion Computational Modeling

LEWICE – 2D Ice Accretion Code

Ice Shape Tracing; Validation Database

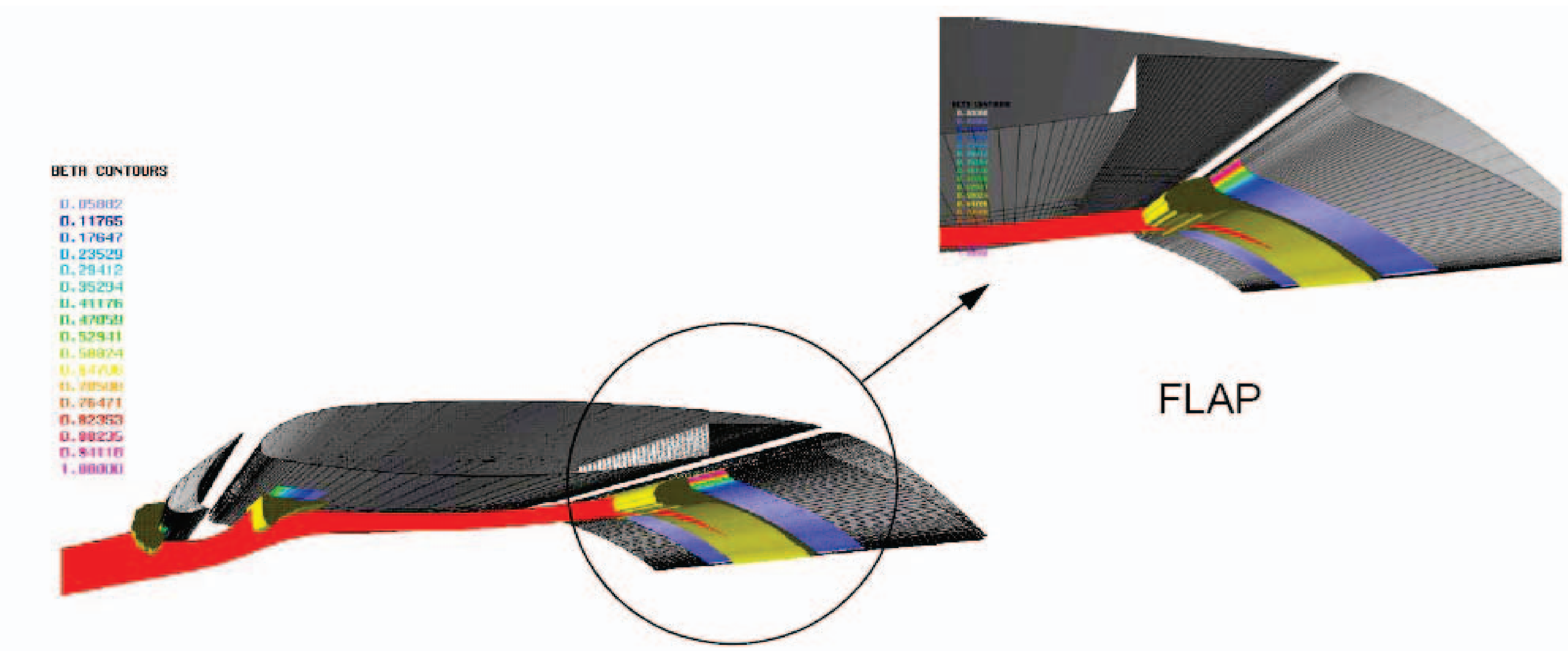


Ice Shape Comparison Results Comp. vs. Exp.



Ice Accretion Computational Modeling

LEWICE3D – 3D Ice Accretion Code



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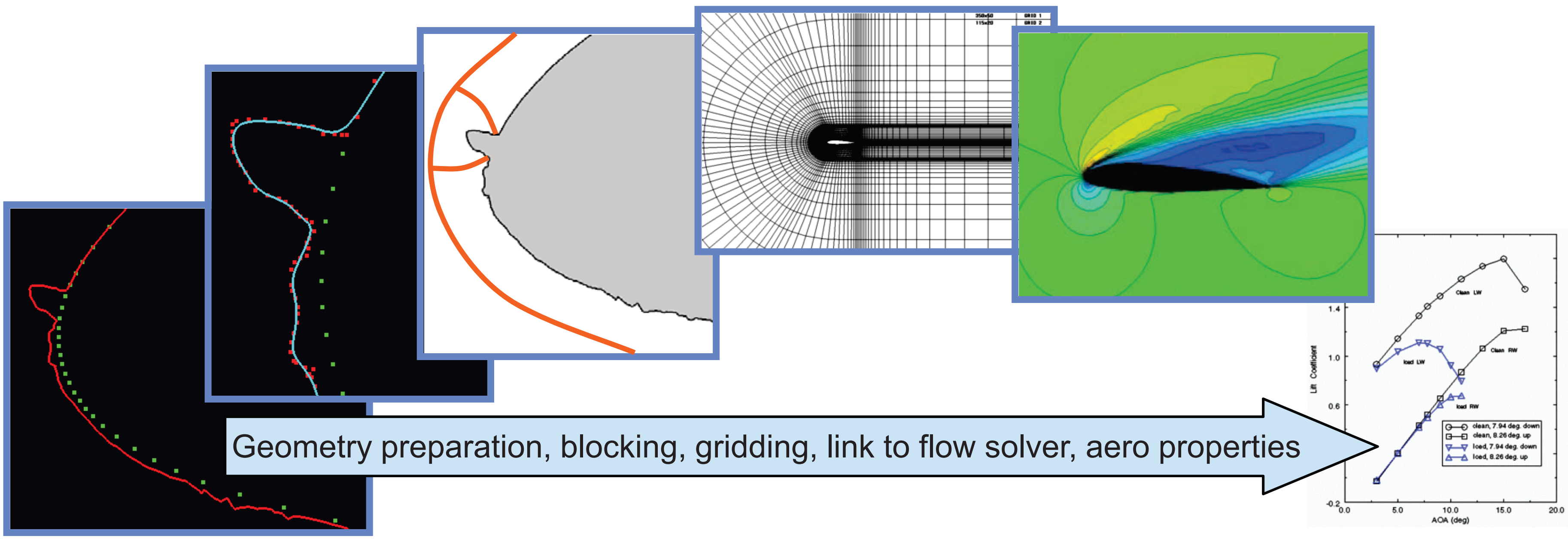
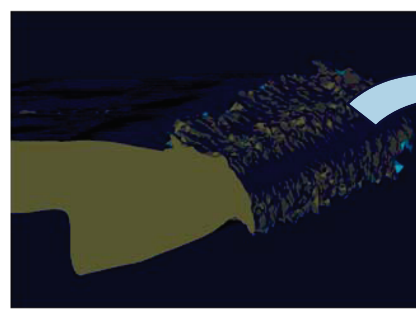
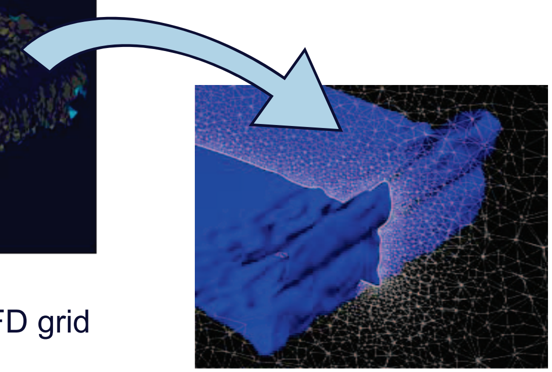
Iced Aircraft CFD Modeling



- Ice feature effects
- Identification of critical ice shapes
- Surface modeling and grid generation
- Turbulence modeling and multi-phase flow
- Time dependent/adaptive gridding
- CFD modeling for 3D surfaces
- Roughness effects (unsteady, multi-scale)
- 3D particle tracking through unsteady/separated flow





Scanned solid to CFD grid

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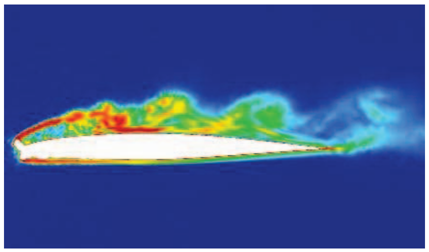
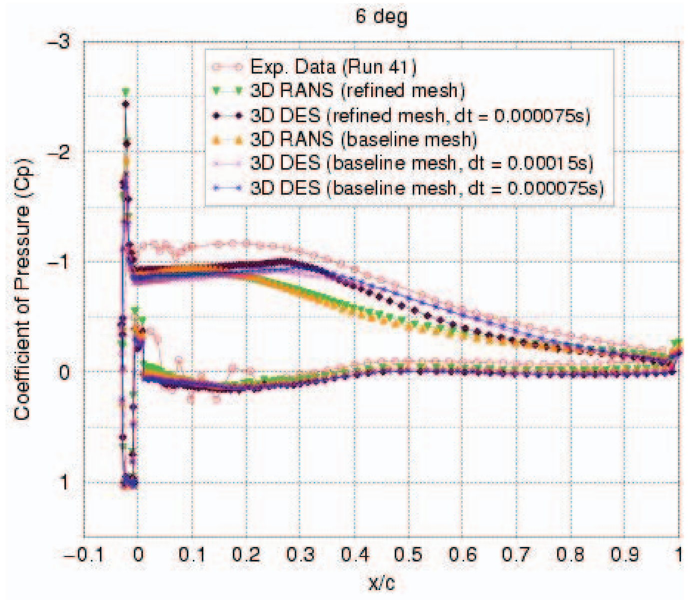
Iced Aircraft CFD

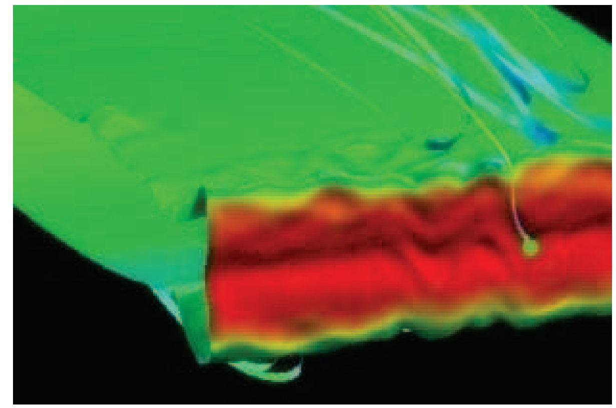
CFD Studies

1.) Ice feature effects, identification of critical ice shapes



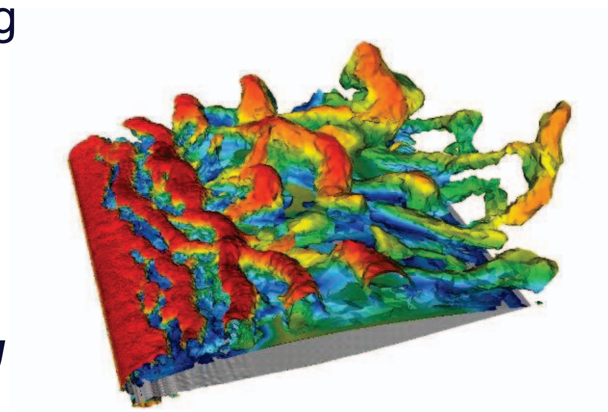


3.) CFD modeling for 3D surfaces

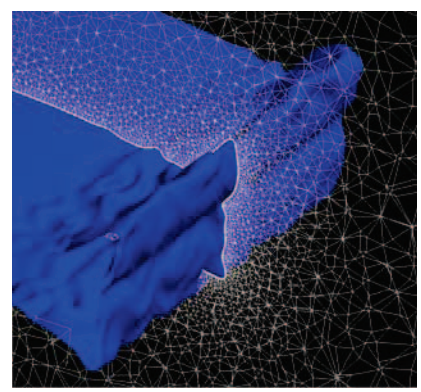


2.) Turbulence modeling and time dependent/ adaptive gridding for icing topology

Turbulence generation behind a leading edge ice shape



4.) Roughness effects (unsteady, multi-scale)



Historical Progress in Technology

Computational Methods - LEWICE

1991 – Release of LEWICE version 1.0; capable of predicting rime ice accretion

1993 – Release of LEWICE 1.3; enhancements to glaze ice accretion capability

1995 – Release of LEWICE 1.6; improved ability to simulate long duration ice accretions, enhancements to usability

1998 – Release of LEWICE 2.0; major overhaul to improve accuracy, reliability, and robustness; implemented industry-standard software development and maintenance methods; transition from research tool to production tool

2002 – Release of LEWICE 2.2; added capability to analyze thermal ice protection systems

2004 – Release of LEWICE 3.0; added capability to use LEWICE with an adaptive grid Navier-Stokes code

2006 – Release of LEWICE 3.2.2; added SLD capabilities

Historical Progress in Technology
Computational Methods – LEWICE3D

1991	Initial version of LEWICE3D with integrated 3D Hess-Smith Panel Code
1993	Initial version of grid based LEWICE3D for body fitted grids
1994	Support for unstructured flow solutions added.
1995	Support for simple cartesian grids added for 3D panel code interface
1996	Support for Oct-tree type grids add for improved 3D panel code interface. ICEGRID3D developed to generate Oct-tree type grids about panel models.
1997	Monte-Carlo trajectory algorithm developed for complex regions such as ducts, radomes, wing roots
1998	Capability to handle Navier-Stokes based grids added.
1999	Developed simpler, faster, Oct-tree type grid code for 3D panel code interface (PATCHGRID).
2001	Development of LEWICE3D post-processor to generate off-body concentration ratios (CONFAC3D)
2002–Present	Parallelization of LEWICE3D, with both Open MP and MPI, leads to significant decreases in turn around time

Historical Progress in Technology

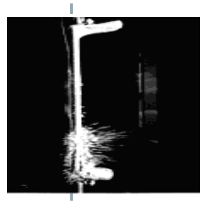
Computational Methods – Performance Analysis

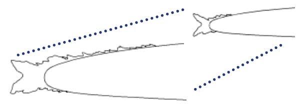
1983 – 1991	Examined use of existing 2D and 3D CFD tools; results indicated that methods could be used for pre-stall conditions; difficult to generate grids for ice shape geometries; identified approach for analysis of rotorcraft performance losses due to icing
1995 – 1999	Investigated use of new turbulence models and began development of tools to aid in grid generation for ice shape geometries; use of new turbulence models improved capability to determine stall behavior however will require move to unsteady analysis and LES/DES methods; grid sensitivity studies indicate that some smoothing of surface geometry to allow easier grid generation is allowable
2000 – present	First release of SmaggICE, computational tool to aid in development of grids for ice shape geometries
Current	Use 3D unsteady methods to identify stall behavior of iced aircraft

National Aeronautics and Space Administration

Historical Progress in Technology

Flight Dynamics





1980s

- **Initial testing of stability & control parameters on NASA Twin Otter**
- **Classic longitudinal flight test techniques with artificial ice shapes**
- **Application of digital inertial data system for stability and control derivative estimation for artificial ice and natural conditions**
- **Tailplane Icing Project develops methods for evaluation of stability and control parameters for iced aircraft**

1990s

- **Refinement of analysis techniques and flight test techniques with artificial ice shapes**
- **Tailplane Icing Project builds upon prior experience to quantify iced tailplane effects**
- **Investigations of scale model tailplane performance parameters**
- **Investigation of effects of tailplane icing using scaled and full-scale wind tunnel tests.**

2000s

- **Subscale model testing of Twin Otter in Bihrle Applied Research spin tunnel**
- **Iced aircraft state assessment research at UTSI supported through NRA**
- **Flight testing to develop parameter ID methods in support of Smart Icing Systems studies and Systems Technology, Inc. SBIR.**
- **Development of Ice Contamination Effects Flight Training Device (ICEFTD) to train pilots on effects of ice accretion.**
- **Development of iced aircraft flight simulation model of Twin Otter and Cessna business jet.**
- **Dynamic wind tunnel testing of iced S-3B Viking to obtain data for simulation model.**

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Icing Effects on Aircraft Controllability

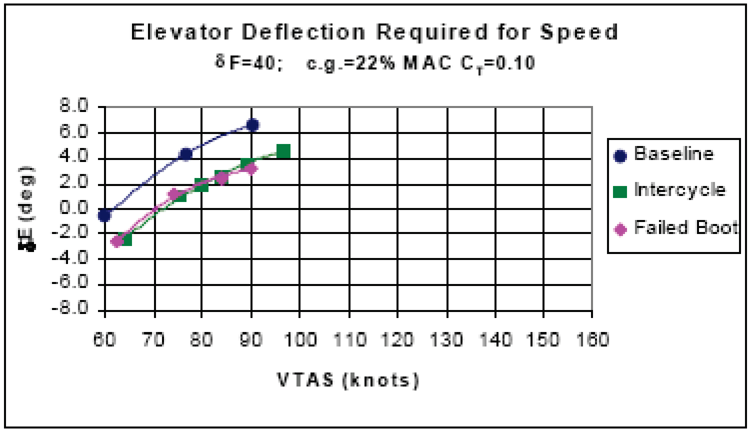
Preventing Iced Flight Dynamics Loss of Control

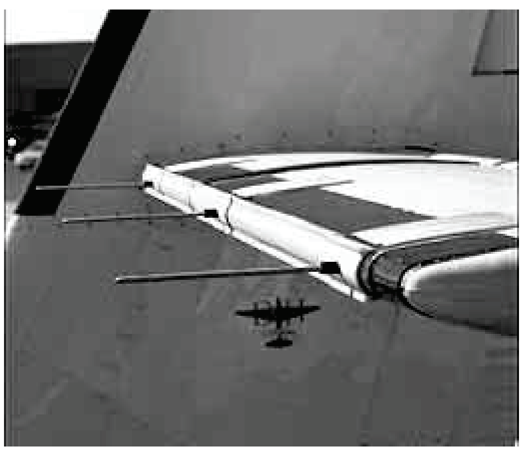
- Technical Approach
  - Develop understanding of how “clean” aero-performance and S&C models are affected by ice accretions
    - Analysis of flight data (existing and future) using PID methods
      - Simulated and natural ice records with flight dynamics package
    - Develop and use iced aerodynamic CFD tools to predict aircraft response
  - Develop onboard vehicle state assessment technologies to determine the S&C authority margins as ice accretes on airframe or as flight conditions lead to upset
    - Alert pilots through IIFD products to exit icing conditions and/or change flight condition
  - Develop modified control laws to prevent LOC or manage recovery
    - Limit flight envelope to enable recovery and safe landing

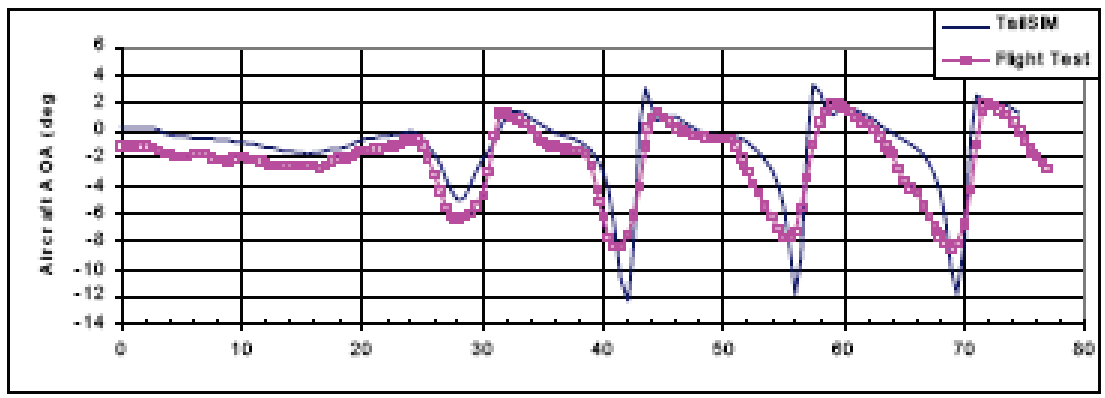
Fligth Dynamics

Tailplane Icing Effects

- Various artificial ice shapes tested
- Static testing performed to determine degradation on performance parameters
- Dynamic testing performed using zero-G pushover maneuver



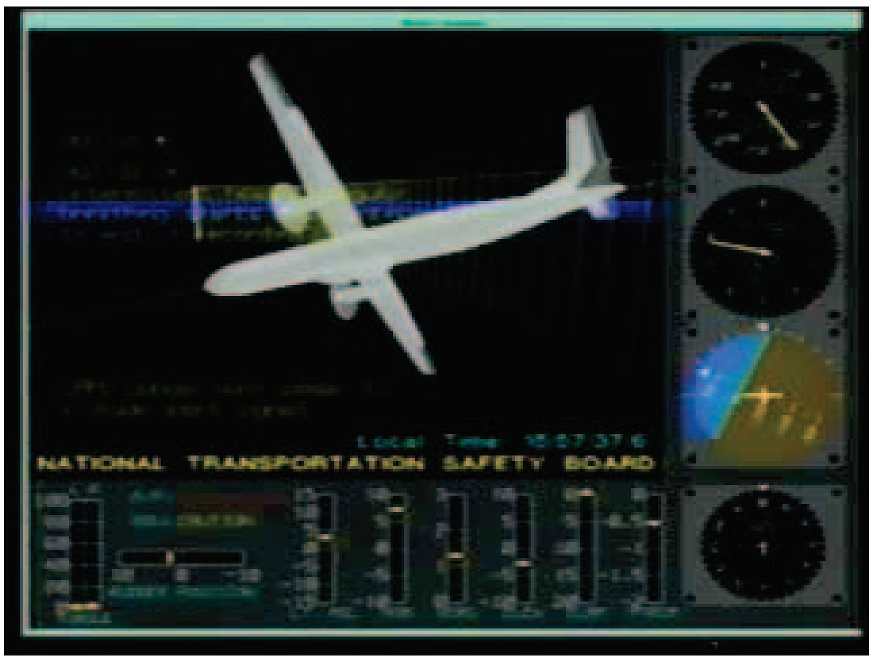




Icing Effects on Aircraft Controllability

Iced Flight Dynamics Loss of Control (LOC)

- Multiple incidents and fatal accidents have occurred recently in which ice accretions were a causal factor
  - IPS usually operating, autopilot masked control changes
- Aircraft icing LOC research areas
  - Identification and modeling: premature stall and control authority margin
  - Reconfigurable controls for recovery
  - Envelope limiting methodology for continued flight through landing



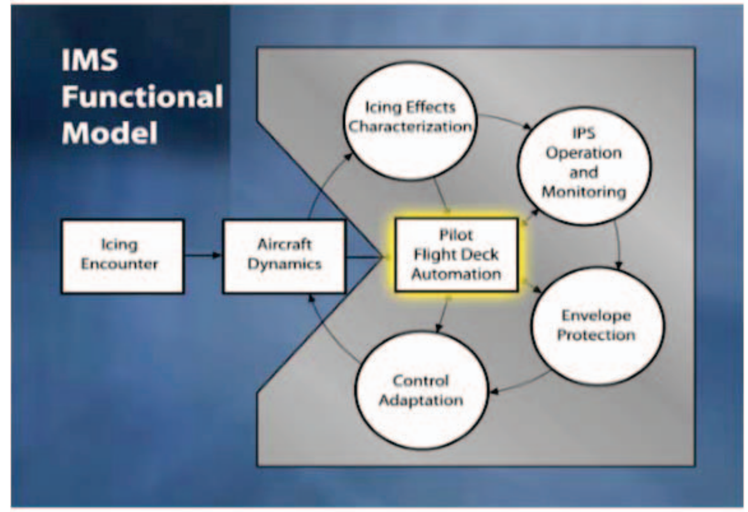
1994 - ATR-72, Roselawn, IN

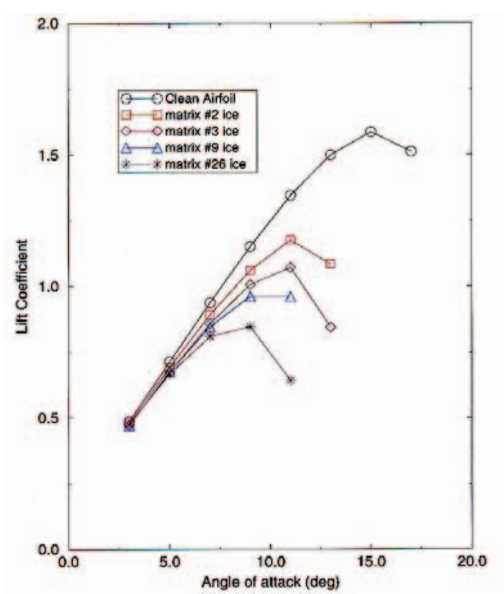
- 68 fatalities
- Aileron hinge moment reversal with ridge of ice beyond the deicing boots

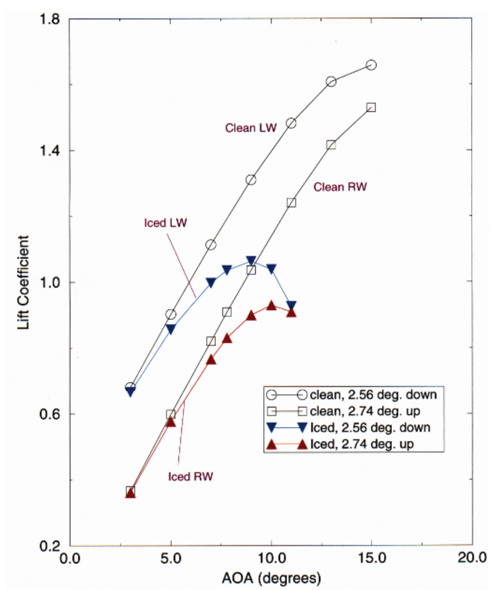
Click to play movie

Research in Iced Flight Dynamics

- Smart Icing Systems (SIS)
  - Concept that senses the presence of ice, activates and manages the IPS, provides the pilot with information on aircraft performance and S&C
  - PID methods were researched to characterize aerodynamic state of the vehicle. Flight envelope and autopilot models were developed. Flight management systems were examined for control response automation
- Aero-performance CFD
  - GRC iced aero CFD tools identified premature stall and subsequent roll-off in aircraft trajectory consistent with DFDR data







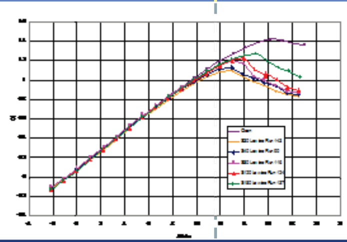
Final NTSB report on Comair Flight 3272 released on November 4, 1998

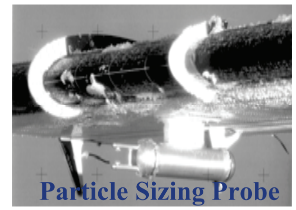
- The Findings state: *"The accident airplane's left roll tendency was precipitated by a thin layer of rough ice"* and may have been further affected by an asymmetric ice shed or aileron deflection

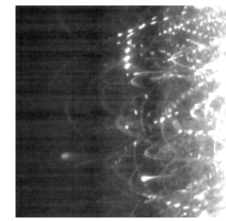
Historical Progress in Technology

Experimental Databases

1980s	1990s	2000s







1980s

- **Ice shape profiles from various airfoils obtained in the IRT**
- **Ice shape profiles and icing cloud conditions from in-flight measurements on the NASA Twin Otter**
- **Iced airfoil performance characteristics using simplified artificial ice shape geometries**

1990s

- **Iced airfoil performance characteristics using complex casts of actual ice shape geometries**
- **Scaled ice shape data covering an extensive range of App. C conditions**
- **Collection efficiency data covering a range of airfoil and engine inlet geometries**
- **Icing cloud data for characterization of SLD icing environment**
- **Ice shape castings and photos from swept wing geometries used to identify mechanism of scalloped ice shape formation**

2000s

- **Extension of ice shape profiles and collection efficiency databases to include SLD conditions**
- **Scaling databases extended to include SLD conditions**
- **Creation of droplet splashing and ice mass databases; aid in identification of SLD conditions and in validation of SLD computer simulation codes**
- **Performance degradation data for finite swept wing with scallop ice shape castings**
- **Stability and control data from sub-scale and full scale iced Twin Otter models**

Historical Progress in Technology

Experimental Database Development

1983 – present	Ongoing accumulation of ice shape tracings provides extensive data for use in validation of ice shape simulation methods; Database made available to public via Web
1985 – 2001	Development of collection efficiency database in collaboration with Wichita State University
1995 – 2000	Modern Airfoil Project develops ice shape and associated airfoil performance database on airfoils representative of current usage
1996	Electro-thermal ice protection system model tested to provide database for validation of thermal ice protection system simulation software
1999-2002	Tailplane Icing effects on sub-scale & full-scale business jet T-Tail
2002	Testing of swept wing model to determine effects of sweep on ice shape development and resulting performance losses
2007	Development of SLD ice shape database for validation of simulation tools

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Summary of Airframe Icing Goals

- ✓ Continue to meet customer needs for icing simulation tools and databases
- ✓ Reduce costs of icing certification through use of simulation methods
- ✓ Enhance safety of flight by allowing simulation of conditions unattainable through flight testing
- ✓ Improve accuracy, reliability, range, and usability of simulation tools through creation of comprehensive validation databases

NASA/CP—2009-215797

NASA Iced Aerodynamics and Controls Current Research

Gene Addy
Co-Associate Principal Investigator
Integrated Resilient Aircraft Controls Project
Aviation Safety Program

Current airframe icing research at NASA is funded through:

Aviation Safety Program
Integrated Resilient Aircraft Controls (IRAC) Project

- IRAC Scope:

  ...to advance the state of aircraft flight control to provide onboard control resilience for ensuring safe flight in the presence of adverse conditions.

- IRAC Goal:

  ...to arrive at a set of validated multidisciplinary integrated aircraft control design tools and techniques for enabling safe flight in the presence of adverse conditions.

IRAC Project Plan

Adverse conditions categorized as:

- **Failures** – Static and dynamic actuator failure effects (single and multiple)
  - ex.: locked stabilator (F-15), stabilator driven to local angle-of-attack, reduced control surface effectiveness due to icing
- **Damage** – aerodynamic and structural damage (wing and/or tail)
  - ex.: destabilizing angle of attack feedback to the canards, wing damage simulation (F-15), locked flaps (F-18), aerodynamic uncertainty caused by icing, engine degradation due to icing
- **Upset** – Unusual attitudes, stall/departure
  - ex.: elevated AOA (pre-stall), stall

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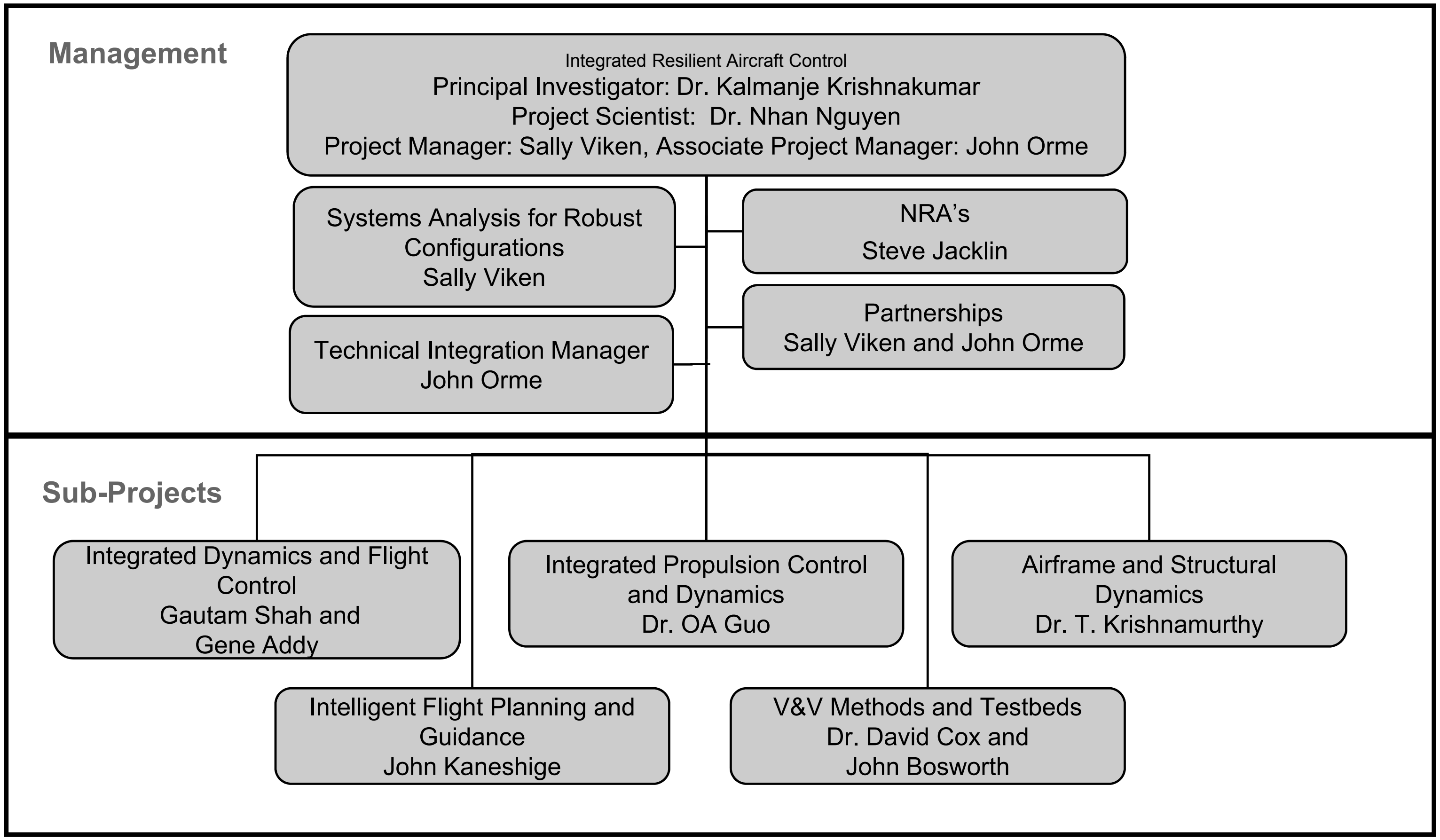
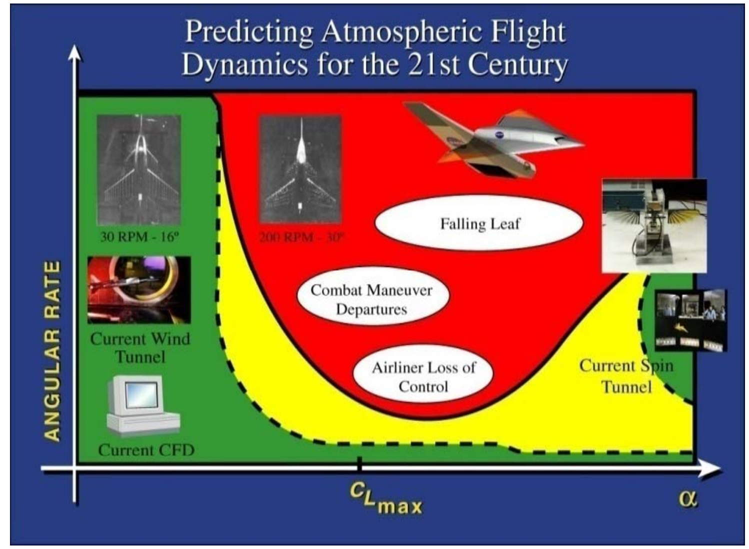
National Aeronautics and Space Administration

Aviation Safety Program
Integrated Resilient Aircraft Control



IDFC- Modeling Overview

- Objective
  - Develop experimental and computational methods to model and predict aircraft responses during IRAC adverse conditions: damage, upset, failures, including icing.
  - Develop models suitable for simulation, analysis, and flight control design
- Technical Challenge
  - Conventional modeling techniques provide limited to poor aircraft response prediction under IRAC adverse conditions where aerodynamics are characterized by separated flows, vortical flows, shock waves, or nonlinear-unsteady behaviors.



- Technical Approach
  - Develop advanced modeling and test techniques to characterize aircraft responses and validate via wind tunnel, simulation, and flight testing.
- Significance
  - Ensure scientific validation of models and control laws
  - Characterize uncertainties, reduce risks, increase efficacy of designs

Icing research in support of IRAC Project:

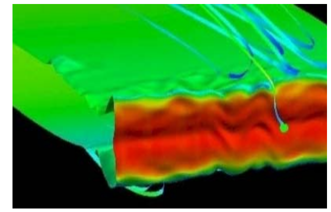
- **Aircraft Icing Modeling**
  - **Ice-Contaminated Aerodynamics Modeling**
    - ❑ Effects of ice contamination on aircraft aerodynamics
    - ❑ CFD modeling of ice-contaminated aircraft aerodynamics
  - **Advanced Ice Accretion Process Modeling**
    - ❑ Physics of ice accretion on complex geometries
    - ❑ Computational modeling of ice accretions

Development of Iced Airframe Aerodynamic Parameters for Control Analysis Input

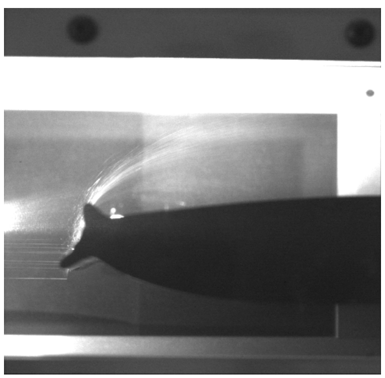
Icing Physics Studies

Ice Accretion Simulation

Icing CFD Analysis

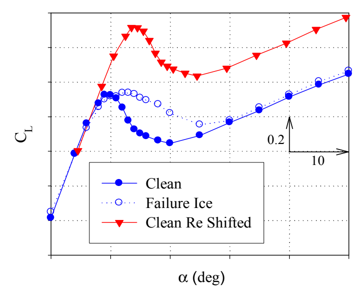


Ice Shape Database



Iced Airframe Aerodynamic Database

Iced Airframe Aerodynamic Model



Control system modeling that includes icing

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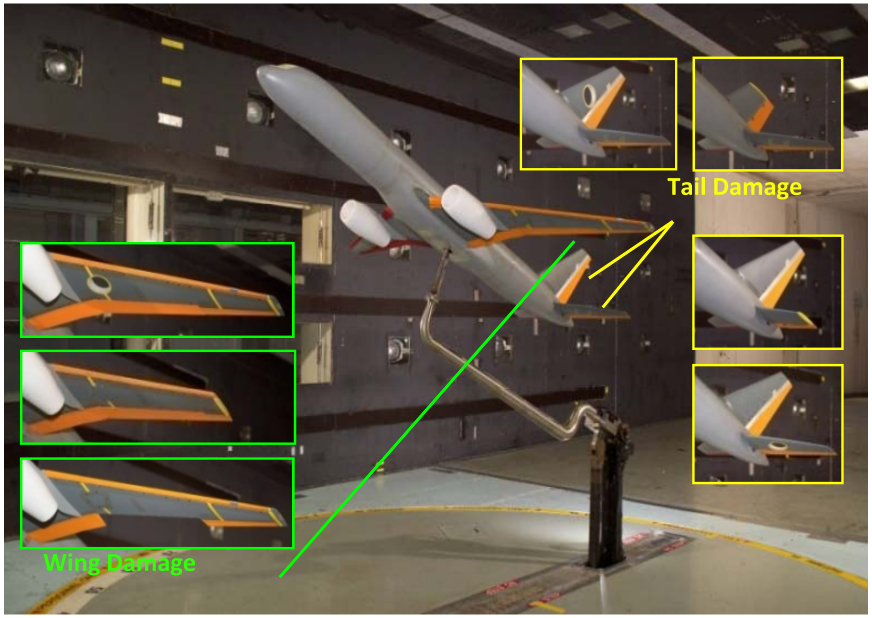
IRAC Testbed



GTM Wind Tunnel Testing, NASA Langley 14x22

- Generic Transport Model (GTM)
  - Small scale models of a large commercial transport – both wind tunnel (3.5%) and flight (5.5%) available

8

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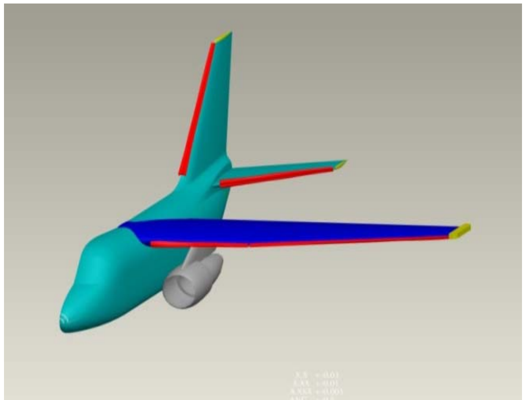
Iced GTM aerodynamics studies

Objective

- Investigate the effects of icing on GTM aerodynamics

Approach

1. Use LEWICE ice accretion codes to predict ice shapes for full scale GTM
2. Use ice shapes obtained from LEWICE in conjunction with CFD code USM3D to determine aerodynamic effects of ice on GTM
3. Scale, using geometric scaling and engineering judgment from previous icing scaling research, the ice shapes from LEWICE to obtain aerodynamically similar ice shapes
4. Manufacture these ice shapes, attach them to GTM wind tunnel model, and perform wind tunnel tests to study the effects of ice contamination on model aerodynamics
5. Perform CFD study of ice contaminated, subscale GTM
6. Provide data from wind tunnel study to researchers running GTM simulation for Intelligent Flight Planning and Guidance



LEWICE used to predict ice shapes

Artificial ice shapes attached to scale model S-3 wing

GTM method is based upon prior research with S-3.

Scale model S-3 with ice shapes attached on wind tunnel force balance

IRAC Icing Research Outcomes & Impact

Outcomes

- More thorough understanding and models, theoretical and empirical, of icing physics and ice accretion processes for complex (3D) airframe shapes
- Advanced 3D ice accretion prediction codes
- CFD methods for iced aerodynamics
- Better understanding of aircraft iced aerodynamics and its effects on control surface effectiveness

Marks of progress – impact on aircraft icing technology

1. 3D ice accretion codes more widely accepted and used by industry and government agencies for both design and development as well as aircraft icing certification
2. Iced aerodynamics methods are employed by industry for design, development, and certification
3. Perform validation exercises in order to achieve success
    - Ultimately, full-scale testing is needed to provide validation

Airframe Icing Research Collaborations

- Space Act Agreements
  - American Kestrel – LEWICE2D dissemination and support
  - Boeing – LEWICE3D development
  - Goodrich – icing physics
- International Agreements
  - INTA (Spain) – icing physics, droplet dynamics
  - ONERA (France) – iced aerodynamics
  - NRC-Canada – thermal scaling for IPS operation and runback icing
- NASA Research Announcements (NRA)
  - University of Tennessee Space Institute (UTSI) – aircraft health monitoring for icing

NASA/CP—2009-215797

National Aeronautics and Space Administration

Icing Branch Current Research Activities in Icing Physics

Mario Vargas

Airframe Icing Workshop
NASA Glenn Research Center

Cleveland, Ohio

June 9, 2009

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Outline

- Swept Wing Icing
- Scaling
- Droplet Break-up –NASA/INTA
- Icing Physics Flow Laboratory

SWEPT WING ICING PHYSICS

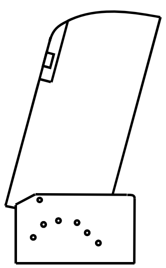
Critical Distance Database

Technical Lead: Mario Vargas

Main Characteristics of Ice Accretions on Swept Wings

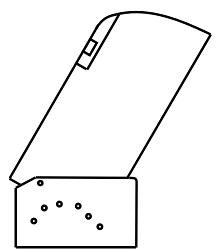
V=150 mph, T_{total}=25°F, LWC=0.75g/m^3, MVD=20µm

No-scallop



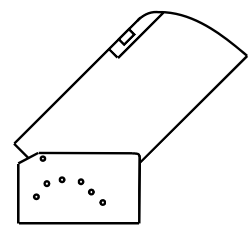
Airfoil at 15°

Incomplete Scallops



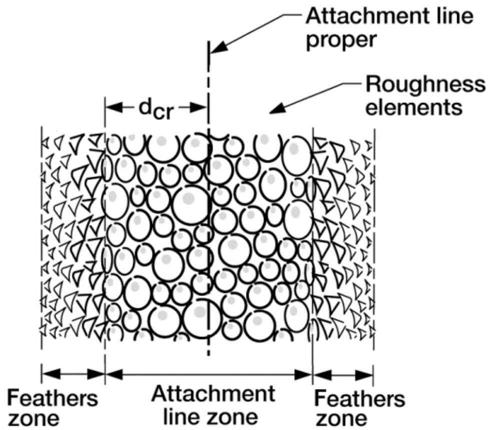
Airfoil at 30°

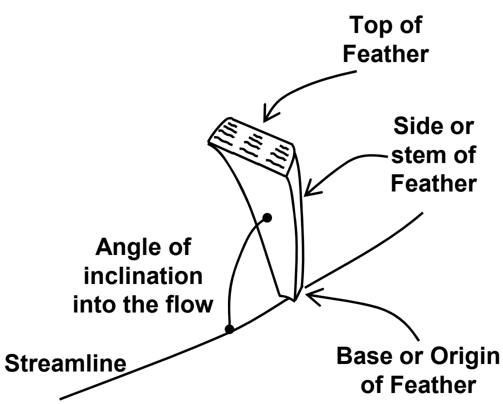
Complete Scallop

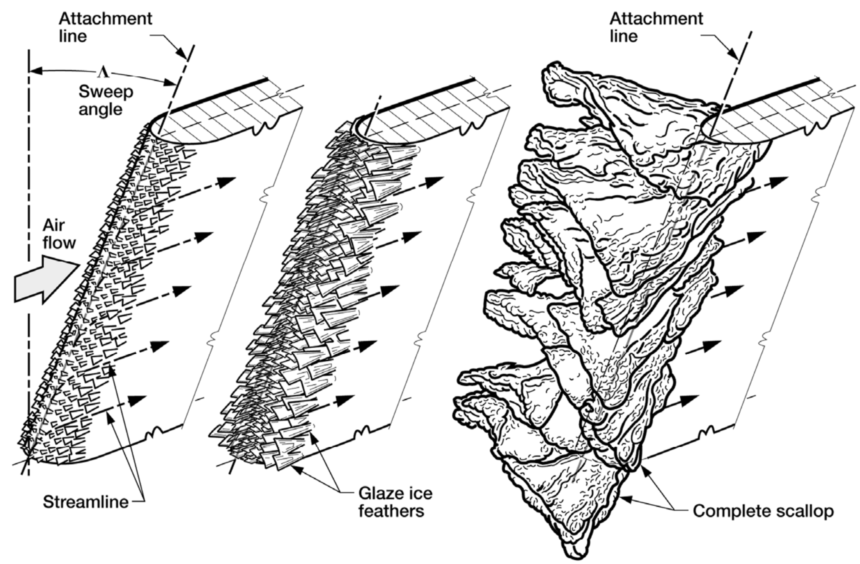


Airfoil at 45°

How Ice Accretions Develop on a Swept Wing







Critical Distance, d_{cr}

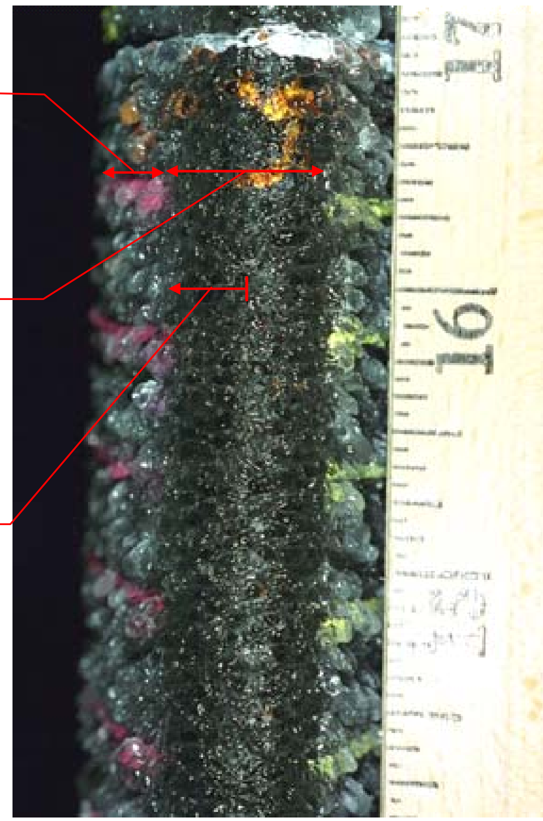
For a given geometry, determines what type of ice accretion will develop

Λ=30^{O}, V=150 mph, T=25 ^{O}F, LWC=0.75 g/m^3, MVD=20 μm, τ=2 minutes

Glaze ice feathers zone

Attachment line zone

Critical distance d_{cr}



Reasons to Develop a Database of d_{cr} Measurements

- Prediction of the critical distance for a given geometry will allow us to determine in advance what type of ice accretion will form: complete scallop, incomplete scallop or no-scallop

- A database of critical distance measurements against icing conditions will be used to develop and validate a model of where the feathers develop with respect to the attachment line. The model will be implemented in LEWICE 3D

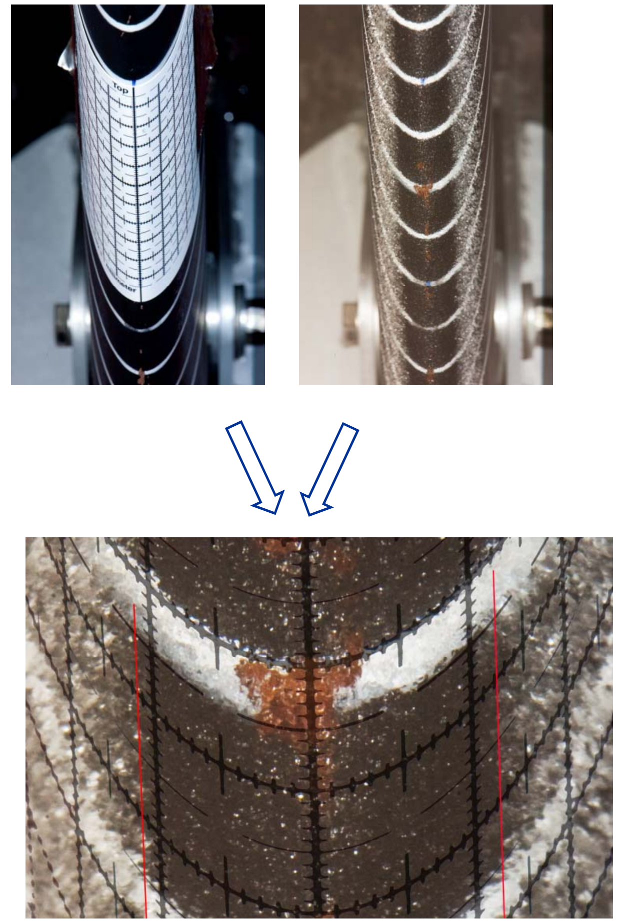
Current Research Work

- Initiated Development of Database of Critical Distance Measurements against Appendix C Icing Conditions
- Three Experiments were conducted
  - Two at the Goodrich Icing Wind Tunnel (IWT), February and April 2009
  - One at the Icing Research Tunnel (IRT), May 2009
- Data is being analyzed and the results will be presented at the 2009 AIAA 1st ASE conference in San Antonio, TX
- Work is funded under the NASA Integrated Resilient Aircraft Controls (IRAC) Project of the Aviation Safety Program and is listed as a milestone for the project

Critical Distance Measurement Experiment

Goodrich IWT Test Setup

Measurement Technique



- Time Sequence Imaging Technique (TSIT)
- Three cameras used
- One image every 2 seconds
- Grid image and ice accretion image combined to obtain measurement of d_{cr}

Extension and Validation of Scaling Methods

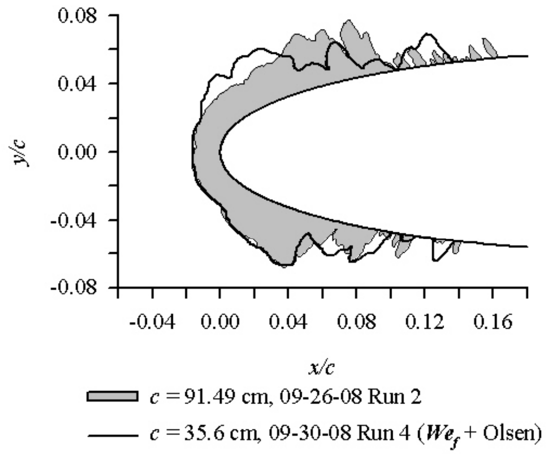
Technical Leads: Jen-Ching (Paul) Tsao and Eric Kreeger

Develop Scaling Methods in SLD

- Develop scaling methods for SLD conditions
  - Evaluate the film Weber number scaling proposed by Dr. Alex Feo of INTA for glaze icing in SLD
  - Apply the Olsen method to scale *LWC* and T_{st} in SLD & App. C
  - A 3-day test entry (Sep. 08) in the IRT
  - The result will be presented in the 2009 AIAA 1st ASE conference in San Antonio, TX

Develop Scaling Methods in SLD

Evaluate Feo's film Weber number in glaze icing



Date/Run	c, cm	α, 0	t_{st}, °C	t_{tot}, °C	V, kt	MVD, µm	LWC, g/m^3	τ, min	β_0, %	A_c	$\beta_0 A_c$	n_0	We_L, 10^6
09-26-08/2	91.4	0	-11.0	-10.2	76	147	1.68	10.0	94	1.48	1.39	0.32	0.68
09-30-08/4	35.6	0	-8.1	-5.5	142	66	1.17	4.0	94	1.98	1.87	0.29	0.92

Extend Scaling Methods to Swept Wing Icing

- Extend current scaling methods to swept wing icing applications by modifying the expressions for the heat transfer coefficient, the collection efficiency and the freezing fraction at stagnation
  - For the heat transfer coefficient use Reshotko's expression for a clean airfoil:

$$h_{o,\Lambda} = h_{o,\Lambda=0} * (\cos \Lambda)^{0.5}$$

  - For the collection efficiency the proposed expression is:

$$\beta_{o,\Lambda} = \beta_{o,\Lambda=0} * \cos \Lambda$$

- Experimental validation of the analytical expression for $\beta_{o,\Lambda}$ on a swept NACA 0012 wing section
  - A total of 5-day entry (May & Sep. 08) in the IRT
  - The result will be presented in the 2009 AIAA 1st ASE conference in San Antonio, TX

Extend Scaling Methods to Swept Wing Icing

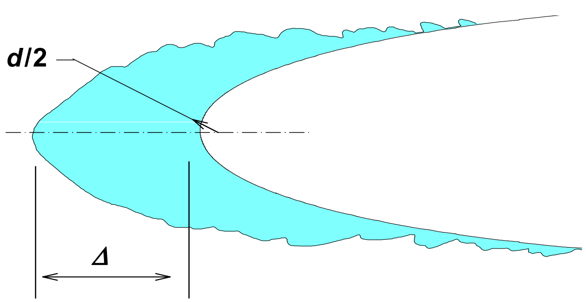
Stagnation Collection Efficiency from Experiment, $\beta_{0,\Lambda}$

Proposed β_0 for NACA 0012 at sweep Λ

$$\beta_{o,\Lambda} = \beta_{o,\Lambda=0} * \cos\Lambda$$

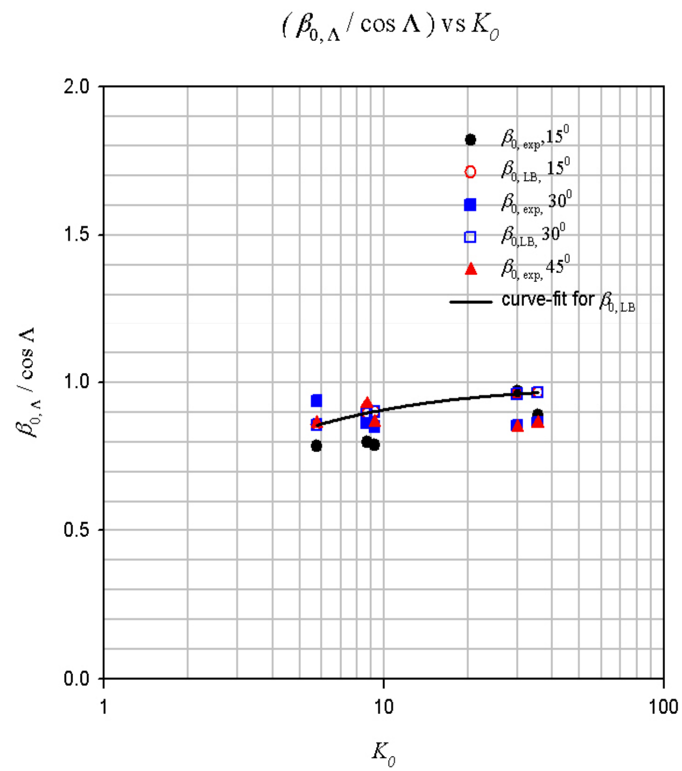
Experimental Validation

$$\beta_{o,\Lambda} = \Delta / (d * n_o * A_c)$$



Δ **Stagnation Ice Thickness**

D **2x Airfoil L.E. Radius**



Extend Scaling Methods to Rotorcraft Icing

- Extend current scaling methods to rotorcraft icing applications
  - Evaluate existing scaling methods for NACA 0012 airfoils at non-zero angle of attack (AoA)
  - A total 7-day entry (Sep. 08 & Feb. 09) in the IRT
  - The result was just presented in the AHS International 65th Annual Forum & Technology Display in Grapevine, TX
- All current scaling work is supported by the NASA Subsonic Rotary Wing (SRW) Project of the Fundamental Aeronautics Program.
- The scaling method development supported by SRW is also applicable to the IRAC goals

National Aeronautics and Space Administration

Droplet Break-up

NASA/INTA Space Act Agreement Research Work

Technical Lead: Mario Vargas

www.nasa.gov

Overview

- Objective of the research effort:
  - *To study large droplet deformation and break-up near the leading edge of large transport airfoils*
- Collaborative effort between NASA and the Instituto Nacional de Técnica Aerospacial (INTA) through a Space Act Agreement.
- Technical lead at INTA is Dr. Alejandro Feo Palacios
- Work is funded under IRAC

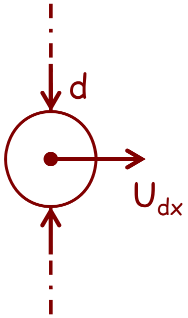
Current Activities

- Icing Branch research participation
  - To develop a high-speed imaging technique in collaboration with the Glenn Imaging Technology Center (ITC) that allows:

    (1) to follow a single droplet time history to deformation and break-up

    (2) to measure diameter, velocity and acceleration of the droplet
  - Lead and participate in the experiments conducted at the INTA test cell
- Low-speed experiment (66 m/s) was conducted at the INTA test cell in Madrid in November of 2008
- High speed experiment (90 m/s) will be conducted in November of 2009 at the INTA test cell

Droplet Break-Up Experiment



VARIABLES

ρ_a; U_{dx}; U_{ax}; d; μ_a; $\sigma_{w/a}$; $(\Delta U_{dx}/\Delta t)$

U_{dx} ≡ droplet velocity in body axis

U_{ax} ≡ air velocity

Icing Physics Flow Laboratory

Technical Lead: Andy Broeren

NASA/CP—2009-215797

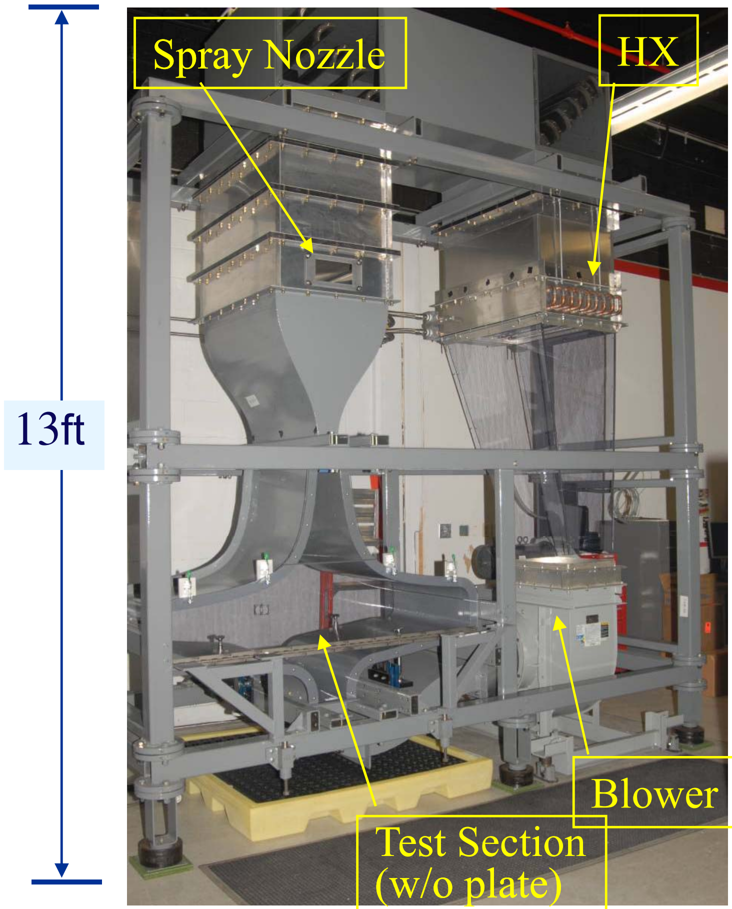
Icing Physics Flow Lab

- Two research facilities are located in the Icing Physics Flow Lab

Vertical Icing Studies Tunnel (VIST)

Droplet Imaging Flow Tunnel (DrIFT)

VIST Dimensions and Specifications



- **Tunnel Dimensions**
  - Plenum: 24-in x 36-in
  - Contraction: 4-in x 30-in
  - Test Section: 64-in x 30-in

- **Tunnel Specifications**
  - Planar stagnation point flow
  - Max Airspeed at contraction 25 m/s
  - Design point V_o = 17 m/s
  - Air Temperature Min = -15°C
  - Planned LWC: 0.1 – 1.5 g/m3
  - Planned MVD: 20 – 2000 µm

VIST Research Activities

VIST Test Section

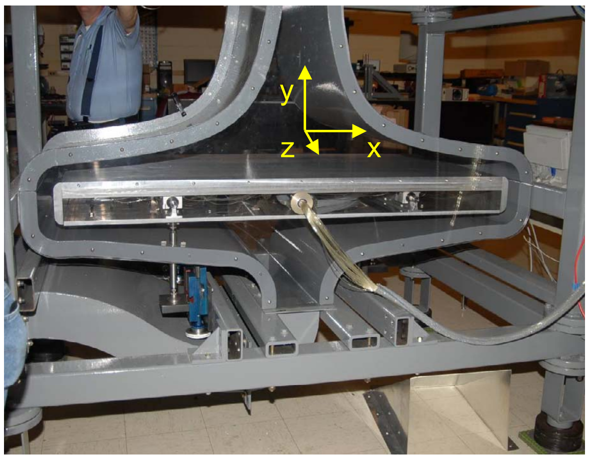


Plate Design

- 60” x 30” in Six Layers:
- Highly polished AL surface w/ 38 pres. taps
- Imbedded heat flux gauges w/ TCs
- Heaters to control surface temp

- **Objective**
  - To understand ice accretion physics in the stagnation region
- **Approach**
  - Create a thick, low-speed planar stagnation boundary layer to allow visualization and measurement of the air-water-ice interface
- **The design point**
  - Re_δ = 630 (δ_{99} = 2 mm, V_{edge} = 17 m/s)
  - Dynamically similar to the stagnation point flow on a large transport wing at $Re_c = 10^7$ by matching Re_δ of the first 2% chord
- **Current Research Activities**
  - Validation and calibration of the facility
  - Measuring flow quality
- **Facility not yet operational, additional resources needed to have it research-ready in FY10**

DrIFT Research Activities

Droplet Imaging Flow Tunnel (DrIFT)

- **Objective**
  - **To develop visualization methods for investigating droplet splashing around an iced airfoil**
- **Approach**
  - **Introduce a stream of mono-dispersed large droplets to impinge on a pre-defined region of an artificial ice shape mounted on an airfoil**
  - **Record with a high-speed imaging and laser-sheet illumination trajectories and deformation**
- **Capabilities**
  - **6” x 6” Test Section**
  - **175 mph (empty tunnel)**
  - **Phantom High Speed Camera**
  - **Sheet Laser and Intensified Camera**
  - **Phase Doppler Particle Analyzer (PDPA)**
- **Current Research Activities**
  - **Development of high speed imaging techniques to measure diameter, velocities, acceleration and deformation of large droplets near a leading edge (NASA/INTA work) funded under IRAC**

NASA/CP—2009-215797

Icing Simulation

Colin Bidwell

NASA Glenn Research Center

June 9, 2009

Outline

- LEWICE
  - Version 3.2.2 Status
  - Current Development
- LEWICE3D
  - Version 2 Status
  - Current Development

LEWICE Major Applications

- General application is the determination of amount and location of ice accretion on an aircraft.
- Used to determine water loading on aircraft surfaces so that the size and location of the ice protection system can be determined.
- Used to design and analyze hot air and electro-thermal ice protection systems.
- Used to determine ice shapes for FAA failed ice protection system test. These ice shapes are built and attached to aircraft by manufacturers for flight tests to insure that the aircraft can still fly with ice resulting from a failed ice protection system.

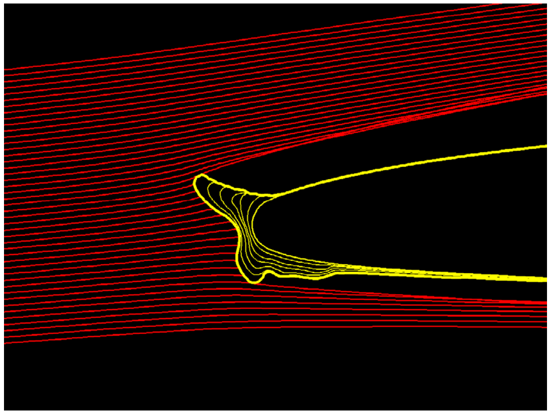
LEWICE 3.2.2 Methodology

- Flow Solver
  - Uses Hess-Smith 2D potential panel code or 2D Navier-Stokes flow solver to determine flow field about surface
- Droplet Trajectories
  - Calculate water droplet trajectories from some upstream location until impact on the surface or until body is bypassed using 4th order predictor-corrector method
- Water Collection
  - Determine water droplet impact location pattern between impingement limits
- Heat Transfer
  - Perform quasi-steady analysis of control volume mass and energy balance in time stepping routine using integral boundary layer method with roughness effects
- Ice Growth
  - Ice growth calculated using scheme based on Messinger Model. Density correlations used to convert ice growth mass into volume
- Iterate
  - With new ice shape, iterate entire routine

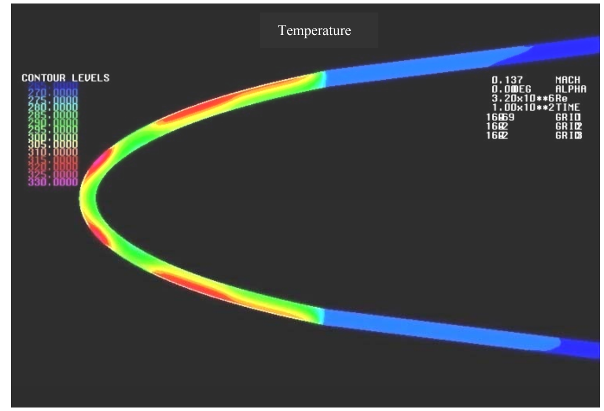
LEWICE Version 3.2.2

- Version 3.2.2 released September 2005
- Version 3.2.2 features
  - Analysis of Hot air and electro-thermal ice protection systems
  - SLD droplet splashing model
  - Droplet breakup model
- Approximations
  - Multi-time step
  - Flow calculated using 2D panel code or 2D Navier-Stokes flow solver
  - Messinger quasi-steady control volume icing model
  - Heat transfer calculated using integral boundary layer algorithm with roughness effects.
  - Surface water loading generated from trajectories calculated from free-stream to surface.

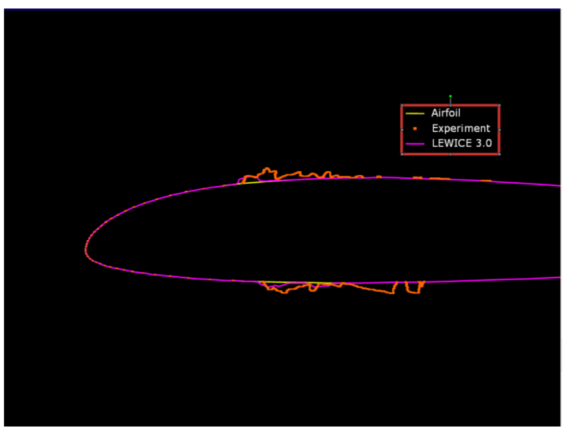
LEWICE – 2D Icing Tool



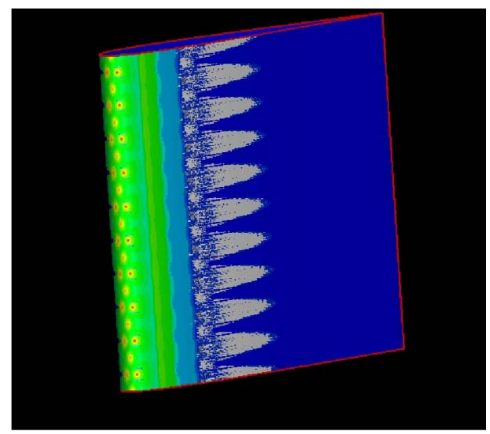
Droplet Trajectory and Ice Shape Prediction



Electro-Thermal System Performance



Residual Ice Prediction



Bleed Air System Performance

Current LEWICE Development

- Mixed phase capability
  - Surface energy balance with ice instead of super-cooled water
- Particle energy balance
  - Evaporation (super-cooled drops)
  - Sublimation (ice particles)
- Automated multi-time step ice accretion using unstructured Navier-Stokes (FUN2D)

LEWICE3D Major Applications

- General application is the determination of amount and location of ice accretion on an aircraft.
- Used to determine water loading on aircraft surfaces so that the size and location of the ice protection system can be determined.
- Used to determine ice shapes for FAA failed ice protection system test. These ice shapes are built and attached to aircraft by manufacturers for flight tests to insure that the aircraft can still fly with ice resulting from a failed ice protection system.
- Used to determine location of icing sensors (don't want to put a sensor in a position where there is no ice).
- Used to determine corrections for cloud measurement instruments (e.g. droplet size probes, liquid water content probes) on an aircraft (the aircraft causes a flow disturbance the result of which is that an instrument mounted on the aircraft will not read the correct free stream cloud properties).

LEWICE3D Methodology

- Flow Solver
  - User supplies grid based flow solution. LEWICE3D can handle multi-block structured grids, "VSAERO" type structured grids, adaptive cartesian grids (ICEGRID/PATCHGRID), and unstructured grids
- Droplet Trajectories
  - Trajectories are calculated using 4th order Adams-type predictor-corrector method developed by Hillyer Norment.
- Water Collection
  - Collection efficiencies for simple 2D or 3D regions can be calculated using a modified LEWICE2D scheme.
  - Collection efficiencies for complex regions are calculated using a quadtree area based collection efficiency method.
- Heat Transfer
  - Perform quasi-steady analysis of control volume mass and energy using integral boundary layer method with roughness effects using 3D strip approach.
- Ice Growth
  - Ice growth calculated using modified LEWICE2D scheme based on Messinger Model. Ice Density model with additions for "scalloped" ice shapes.

LEWICE 3D Version 2

- Version 2 Released March 2007
- Version 2 Features
  - Automated most users inputs
  - Roughness model incorporated
  - Ice density model for scallop ice shapes
  - Variable area collection efficiency method installed which reduces calculation times and insures convergence
  - Dynamic memory allocation and OpenMP and MPI parallelization has been incorporated to optimize memory and speed on modern computers.
- Approximations
  - Single time step
  - Ice shapes calculated along 3D strips
  - Steady or time averaged flow solutions required
  - Grid based application requires user supplied 3D flow solutions on structured, or unstructured grids
  - Messinger quasi-steady control volume icing model
  - Heat transfer calculated using integral boundary layer algorithm with roughness effects
  - Surface water loading generated from trajectories calculated from upstream to surface

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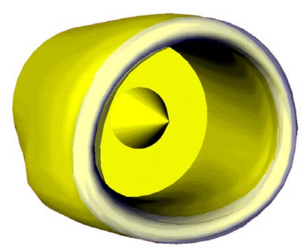
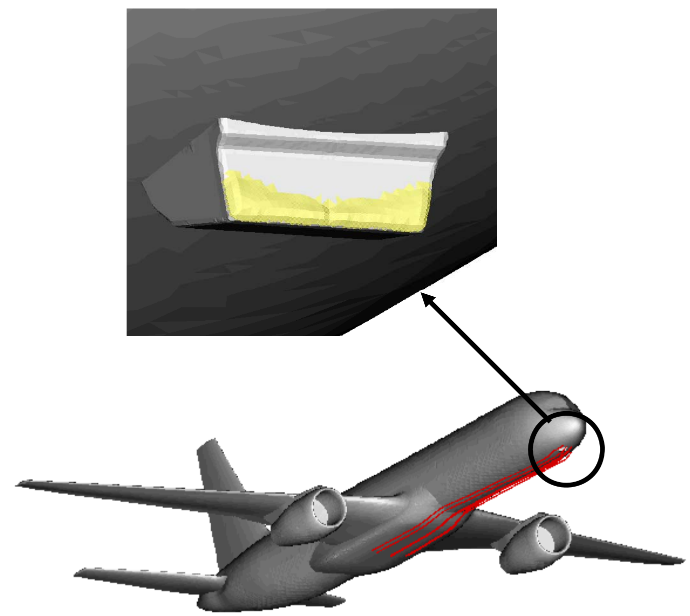
LEWICE3D - 3D Icing Tool

Version 2 of the LEWICE 3D ice accretion computational tool calculates water and ice accretion on complex aircraft surfaces



Boeing 737-300 Inlet



Boeing 757 with FLIR Pod

Current LEWICE3D Development
(LEWICE3D Version 3)

- A grid block transformation scheme which allows the input of grids in arbitrary reference frames, the use of mirror planes, and grids with relative velocities has been developed.
- A simple ice crystal and sand particle bouncing scheme has been included.
- Added an SLD splashing model based on that developed by William Wright for the LEWICE 3.2.2 software.
- A new area based collection efficiency algorithm will be incorporated which calculates trajectories from inflow block boundaries to outflow block boundaries. This method will be used for calculating and passing collection efficiency data between blade rows for turbo-machinery calculations.

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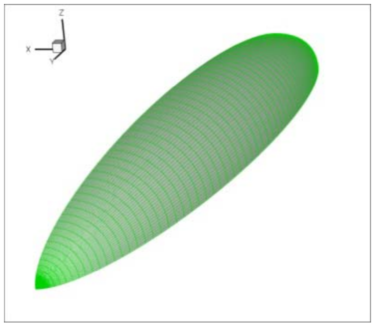
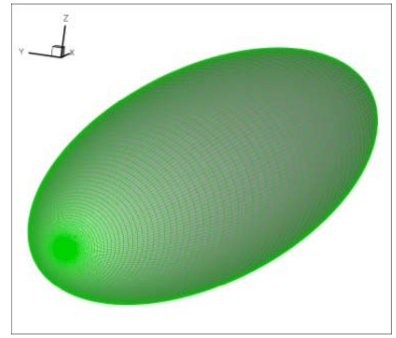
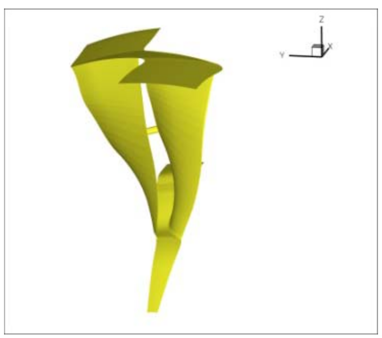
Grid Block Transformation and Mirroring Scheme

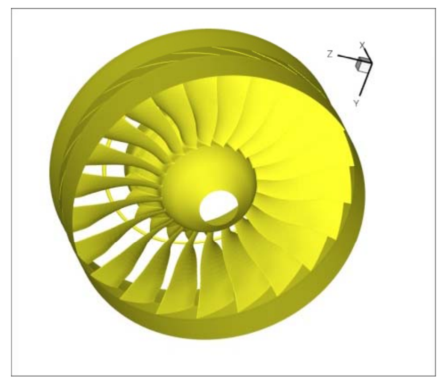


Rotation and Symmetry Plane Mirroring

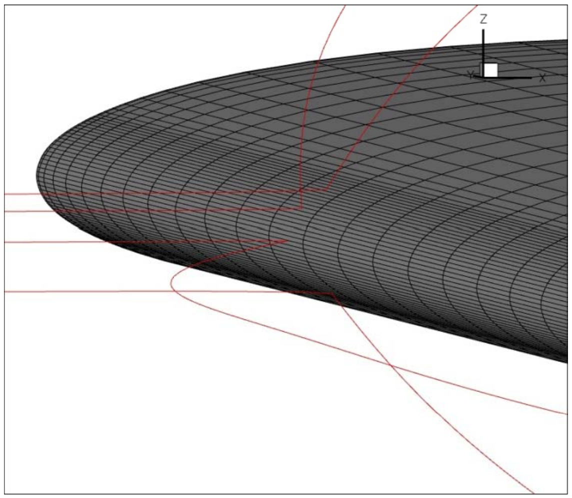


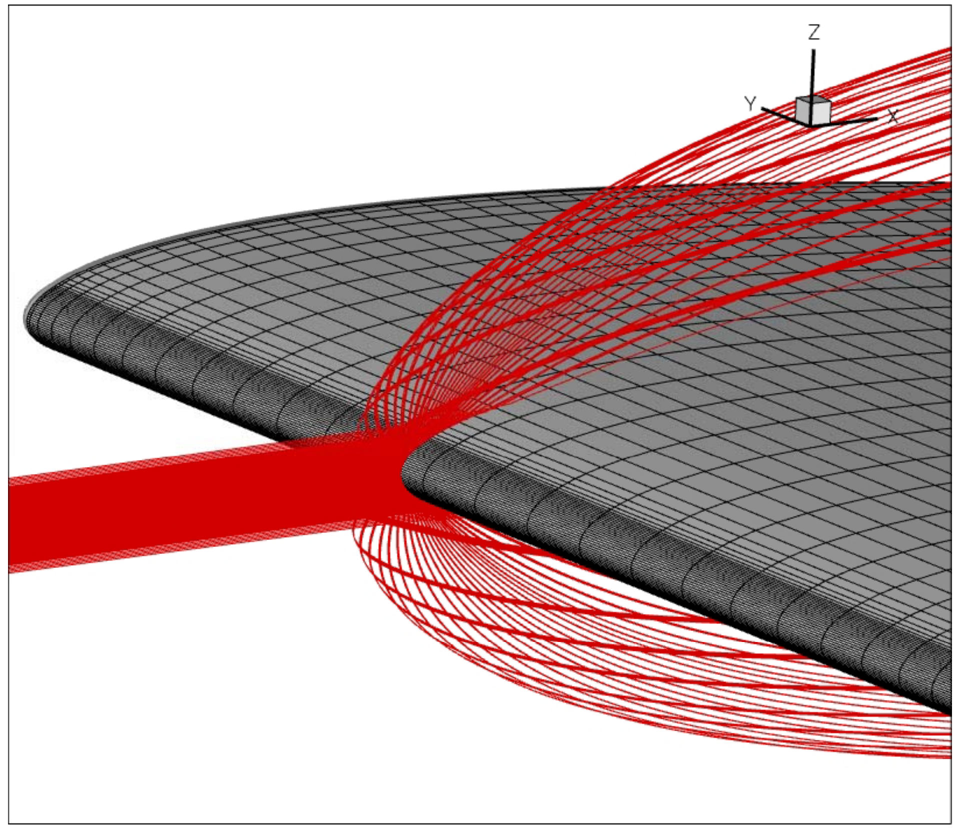


Radial Mirroring with Relative Velocities



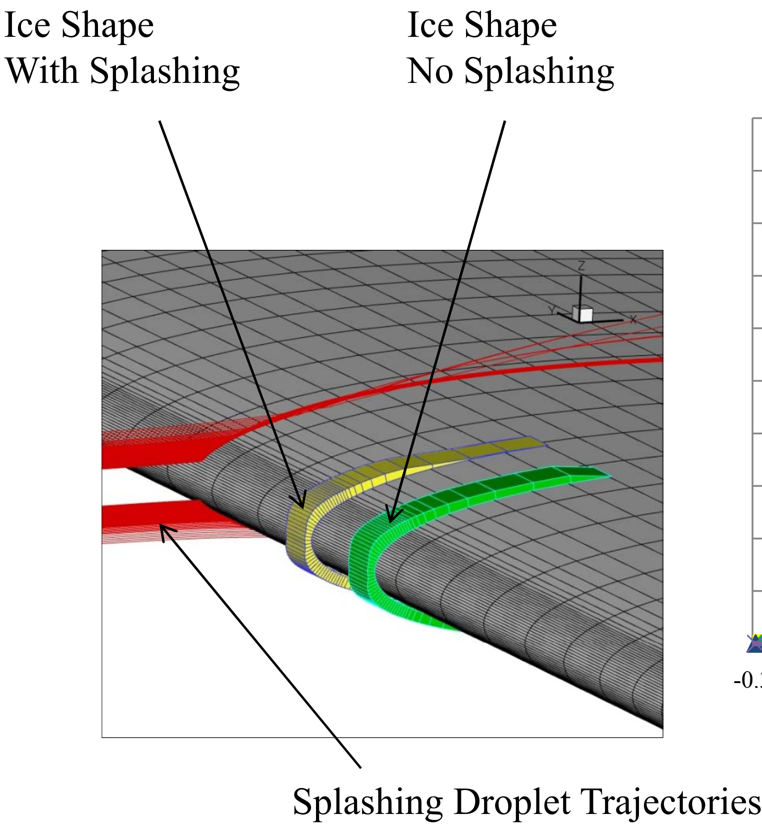
Particle Reflection Model For Bouncing Sand and Ice Crystals

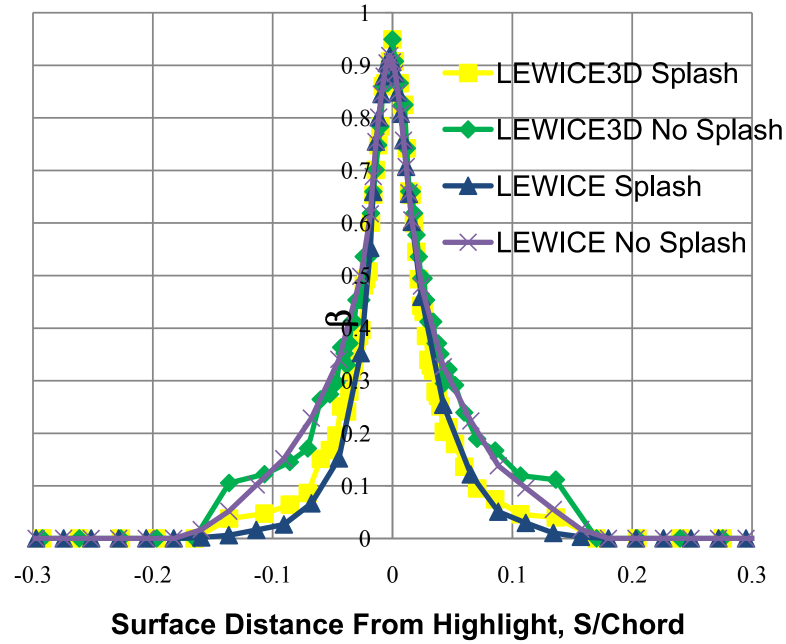




SLD Splashing Model Based On Wrights LEWICE 3.2 Model

(NACA 0012; MVD=160 Microns; V=87 m/s)





Future LEWICE3D Validation Requirements

- Ice accretion data for 3-dimensional configurations needs to be generated to validate icing calculations (e.g., swept wings, radomes, inlets, etc.). The available data for validation is limited and most of it is proprietary.
- Ice crystal and sand rebound models need to be validated. Some data exists for sand but no data exists for ice crystals.
- A more sophisticated SLD splashing model and more detailed experimental splashing data needs to be generated to handle complex configurations such as multi-element wings with multiple impingement regions. The current model has been tuned to match data for simple configurations with single leading edge impingement regions. The current model approximates the splashed water from a droplet impact as a single drop which has limited accuracy for predicting the location of secondary impact zones.

National Aeronautics and Space Administration

Airframe Icing Research Gaps
NASA Perspective

Airframe Icing Workshop
NASA Glenn Research Center

Cleveland, Ohio

June 9, 2009

www.nasa.gov

Current Airframe Icing Technology Gaps (1/2)

Computational Methods

- Development of a full 3D ice accretion simulation model
- Development of an improved simulation model for SLD conditions
- CFD modeling of stall behavior for ice-contaminated wings/tails
- Computational methods for simulation of stability and control parameters
- Analysis of thermal ice protection system performance

Experimental Methods

- Quantification of 3D ice shape geometric characteristics
- Development of accurate ground-based simulation of SLD conditions
- Development of scaling methods for SLD conditions
- Development of advanced diagnostic techniques for assessment of tunnel cloud conditions
- Identification of critical ice shapes for aerodynamic performance degradation
- Aerodynamic scaling issues associated with testing scale model ice shape geometries
- Development of altitude scaling methods for thermal ice protections systems

Current Airframe Icing Technology Gaps (2/2)

Flight Dynamics

- Development of accurate parameter identification methods
- Measurement of stability and control parameters for an ice-contaminated swept wing aircraft
- Creation of control law modifications to prevent loss of control during icing encounters

Experimental Databases

- 3D ice shape geometries
- Collection efficiency data for ice shape geometries
- SLD ice shape data, in-flight and ground-based, for simulation verification
- Aerodynamic performance data for 3D geometries and various icing conditions
- Stability and control parameter data for iced aircraft configurations
- Thermal ice protection system data for simulation validation

Airframe Icing Research
Aviation Community Areas of Interest

Fixed Wing Airframe Icing

- Ice Accretion Simulation
  - Ground based facilities
  - Computational methods
- Development of SLD 'Means of Compliance'
  - SLD Icing physics
  - SLD scaling methods
  - Modify ground based facilities
  - Modify computational methods
- Iced Aircraft Performance Evaluation
  - Ground based facilities
  - Computational methods
  - Flight Simulation

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Fixed Wing Airframe Icing

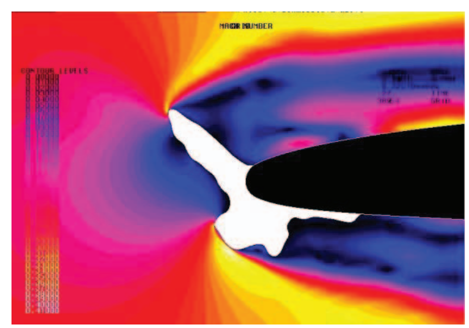
Ice Accretion Simulation

Issue: Methods are needed to simulate, experimentally and computationally, the process of ice growth on aircraft surfaces to reduce flight test cost and to improve safety. These methods are used for design, analysis, and certification efforts performed by industry and government.

Gaps: Our ability to model ice growth on swept wings, future generation aircraft configurations (e.g. blended wing body), and for Supercooled Large Droplet (SLD) (i.e. freezing drizzle and rain) conditions are limited and lack a comprehensive database for validation. Ice accretion physics, such as, water film dynamics on ice substrates and heat transfer augmentation on complex rough ice surfaces are not well understood and require further research. Also, ice accretion scaling methods need to be extended and validated for large scale configurations envisioned for next-generation aircraft.

Current NASA effort: Ice growth on subscale swept wings is being investigated in understanding intelligent controls response to an icing encounter.

Potential NASA Role to Fill Gaps: Full scale swept wing and SLD ice accretion simulation research.



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Current Airframe Icing Technology Gaps (1/2)

Computational Methods

- Development of a full 3D ice accretion simulation model
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Current Airframe Icing Technology Gaps (2/2)

Flight Dynamics

- Development of accurate parameter identification methods
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Fixed Wing Airframe Icing

Development of SLD ‘Means of Compliance’

Issue: Methods are needed to simulate, experimentally and computationally, the process of Super-cooled Large Droplet (SLD) ice growth on aircraft surfaces to reduce flight test cost and to improve safety. These methods are needed for industry to have a ‘means of compliance’ with proposed regulations for flight in SLD conditions.

Gaps: Modifications to the Icing Research Tunnel (IRT) and associated instrumentations are needed to simulate SLD environments. Deficiencies in knowledge of droplet dynamics (i.e. droplet breakup, impingement, and splashing) and feather formation for SLD conditions still exist. Computational modeling is largely based upon empirical information and correlations. Current means of compliance does not cover the full range of SLD conditions. Scaling methods are not adequately validated for SLD environments. Note: These gaps are in addition to those in “ice accretion simulation.”

Current NASA Effort: Testing at a limited set of SLD conditions is currently performed as part of the existing icing physics programs.

Potential NASA Role to Fill Gaps: Expansion of limited IRT SLD capabilities; improve and validate scaling methods for SLD; more comprehensive SLD physics studies performed at icing physics flow lab; improve and validate ice accretion models

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Current Airframe Icing Technology Gaps (1/2)

Computational Methods

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Fixed Wing Airframe Icing

Iced Aircraft Performance Evaluation

Issue: Methods are needed to simulate, experimentally and computationally, the degradation in performance of an aircraft exposed to in-flight icing conditions. These methods are used for design, analysis, and certification efforts performed by industry and government. Information from this research is used to provide input to controls-based remediation efforts.

Gaps: Limited capability with either experimental or computational methods to determine performance changes (lift, drag, stability and control) for iced aircraft. This is related to limited understanding of Reynolds number and ice accretion geometry scaling for swept wing and full aircraft configuration. Applications of computational methods (e.g. turbulence, roughness, grid generation) to iced surface has not been adequately validated.

Current NASA Effort: Use Generic Transport Model (GTM) for examination of controls response to ice build-up. Note: Experimental effort is subscale and computational effort is both full- and subscale. Development of a CFD approach to calculate influence of ice build-up on aircraft aerodynamics and resulting control system behavior.

Potential NASA Role to Fill Gaps: Full scale, high Re number iced modern aircraft (e.g. swept wing) aerodynamic research and validation database development

Current Airframe Icing Technology Gaps (1/2)

Computational Methods

- Development of a full 3D ice accretion simulation model
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- Thermal ice protection system data for simulation validation

Discussion of Airframe Icing Technology Gaps

It is our desire to compare the technology gaps identified in this presentation with those deemed of importance to industry and other government organizations and come to some consensus on what research areas should be pursued if appropriate resources become available.

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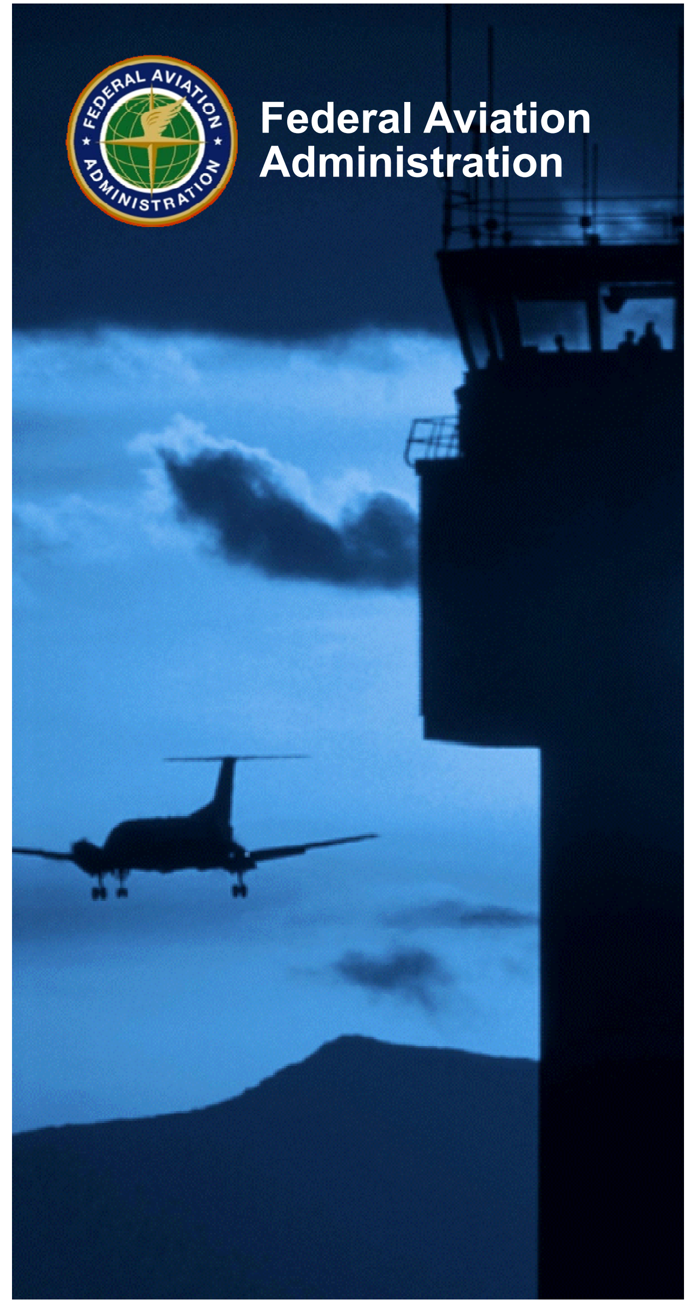
NASA Airframe Icing Workshop

FAA Perspective

By: Tom Bond, CSTA – Aircraft Icing

Date: 9 June 2009



Pitch to NASA (1/3)

- ***Thank you*** **for putting this workshop together**
- **NASA *owns* the U.S. national research expertise in in-flight aircraft icing. It is held in very high regard across the aerospace industry – both here and abroad**
  - The FAA and industry rely on this expertise to
    - Develop new engineering tools to support airworthiness (certification) - experimental and analytical methods
    - Develop benchmark databases
    - Explore the sciences of aircraft icing to understand, model, and simulate the physical mechanisms associated with ice accretion and iced aerodynamics
    - Support and develop icing facilities for R&D and testing

Pitch to NASA (2/3)

- **NASA has a rich heritage in aircraft icing. Working with its academic partners, it has built the fundamental building blocks and the current capabilities for many of the modern experimental and analytical tools used by industry**
  - Icing physics and scaling
  - 2D experimental iced aerodynamics
  - LEWICE CFD tools: regarded as the "gold standard" that others compare to
  - IRT: considered the premier icing wind tunnel for R&D, provides leadership for new simulation practices

Pitch to NASA (3/3)

- **The aerospace community cannot go forward to solve major R&D thrusts in aircraft icing such as turbojet engine ice crystal ingestion, SLD means of compliance, 3-D iced aerodynamics, or other airframe icing research without NASA's leadership**

Please sustain your core competency and level of investment in this area – it is essential to national interests in the development of engineering tools and aviation safety for aircraft icing

Outline

Gap Areas – FAA Perspective:

- **Near Term Need**
  - **SLD Engineering Tools**
- **Intermediate Term Need**
  - **Iced Aerodynamics**
- **Other Gap Areas**
- **Summary**

SLD Engineering Tools

SLD Engineering Tools – History

- **The Ice Protection Harmonization Working Group (IPHWG) was tasked to:**

  Review National Transportation Safety Board recommendations A-96-54, A-96-56, and A-96-58, and advances in ice protection state-of-the-art. In light of this review,

  define an icing environment that includes supercooled large droplets (SLD), and devise requirements to assess the ability of aircraft to safely operate either for the period of time to exit or to operate without restriction in SLD aloft,

  in SLD at or near the surface, and in mixed phase conditions if such conditions are determined to be more hazardous than the liquid phase icing environment containing supercooled water droplets. Consider the effects of icing requirement changes on 14 CFR part 23 and part 25 and revise the regulations if necessary…

SLD Engineering Tools – History

- **New rulemaking for SLD is in progress. Target for the NPRM release is early 2010. In order to comply, aircraft manufacturers must be able to design for SLD icing conditions and provide "proof of performance" for certification**
- **This requires the capability to simulate SLD icing conditions and have SLD engineering tools (analytical and experimental) and icing facilities that provide means of compliance.**
- **The engineering tools need to determine the properties of SLD ice accretions on airframe components**
  - ***Shape***
  - ***Location and extent***
- **And, determine the effects of these accretions on the airplane flight characteristics**
  - ***Stall speeds***
  - ***Performance & handling qualities***

SLD Research – NASA's Role

- **NASA has provided major R&D resources during the last ~ 10 years. These included:**
  - Icing Branch researchers, GRC facilities engineers and technicians, computer scientists, other on-lab service groups, and university grant expertise
  - Facilities: Icing Research Tunnel, Icing Research Aircraft (Twin Otter), and partnered tasks in a vertical flow tunnel, and dry air wind tunnels (Iowa State computational lab, UIUC, WSU, etc.)
- **NASA developed and made publicly available its research results, CFD tools, test methods, scaling methods, and facilities improvements.**

SLD – Means Of Compliance

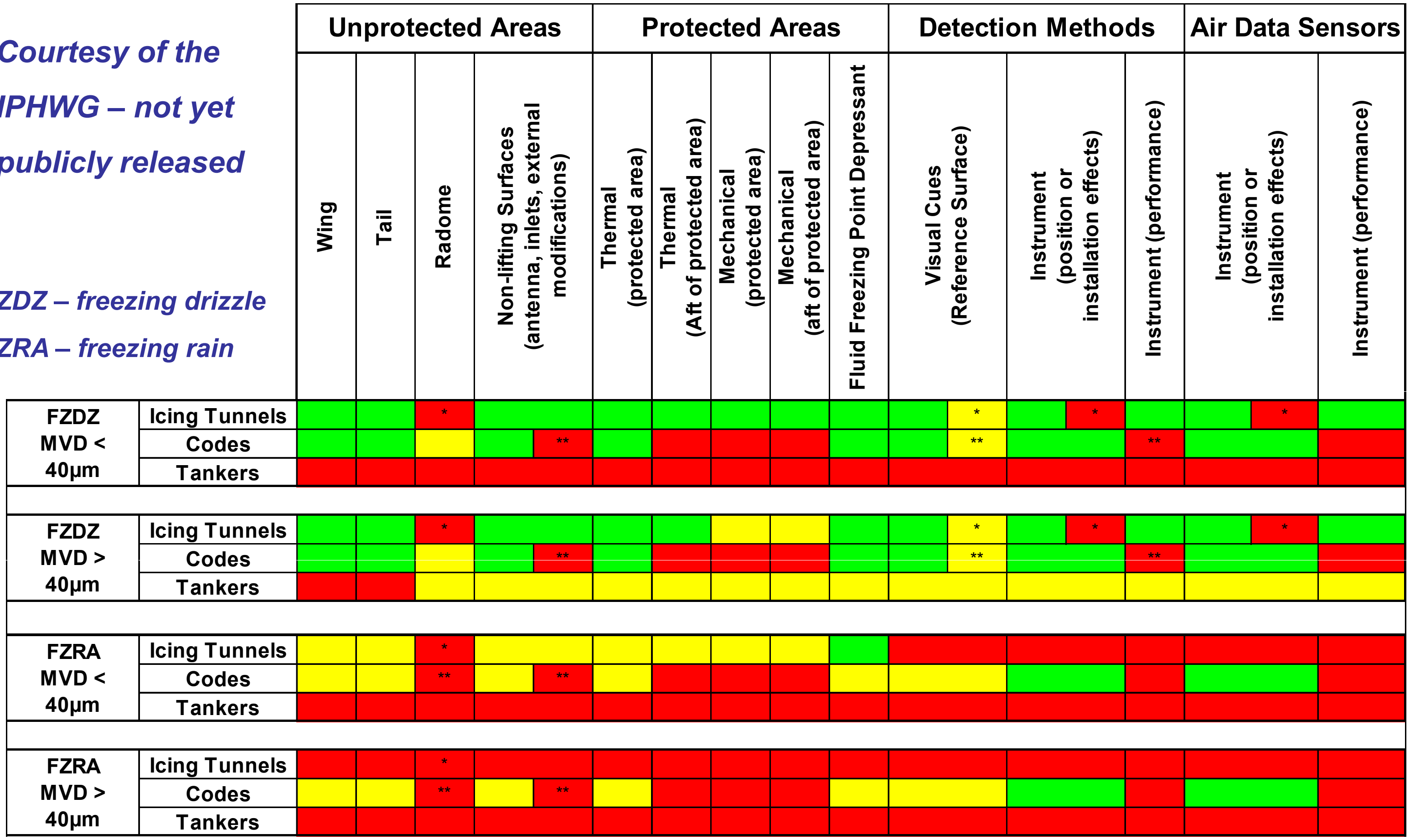
- **The IPHWG developed a Working Group Report for SLD, glaciated, and mixed phase icing conditions. It provided a record of the IPH deliberations and draft new rulemaking language. It also highlighted concerns by manufacturers regarding the state-of-the-capabilities of engineering tools for use in SLD means of compliance (MOC)**
- **A draft document was developed to review the MOC and respond to the groups concerns**
  - The IPHWG developed a MOC table to assess the use of current SLD engineering tools to meet the proposed certification requirements
  - The IPHWG evaluated the engineering tools capabilities against the proposed new SLD certification requirements
- **This exercise provided a clear understanding of where weaknesses and lack of performance for the current SLD engineering tools capability exist**

Assessment of SLD Engineering Tools Capabilities

Courtesy of the IPHWG – not yet publicly released

FZDZ – freezing drizzle

FZRA – freezing rain



LEGEND Updated FEB 2009

(green)	The capability exists today and is suitable to be an element of a MOC
(yellow)	The capability is possible, but has not been demonstrated, or there is limited or no validation.
(red)	The capability is unknown, or does not currently exist

* It may be possible to test small scale installation effects, but large scale installations are not currently feasible

** Current 2D capabilities exist with large droplet effects, but limitations exist in the use of 3D codes for simulation of Appendix X effects

SLD Engineering Tools - Gaps

- **SLD engineering tools capabilities need more R&D**
  - **Incorporate current SLD effects into 3-D CFD codes**
  - **Improve simulation capabilities - replace correlations with physical models where resolution and accuracy increases are warranted**
    - Sensitivity studies to guide research directions
    - Research areas requiring a better understanding: accretion physics and SLD ice feature growth, droplet impact dynamics (splashing, break-up, re-impingement), surface water transport, heat transfer, and roughness formation
  - **Validation database for swept wing airfoils**
  - **Simulation exercises and code evaluation cases to determine use of analytical tools and potential facility test methods (FZRA with MVD < 40 μ) for freezing rain conditions**

3D Iced Aerodynamics

3D Iced Aerodynamics

- **Develop a 3-D iced aero research project to understand the aerodynamic effects of ice accretions on 3-D swept wings and provide a 3-D iced-airfoil public database to support CFD validation**
- **Strategy:**
  – Use extensive experience gained on 2-D iced airfoils R&D and methods developed from the recent NASA-ONERA-UIUC “SUNSET” tests to guide an R&D strategy for 3-D
- **Objectives:**
  – Understand the flow physics and any fundamental differences from the 2-D case
  – Understand aerodynamic performance
  – Establish test techniques, including Re and M effects and scaling
  – Ensure that results are validated by flight-Re data

3D Iced Aerodynamics

- **This research requires significant investments, coordination, and commitment – with shrinking national resources, consider a collaborative partnership with industry and other federal agencies**
  - Bring together expertise and resources for a common pre-competitive research goals
  - Develop an approach for identifying physical phenomena studies, test techniques, and analysis methods
  - Use national research facilities for iced and dry-air wind tunnel tests

Other Gap Areas

- **There are still other important areas for R&D investment in airframe icing that need to be considered**
  - Development of improved calibration, measurement, and diagnostic tools for facilities for evaluating icing cloud conditions and aircraft/ice surface microphysical phenomena
  - Operations: aircraft state/IPS management/icing weather threat assessment tools → intelligent aircraft systems
  - Design & certification → complete aircraft icing performance tools
- **Fundamental research:**
  - Quantify micro-physical events, both 2-D and 3-D (hydrodynamics, ice growth physics, roughness and heat transfer, and boundary layer phenomena)
  - Icing scaling issues for larger droplet sizes, higher speeds, and larger model scale ranges

Summary

- The two most important areas from the FAA perspective for airframe icing are:

1. Continued improvements in SLD engineering tools to meet concerns about MOC
2. 3-D iced aerodynamics – recognizing this will require a substantial collaborative investment to understand 3-D ice accretions and their attendant effects on swept wing aerodynamics

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QUESTIONS?

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Small Airframe Manufacturer's Icing Perspective

Airframe Icing Workshop
NASA Glenn Research Center
June 9th, 2009

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Agenda

- Background/Perspective
- Icing Effects & Mitigation
- Icing Certification
- New Technologies
- Summary and Recommendations

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Background/Perspective

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Product Line

- **Cessna currently offer ten models with FIKI* approval**
  - **Two models offer equipment for inadvertent icing**

*__FIKI__ = Certification for __F__light __I__nto __K__nown __I__cing

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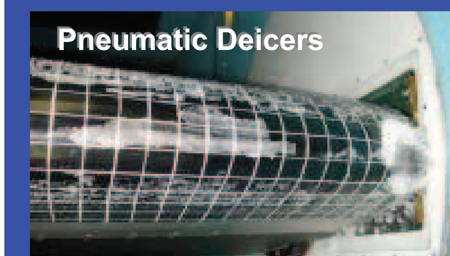
Aircraft Size/Technology

Aircraft	MTOW	Certified Ceiling	Max Cruise Speed	Wing	Stabilizer
Citation X	36,100 lbs	51000 ft	525 KTAS		
Citation Sovereign	30,000 lbs	47000 ft	458 KTAS		
Citation XLS+	20,200 lbs	45000 ft	441 KTAS		
Citation CJ4	16,950 lbs		435 KTAS		
Citation CJ3	13,870 lbs		417 KTAS		
Citation CJ2+	12,500 lbs		418 KTAS		
Citation CJ1+	10,700 lbs	41000 ft	389 KTAS		
Citation Mustang	8,645 lbs		340 KTAS		
Grand Caravan	8,750 lbs	25000 ft	184 KTAS		
Caravan 675	8,000 lbs		186 KTAS		
400 Corvalis TT	3,600 lbs		235 KTAS		
350 Corvalis	3,400 lbs	18000 ft	191 KTAS		



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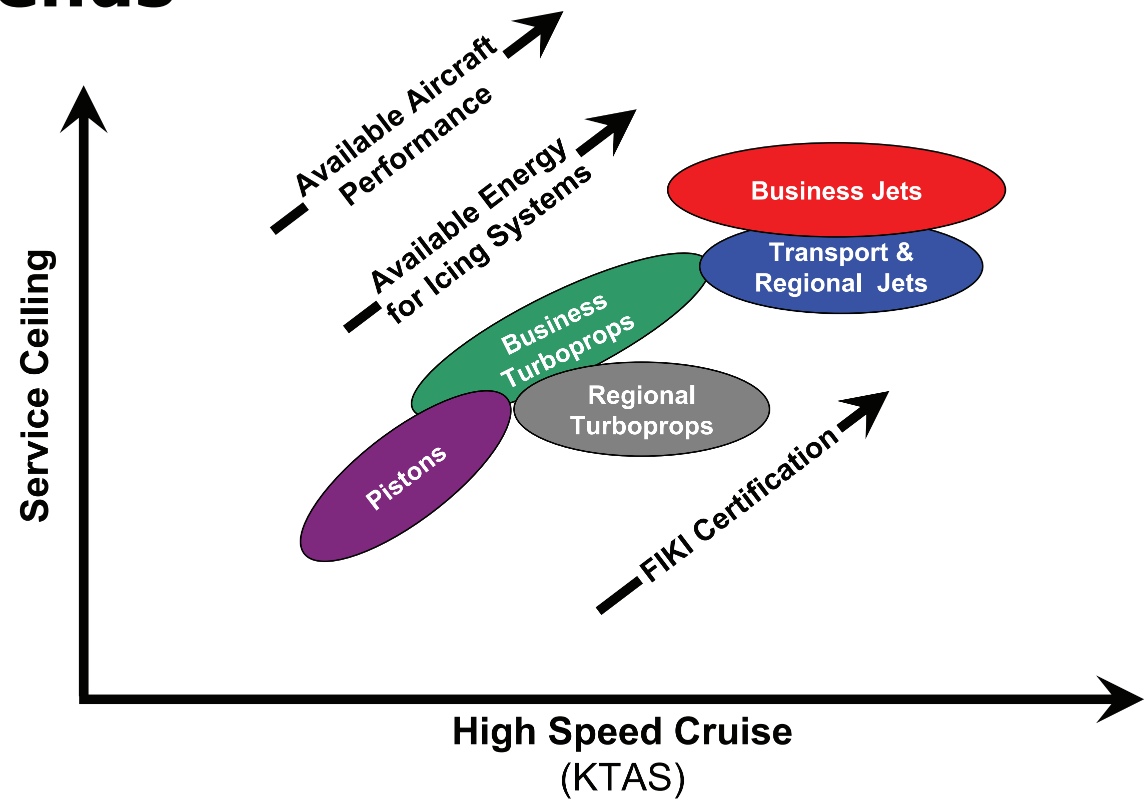
Trends



FIKI = Certification for **F**light **I**nto **K**nown **I**cing

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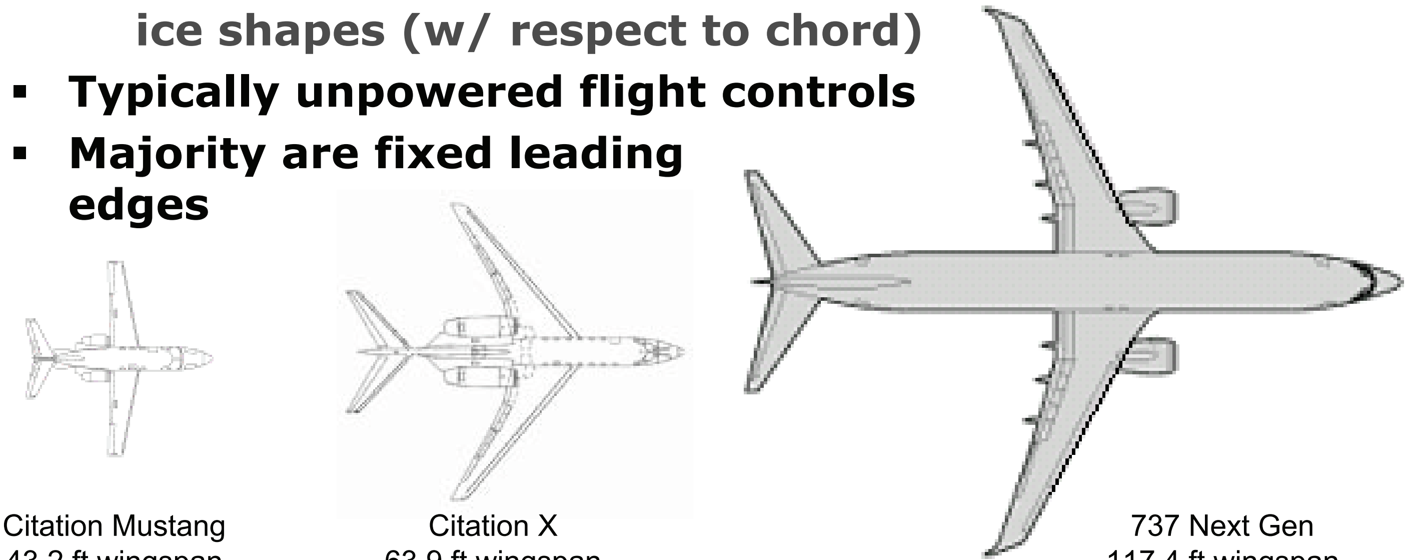
Characteristics of Small Aircraft

- **Small leading edges have high water collection rates**
  - **Increases local water catch rates**
  - **Increases relative size of ice shapes (w/ respect to chord)**
- **Typically unpowered flight controls**
- **Majority are fixed leading edges**



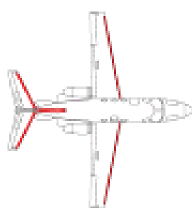
Citation Mustang
43.2 ft wingspan

Citation X
63.9 ft wingspan

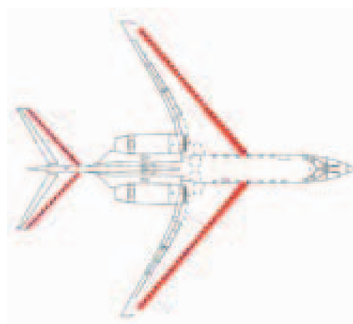
737 Next Gen
117.4 ft wingspan

Protected Areas

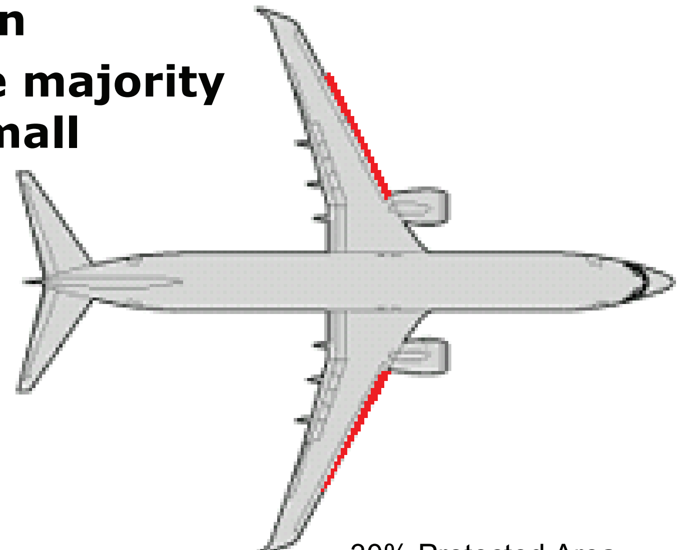
- **Small aircraft typically protect a much larger percentage of the airframe**
- **Large proportion of available energy is required for ice protection**
- **Protected areas provide the majority of aerodynamic effect on small aircraft**



~90% Protected Area



~88% Protected Area



~30% Protected Area

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Icing Effects/Mitigation

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Icing Effects on Small Aircraft

- **Scale effects limit the ability of small aircraft to operate unrestricted in icing**
- **Performance effects can be significant**
- **Current ice protection technology can not protect against "severe" icing**
- **Severe conditions require**
  - **Avoidance**
  - **Monitoring**
  - **Identification and exit**

FAA Aeronautical Information Manual: Severe - The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate flight diversion is necessary.

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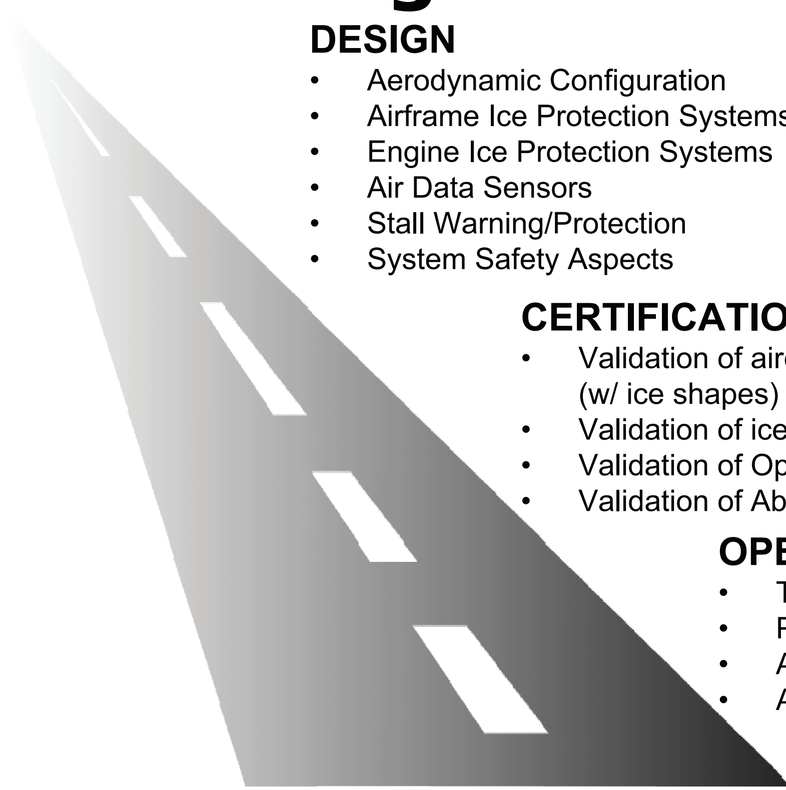
Risk Mitigation



DESIGN

- Aerodynamic Configuration
- Airframe Ice Protection Systems
- Engine Ice Protection Systems
- Air Data Sensors
- Stall Warning/Protection
- System Safety Aspects

CERTIFICATION

- Validation of aircraft performance & handling qualities (w/ ice shapes)
- Validation of ice protection system performance
- Validation of Operating procedures and Limitations
- Validation of Abnormal & Emergency procedures

OPERATION

- Training
- Preflight planning/exit strategies
- Adherence to operating limitations and procedures
- Avoidance and exit from severe icing

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Icing Certification

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Current Icing Certification

- **Icing certification has taken an increasing role in mitigating icing risk**
  - Small aircraft standards amended in 1993
  - Large aircraft standards amended in 2007
  - FAA Guidance/Policy continues to evolve
- **As part of certification, extensive flight testing is performed with artificial ice shapes**
  - Natural icing is typically a validation of the results of the artificial ice shape testing
- **Artificial ice shapes provide the data used to develop performance information, operating procedures and limitations**

NASA's Connection to Certification

- Most small aircraft manufacturers rely heavily on NASA developed simulation tools
- LEWICE 2D/3D are the primary ice accretion codes in use for certification
  - Primarily used for unprotected ice shapes
- LEWICE is also used to provide collection efficiencies and impingement limits that are used in designing protection systems
  - Water catch distributions are also used as input to heat and mass transfer analysis
- NASA IRT is often used for developing protected area ice shapes for certification

Conservative versus Accurate

- **Conservative ice shapes are required for certification**
  - With respect to aerodynamic effect
- **However, excess conservatism can have unintended consequences**
  - Too high of stall speeds adversely affects approach speeds/landing distances
  - Excessive drag can affect performance and climb information
- **As such, conservative <u>and</u> accurate ice shapes are an objective**

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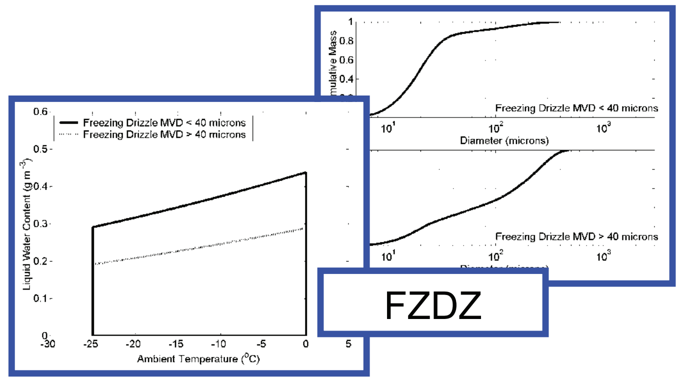
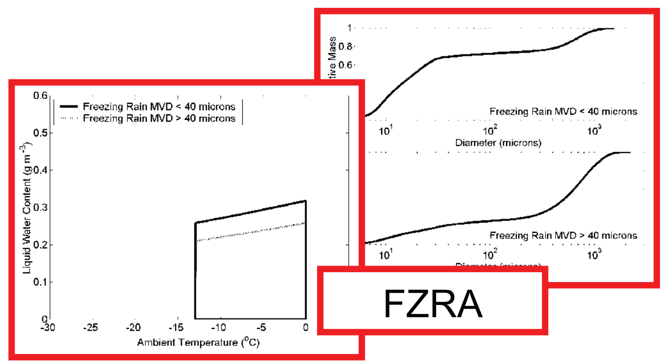
Certification Changes

- Certification ice shapes are transitioning from a single operating point to scenario based shapes
  - Takeoff ice, Final takeoff ice, En route ice, Holding ice, Approach ice, Landing ice, "sandpaper" ice
- Large droplet rulemaking define scenarios for recognition and exit of conditions
  - Requires transitions between Appendix C and Appendix X icing conditions
- Current available version of LEWICE does not address such scenarios

Future Icing Certification

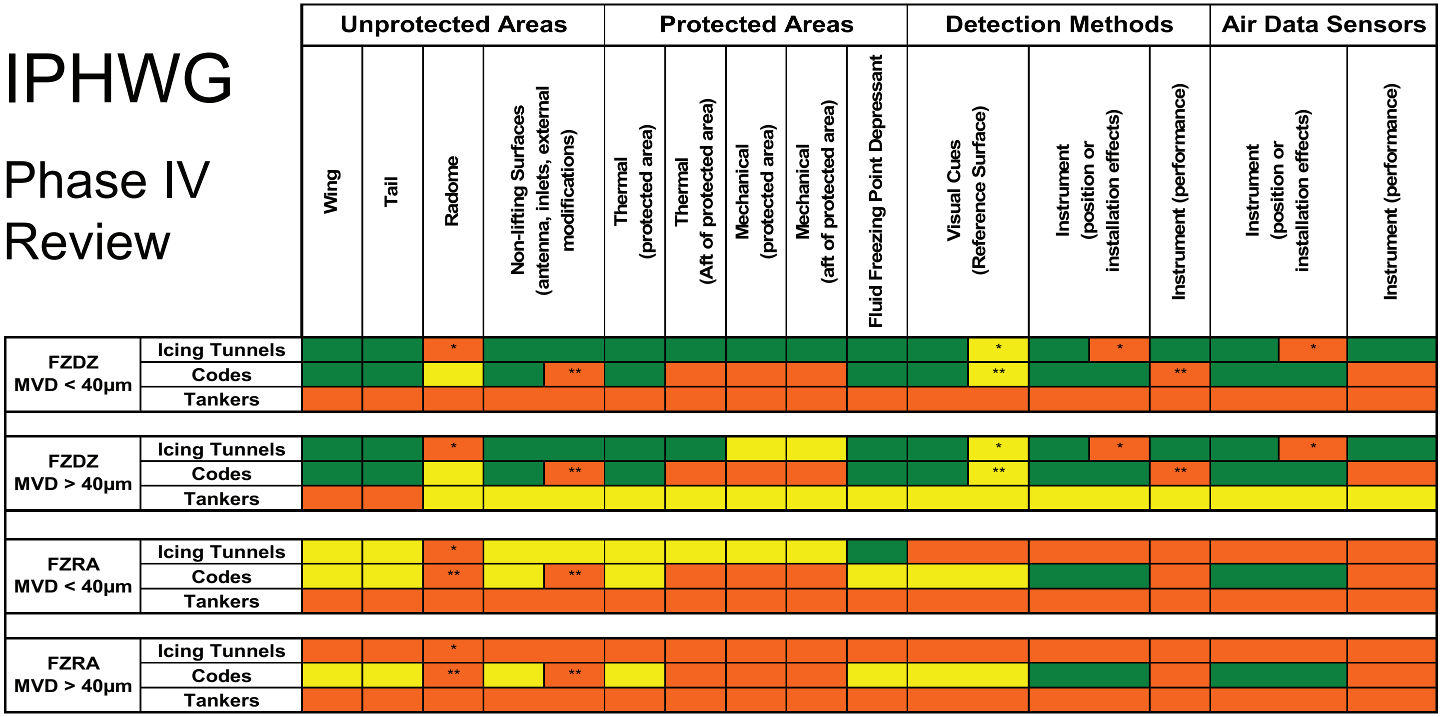
- **Draft rulemaking has been proposed for SLD**
- **Options include:**
  - **Unrestricted operations**
  - **Unrestricted in a portion**
  - **Detect and exit**
- **Simulation and compliance methods are limited**
- **Interim methods focus on detect & exit**





IPHWG

Phase IV Review



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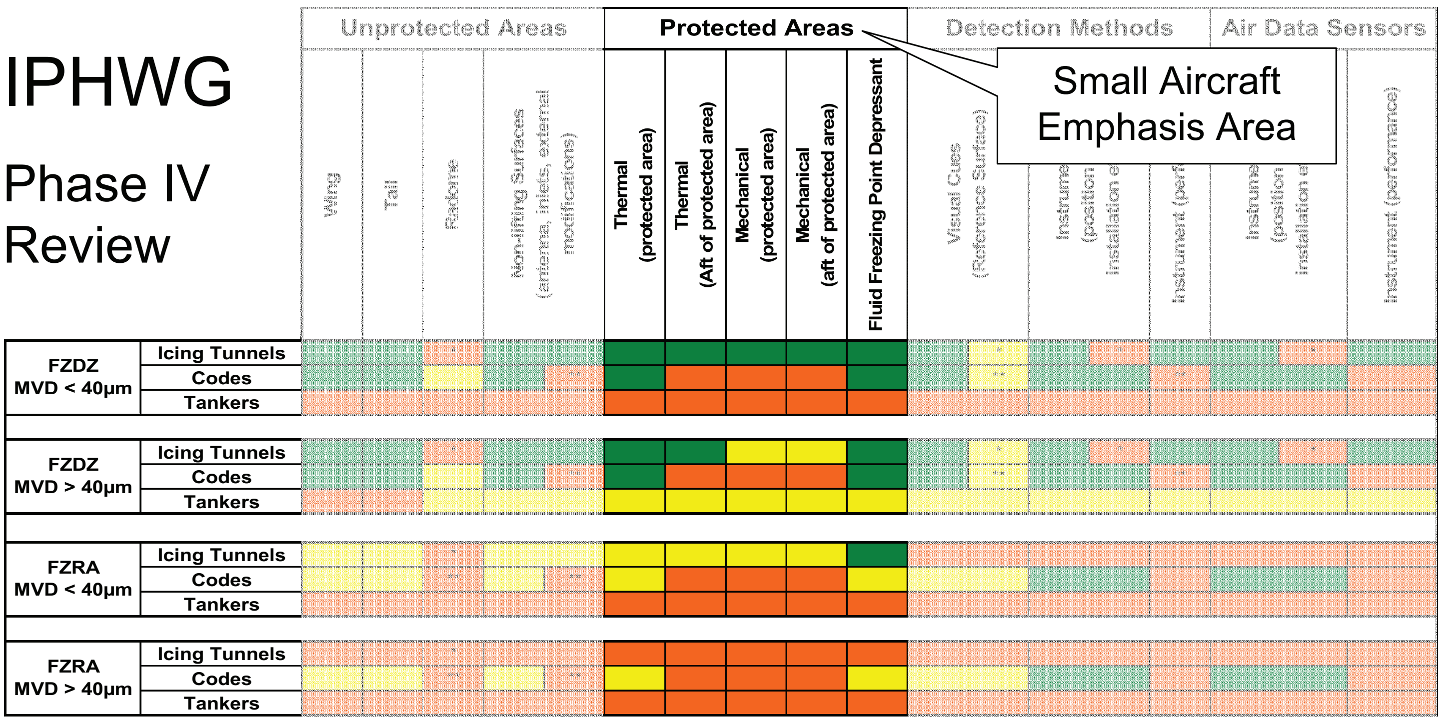
IPHWG

Phase IV Review



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Simulation Efforts

- **As illustrated, much work remains to mature SLD simulation methods**
- **With individual icing tunnel tests on the order of $500k to $1M, no individual manufacturer has the resources to mature simulation methods**
- **This effort is best accomplished through joint efforts between NASA and industry**
  - **Benefits flying public by improving safety**
  - **Conserves limited resources**

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Balance of Needs

- Much of the funding for icing research appears to have shifted towards engine/ice crystal research
  - This area is less mature than SLD and requires significant research and development
- However, the maturity of the SLD simulation methods will likely have a larger near term impact on icing safety
- Continued development of both the ice crystal and SLD technical areas is recommended

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New Technologies

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New Technologies

- **Continued interest in new technology ice protection systems that balance design parameters**
  - Energy requirements
  - Aerodynamic effects
  - Weight
  - Reliability
  - Affordability
- **Severe icing detection methods**
  - For both Appendix C and SLD

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Summary and Recommendations

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Summary

- NASA’s simulation tools are essential for aircraft development and certification
- Artificial ice shapes developed using these tools are fundamental to the certification process
- Continued maturation of SLD simulation tools are essential for future certifications
  - Particularly combined effects of SLD with ice protection systems
    - → Potential accretions aft of protected areas

Needs/Recommendations

- Atmospheric research that supports a detect and avoid strategy
- Aircraft level simulation of icing effects
  - Current certification standards provide a rigorous evaluation prior to field operations
  - Provides the basis for any aircraft specific training that may be required
- Computational simulation of ice accretions during scenarios
  - Changing icing and aircraft conditions, etc.
  - Aligns LEWICE with current regulatory requirements

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Needs/Recommendations (cont.)

- **Performance of ice shapes with well defined separation features is fairly consistent with scale**
  - Can be readily simulated in scale wind tunnel tests
- **Roughness based ice shapes still present challenges with respect to scale**
  - Reynolds number issues
- **Ability to effectively model roughness based ice shapes is critical for design and certification**
  - Improved predictability of full wing stall behavior
  - Ties in with aircraft level simulation of icing effects

Recommendations: NASA's Role

- **Provide technical leadership**
  - Roadmaps, consortiums, industry cooperative programs
- **Fundamental research to be used in simulation methods**
- **Continued support of development and certification tools (with focus on SLD)**
  - Proactive approach to icing safety
  - Addresses the issue before the aircraft are placed in the field

Questions?

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Academic Airframe Icing Perspective

Mike Bragg - Illinois

Alric Rothmayer – Iowa State

David Thompson – Mississippi State

Airframe Icing Workshop
NASA Glenn
June 9, 2009

Introduction

Academic Airframe Icing Perspective

- **What research do we need?**
  - 3-D Ice accretion and aerodynamics
  - Systems-based multidisciplinary research
- **But first:**
  - Some philosophy on university research
  - Some icing research history and lessons learned
- **Then to 3-D and multidisciplinary research**

Why University Research?

Academic Airframe Icing Perspective

- The best university researcher strives to have **Impact** in many dimensions:
  - New discoveries
  - Graduate education
  - Contribution to society
  - Economic development

- University researchers think of research in MS and Ph.D "units"

- University research can be both applied and fundamental

Basic versus Applied Research

Academic Airframe Icing Perspective

- **Traditional Research Continuum**

Basic Research → Applied Research → Development → Production and Operation

- **Quadrant Model of Research**

Consideration of use?

Quest for Fundamental Understanding?	No	Yes
Yes	Pure basic research (Bohr)	Use-inspired research (Pasteur)
No		Pure applied research (Edison)

Pasteur's Quadrant

From "Pasteur's Quadrant" by Donald E. Stokes

2-D Airfoil Icing Aerodynamics

Academic Airframe Icing Perspective

NASA/university 2-D iced-airfoil aerodynamics

- **Evolving goals as we learned more and motivation changed (1980 – 2008)**
  - Understanding of ice accretion effect on lift and drag
  - Support for CFD development and validation
  - Understand iced-airfoil physics
  - Roselawn accident focused us on “use”
  - Aircraft control and more 3-D
  - Effect of airfoil and ice-shape geometry
  - Understanding Re and M effects
  - Ice accretion aero classification and simulation

Aerodynamic Techniques

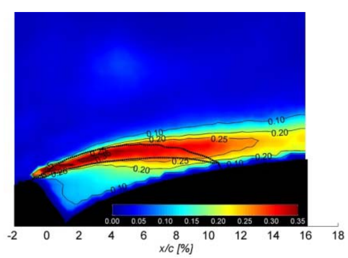
Academic Airframe Icing Perspective

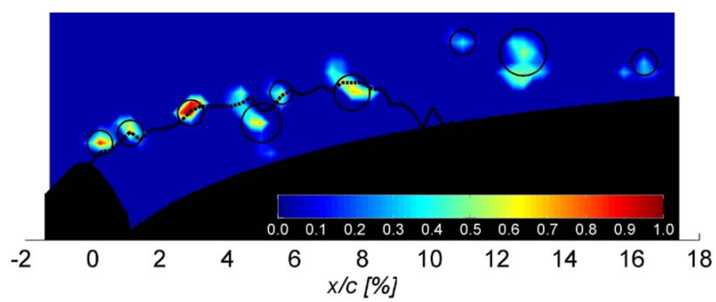
Initial techniques

- Relatively simple steady RANS
- Simple small-scale experiments with large horn ice at low Re

Current techniques

- 3-D unsteady RANS/LES methods
- Pressure tunnels at near-flight Re and M, multiple ice shapes, advance measurement techniques including PIV





What did we learn from 2-D aerodynamics?

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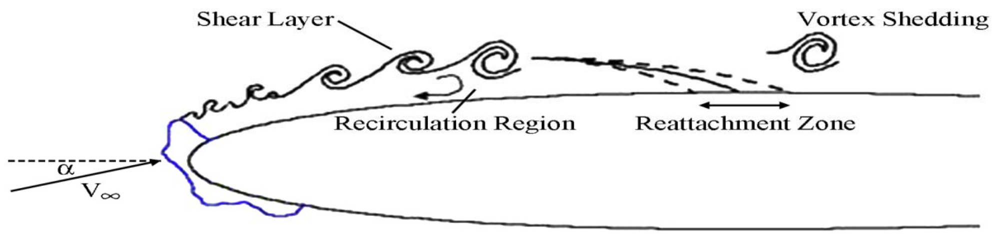
Process

- Re and M important to understand but low-Re data are valuable and provide a cost-effective research method for many cases
- Flowfield understanding critical in reducing “matrix” and understanding simulation
- Flow separation is key and is always unsteady and 3-D
- Roselawn and considering “use” or application led to more focused and **productive** research programs

Physics

- An understanding of the basic relationships between airfoil geometry, ice-accretion geometry, and iced-airfoil aerodynamics and aerodynamic performance including control was accomplished with some fundamental understanding of the flow



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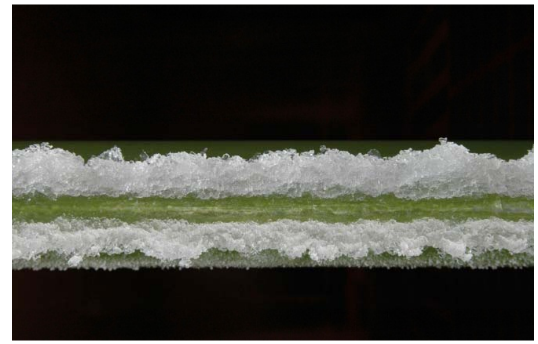
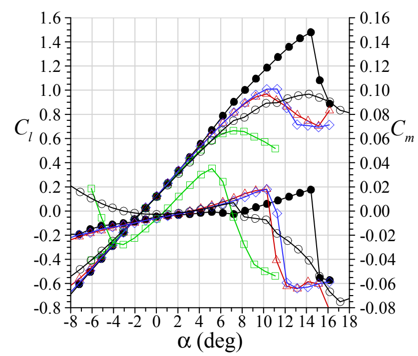
2-D Icing

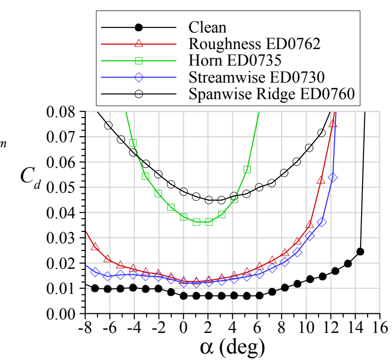
Academic Airframe Icing Perspective

- **Ice Accretion Physics**
  - Droplet trajectory calculations well understood
  - Basic surface water transport and bulk ice growth is understood
  - LEWICE does a good job within its 2-D validation data set



- **Iced-Airfoil Aerodynamics**
  - Understand basic flowfield and gross aerodynamics for the four identified ice shape categories
  - Simulation ice shape methods identified and validated
  - RANS does a reasonable job with gross aerodynamics

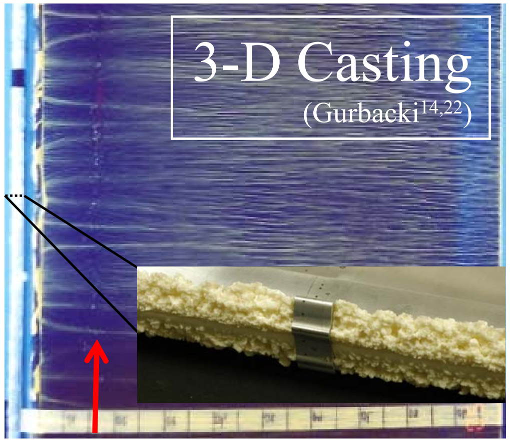




The 3-D Icing Problem

Academic Airframe Icing Perspective

- **Ice accretion**
  - 3-D ice accretion have been observed and documented
  - Scallops have been studied, resulting in a foundation of experimental understanding
  - Fundamental processes in 3-D are not understood well enough for reliable models
- **Aerodynamics**
  - Flow separation including shear layer development is the fundamental flow feature and it is 3-D and unsteady
  - RANS insufficient but full 3-D and unsteady cost/resource prohibitive
  - No 3-D experimental data at near-flight Re and M



3-D Ice Accretion

Academic Airframe Icing Perspective

- **Goals**
  - Understand basic physical processes underlying aircraft icing.
  - Create simplified engineering tools.
  - Understand the accuracy of the engineering tools.

- **What is needed?**
  - Growth mechanisms for complex 3-D accretions (scallops, etc.)
  - Simulation methods for complex 3-D accretions
  - Nonlinear coupled interactions (droplets splashing, surface water transport, impact freezing, etc.)

3-D Ice Accretion (cont.)

Academic Airframe Icing Perspective

Approach

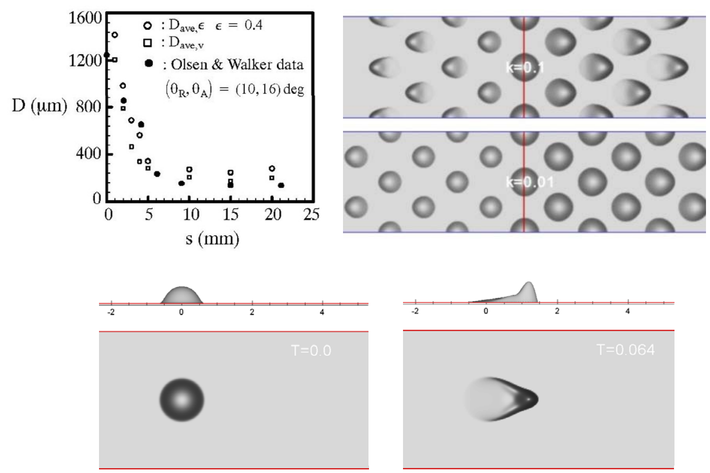
- Understand the basic physical processes underlying aircraft icing:
  - Develop a foundation of understanding based on experiments.
  - Develop detailed physical models which explain the experiments.
- Use icing physics knowledge to help create simplified ice accretion engineering tools.
- Understand the processes which limit the accuracy of the engineering tools.

Example – Surface Physics

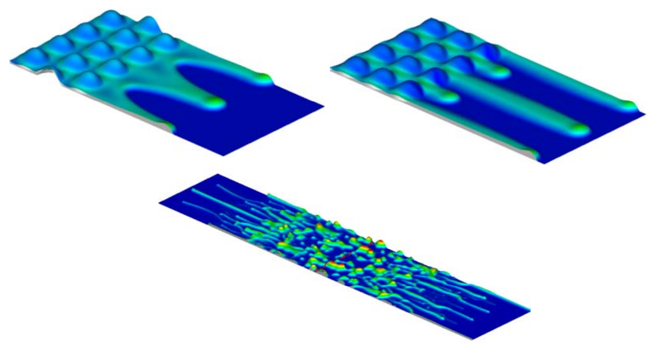
Academic Airframe Icing Perspective

- Basic water transport can be handled using simple models.
- Ice surface roughness can be explained by heat transfer driven instability of the ice surface.
- There is a need to better understand more complex 3-D nonlinear interactions:
  - Growth of complex ice shapes. Nonlinear coupling of droplet impacts, unsteady aerodynamics past complex 3-D ice/water shapes, water transport, and complex ice growth. Coupling to rapid phase transitions when crossing from rime to glaze icing, etc.
- NASA VIST facility and icing physics experiments are important steps to resolve these issues.

Water bead runback



Rivulet interaction with roughness



Source: Rothmayer, Matheis, Otta, Tsao, Wang

3-D Icing Aerodynamics

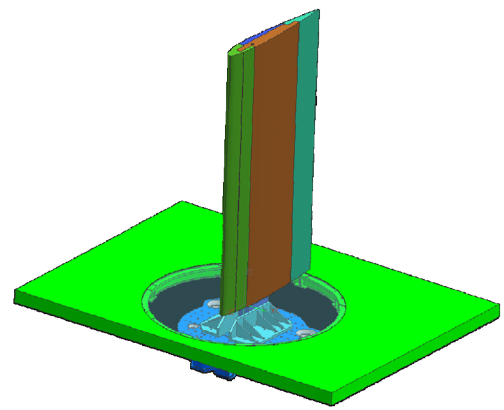
Academic Airframe Icing Perspective

- **Goals**
  - Basic understanding of 3-D iced wing flowfield
  - Simulation methods and a small-scale, low-Re capability
  - Computational methods that accurately predict Clmax and control deflection effects
- **What is needed?**
  - Iced-wing data at high Reynolds number and flight M
  - Data for code development and validation
  - Unsteady, RANS/LES method development
  - Key features: unsteady separated flow, shear-layer development, transition

3-D Icing Aerodynamics

Academic Airframe Icing Perspective

- **Approach**
  - Fundamental studies to aid understanding of key flow phenomena
  - Development of advanced CFD methods
  - High-Re data on representative geometries
  - Validation of CFD methods
  - Experimental and computational tools for practical problems



Example – Hybrid RANS/LES

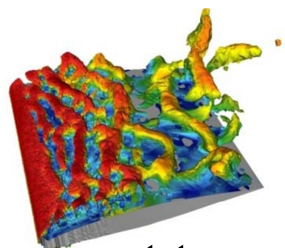
Academic Airframe Icing Perspective

- **Observations**
  - RANS, while highly efficient, requires a high degree of phenomenological modeling, which limits its applicability
  - LES, which models fewer of the turbulent scales, is prohibitively expensive in aero boundary layers
- **Current general consensus**
  - Valid for massively separated flows
  - Problematic for aerodynamically-relevant flows

- **Basic idea**
  - Use RANS in regions of attached flow
    - Consistent with modeling the Reynolds stress
  - Use LES in regions of separated flow
    - Consistent with modeling the subgrid stress
  - Implicit zonal boundary
    - Achieved through a dynamically-varying eddy viscosity

DES for extruded GLC305/944 ice shape

–Selected time steps show development of characteristic “loop” vortices



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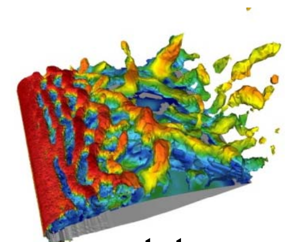

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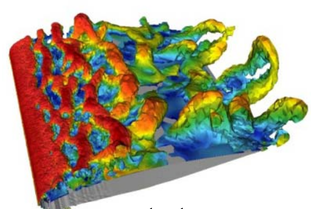

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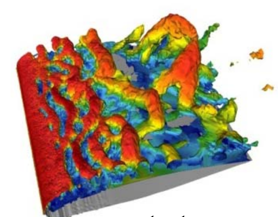

$t=t_4$

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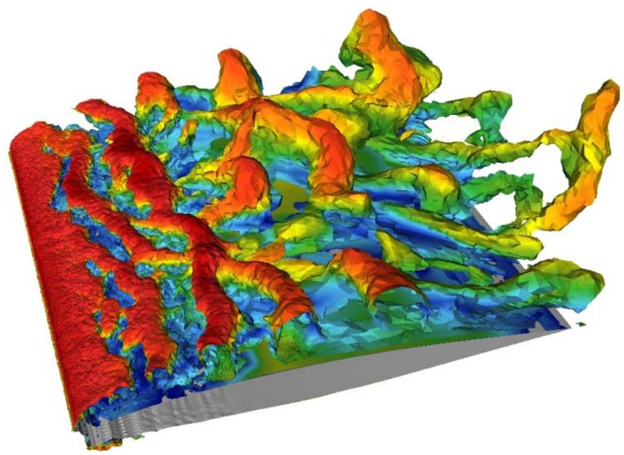
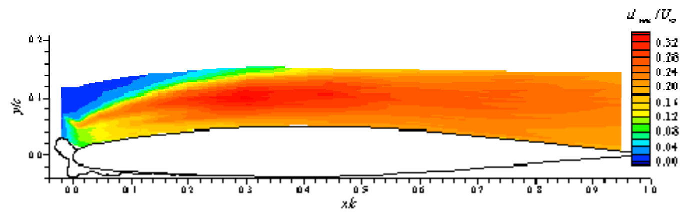
Example – Hybrid RANS/LES

Academic Airframe Icing Perspective

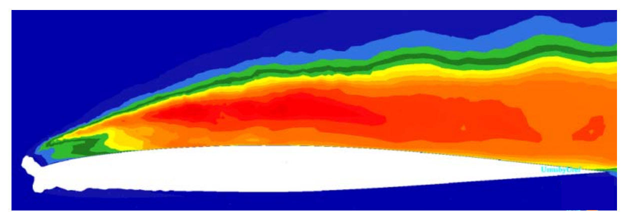
- **DES for extruded GLC305/944 ice shape**
  - Detached Eddy Simulation (DES) (specific form of hybrid RANS/LES)



Three-dimensional unsteady flow in separated region



Experimental data



DES results

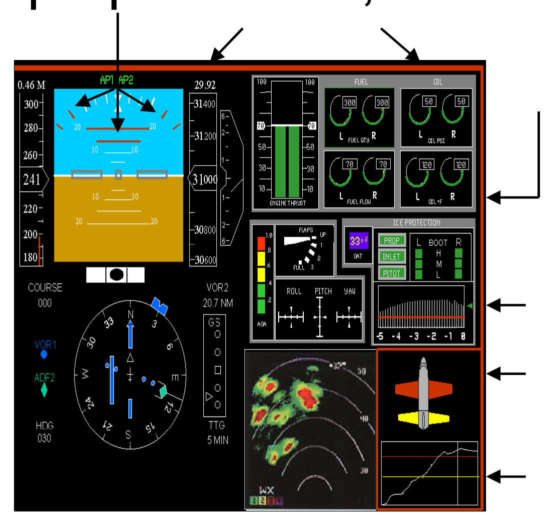
RMS of streamwise velocity fluctuations

Source: Mogili, Thompson (MSU), Choo, and Addy (NASA GRC)

Systems-based Multidisciplinary Research

Academic Airframe Icing Perspective

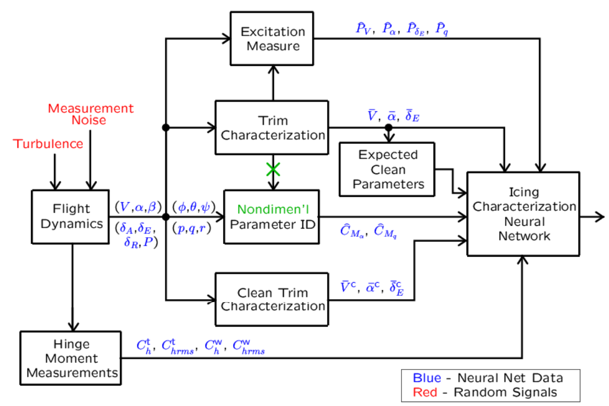
- **Example – Smart Icing Systems**
  - Combined human factors, controls, flight mechanics, and aerodynamics to address icing flight safety system
  - Systems to sense effect of ice accretion on aircraft and operate IPS, provide envelope protection, inform/advise pilot, etc
  - Systems, multidisciplinary approach provides integrated solutions and where needed helps guide new research



Systems-Based Multidisciplinary Research (cont.)

Academic Airframe Icing Perspective

- **Needed Multidisciplinary Research**
  - Couple ice accretion and ice protection modeling with aerodynamics and control
  - Couple flight mechanics, aerodynamics, sensing and flight mechanics and control
  - Bring atmospheric science and route planning into the problem of SLD protection
  - Include Human Factors and training into the research with flight simulation, ice accretion, and flight dynamics
  - Etc.



Summary

Academic Airframe Icing Perspective

- 2-D ice accretion and aerodynamics reasonably well understood for engineering applications
- To significantly improve our current capabilities we need to understand 3-D
  - Important ice accretion physics and modeling not well understood in 3-D
  - Aerodynamics unsteady and 3-D especially near stall
- Larger systems issues important and require multi-disciplinary team approach

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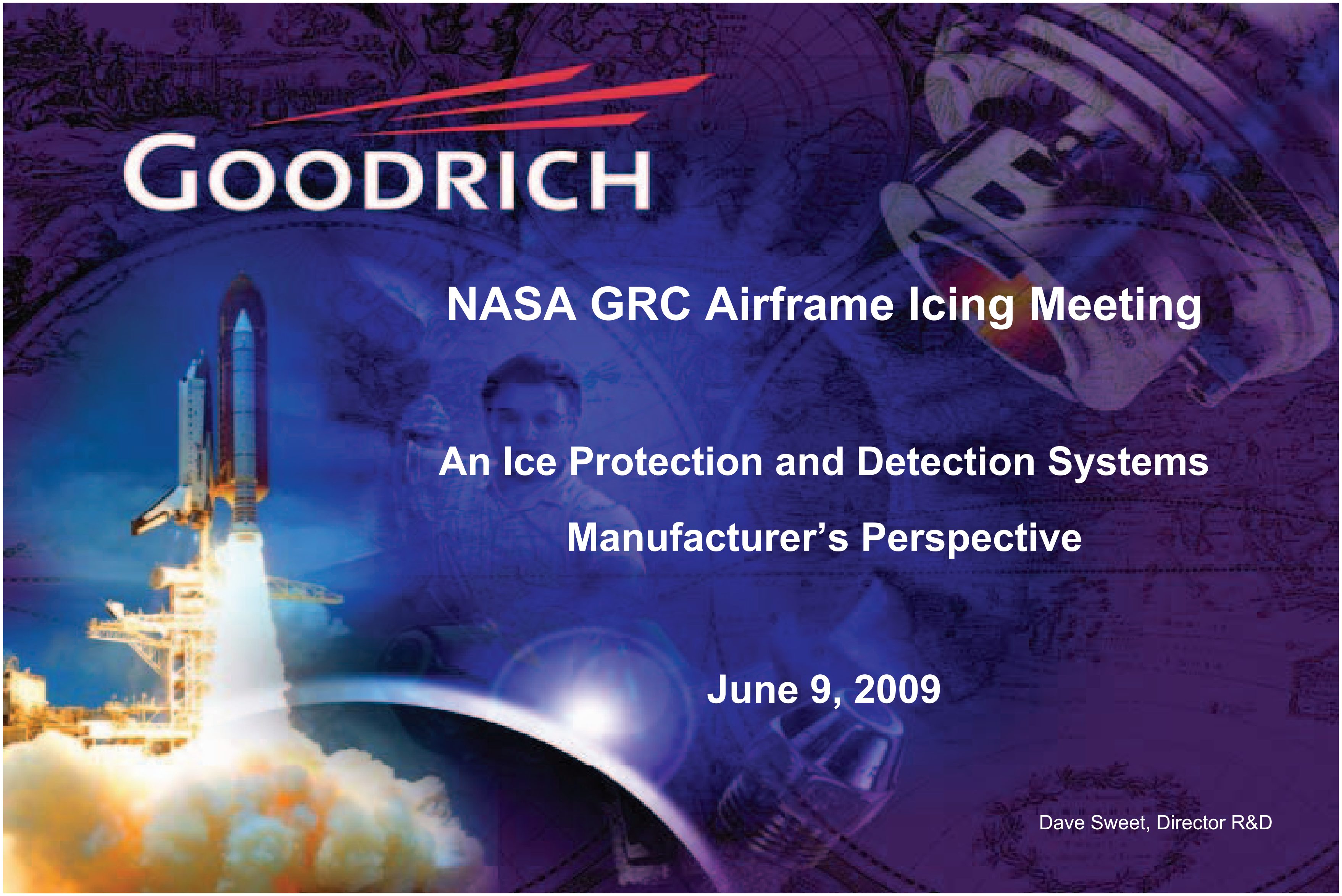
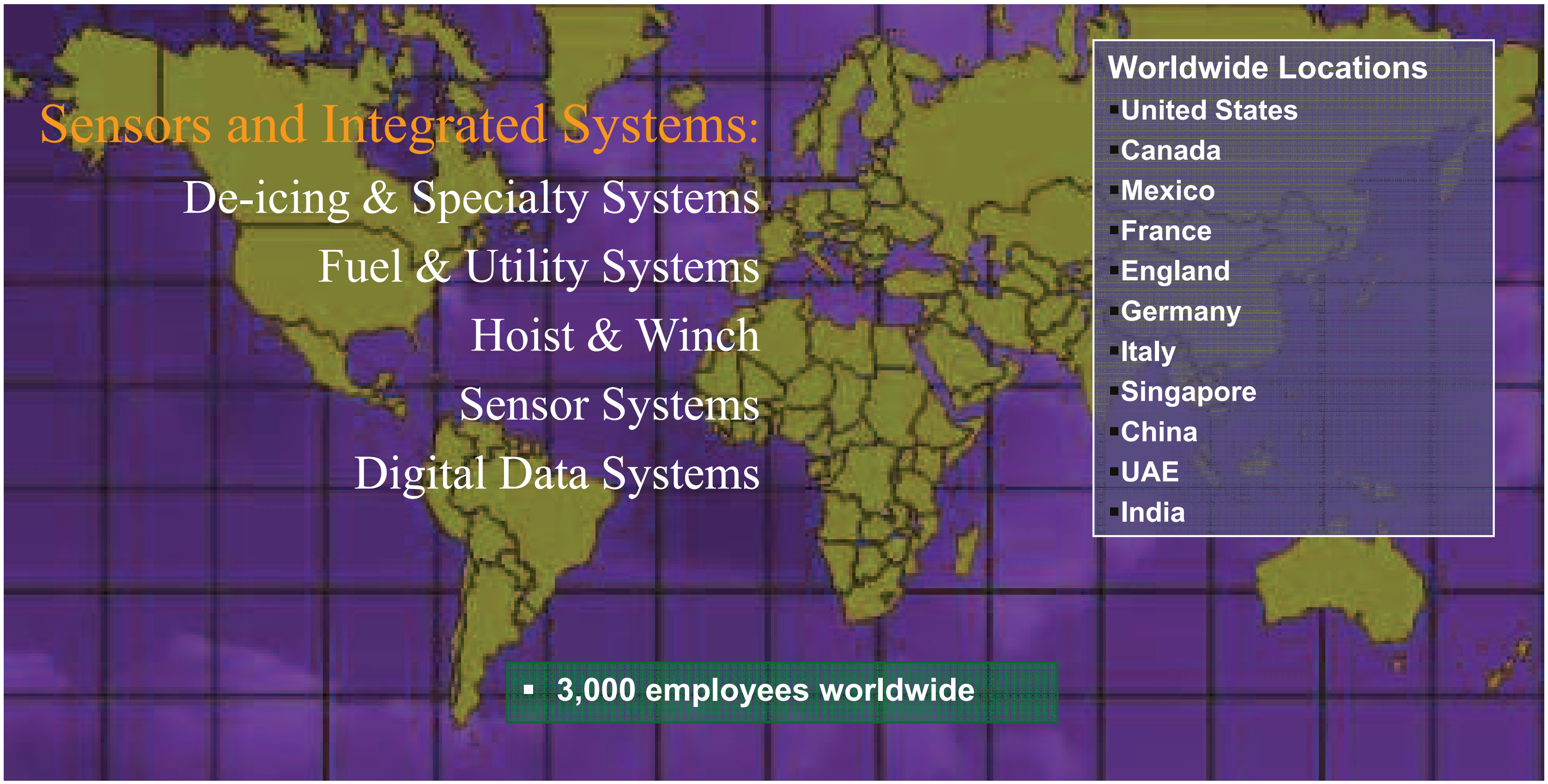


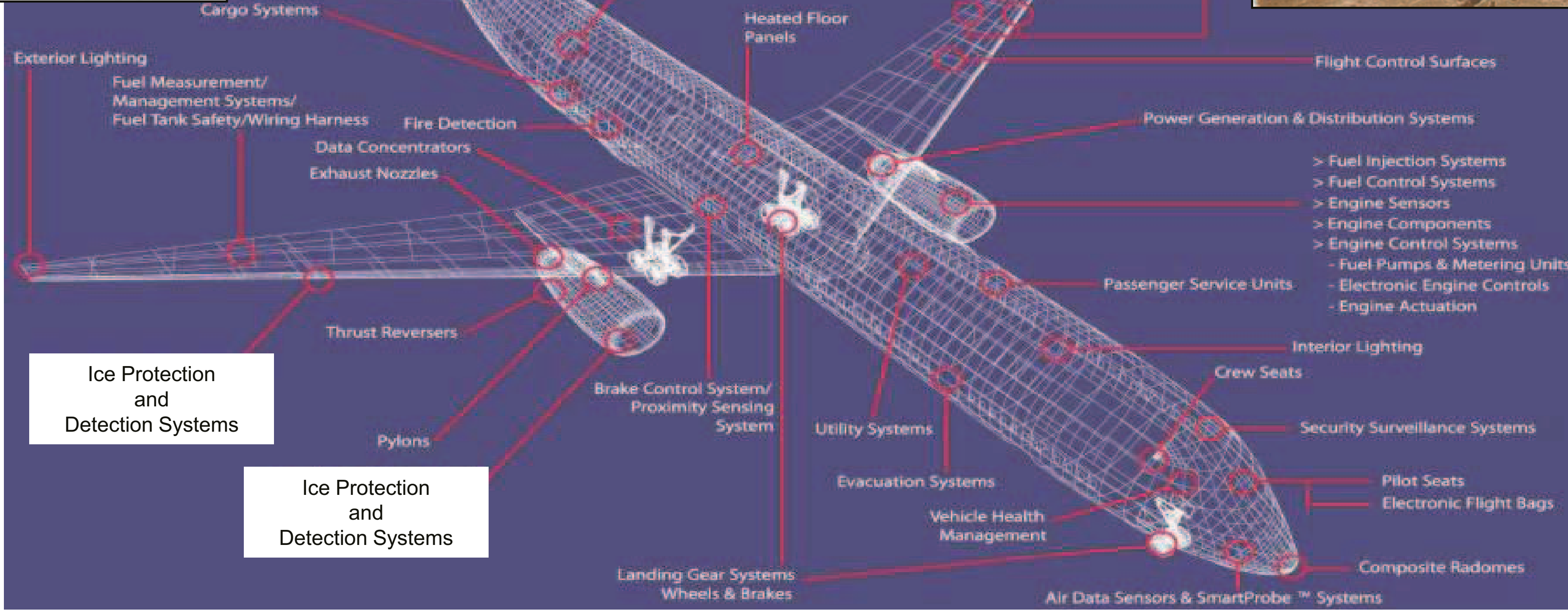

Sensors and Integrated Systems:
De-icing & Specialty Systems
Fuel & Utility Systems
Hoist & Winch
Sensor Systems
Digital Data Systems
Worldwide Locations
▪United States
▪Canada
▪Mexico
▪France
▪England
▪Germany
▪Italy
▪Singapore
▪China
▪UAE
▪India
▪ 3,000 employees worldwide

June 9, 2009

GOODRICH

Sensors and Integrated Systems

NASA GRC Airframe Icing Meeting



1965 - Minneapolis, MN

1930 – Akron, Ohio

June 9, 2009

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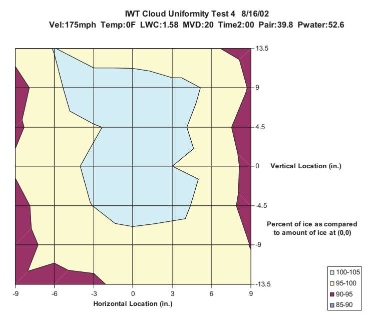
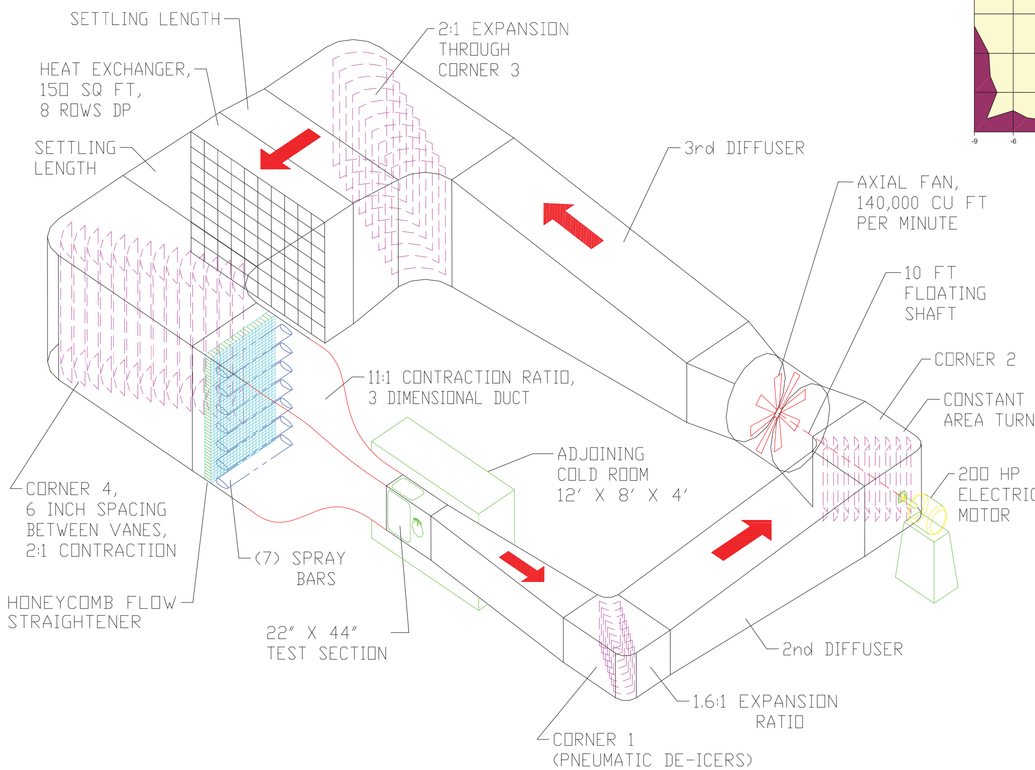
Sensors and Integrated Systems

Goodrich, SIS-OH Icing Wind Tunnel





- Accomplishments – NASA GRC
  - World Class Aircraft Icing Research Center and Facility
  - Primary Sponsor / Partner - Aircraft Icing Consortia / Meetings
  - Icing Research Tunnel
  - Icing Test Aircraft
  - Icing Codes – LEWICE / Scaling, et al
  - Development of New Technologies (SBIR, STTR, et al)
    - Example: Look Ahead Ice Detection
  - Pilot Training Materials
  - Full Cooperation with Academia, Government and Industry

- Recommendations - Codes
  - User Friendly - 3D LEWICE
    - Incorporation of Runback / Evaporation Module
    - Coupled Aero / Thermal / Runback / Ice Shapes
      - Aero with Enhanced Near Field Effects
    - Temperatures / Conditions at which Ice will not Accrete
    - Include SLD and Ice Crystals (Mixed Phase)
      - Splash / Loss of Large Droplets
    - LEWICE Verification
    - Suggestions:
      - Form LEWICE Consortium (User Community Team)
      - Regular User Community Updates through SAE / AIAA, et al
      - Conduct Training Sessions

- Recommendations - Codes
  - Model Icing Wind Tunnels
    - UIUC Proposal – Model IRT – Extend for other tunnels
    - Explain Differences between Facilities
    - Explain Differences between IWT and Flight
  - Develop Thermal Scaling Laws
    - Critical for Next Generation Electrothermal IPS
  - Engine Icing – Internal
  - Rotating Components – Propeller / Propfan / Rotorblade
    - Wind Turbine
  - Ice Shed Trajectory Model
    - How Shed Ice Breaks-Up in the Air Stream
    - Where Shed Ice Strikes the Aircraft

- Other Recommendations
  - IRT / Test Facilities
    - Develop SLD / Mixed Phase / Ice Crystal Test Capabilities
    - Engine Test Facility
      - Nacelle Inlets to Fan
      - Internal to Engine
    - Cost
  - Basic Icing Research
      - Impact Ice Formation
      - Ice Adhesion
      - Impact Ice Physical Properties

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Glenn Research Center (GRC) has a long history of working with its partners towards the understanding of ice accretion formation and its associated degradation of aerodynamic performance. The June 9, 2009, Airframe Icing Workshop held at GRC provided an opportunity to examine the current NASA airframe icing research program and to dialogue on remaining and emerging airframe icing issues and research with the external community. Some of the airframe icing gaps identified included, but are not limited to, ice accretion simulation enhancements, three-dimensional benchmark icing database development, three-dimensional iced aerodynamics modeling, and technology development for a smart icing system.

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