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NASA Airframe Icing Research Overview Past and Current

Airframe Icing Workshop
NASA Glenn Research Center

Cleveland, Ohio

June 9, 2009

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
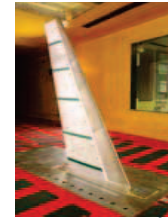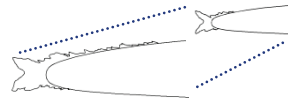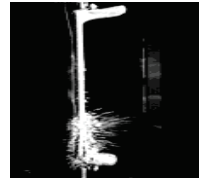## Past and Current

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

- Historical timeline
- Highlights
- Development of major products

Historical Progress in Technology

Experimental Methods		
1980s	1990s	2000s

- **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**

- **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**

- **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**

Experimental Methods

In-Flight Testing Projects

– Icing cloud characterization

– Ice shape measurements

– Instrumentation development

– Aircraft performance measurements with simulated ice shapes

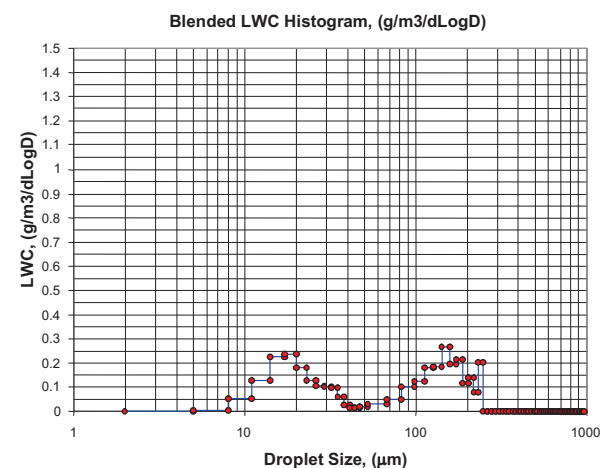– Aircraft handling and stability & control characteristics with simulated ice shapes
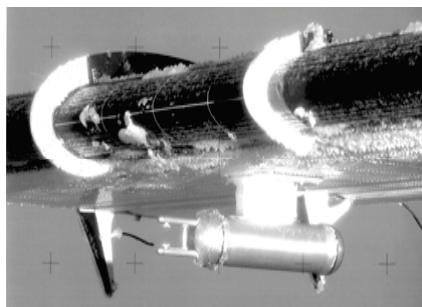
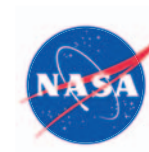Flight No.9768 ; Flight Date: 12/11/97; Time: 15:05:51; Span= 18

Stereoscopic imaging for ice shape documentation
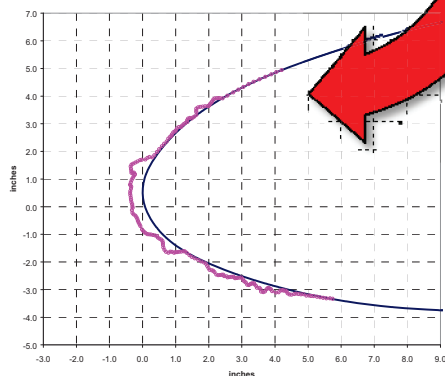
Particle sizing probe mounted on Twin Otter

LWC histogram for Twin-Otter flight in SLD

Blended LWC Histogram, (g/m3/dLogD)

Experimental Methods

NASA/CP—2009-215797

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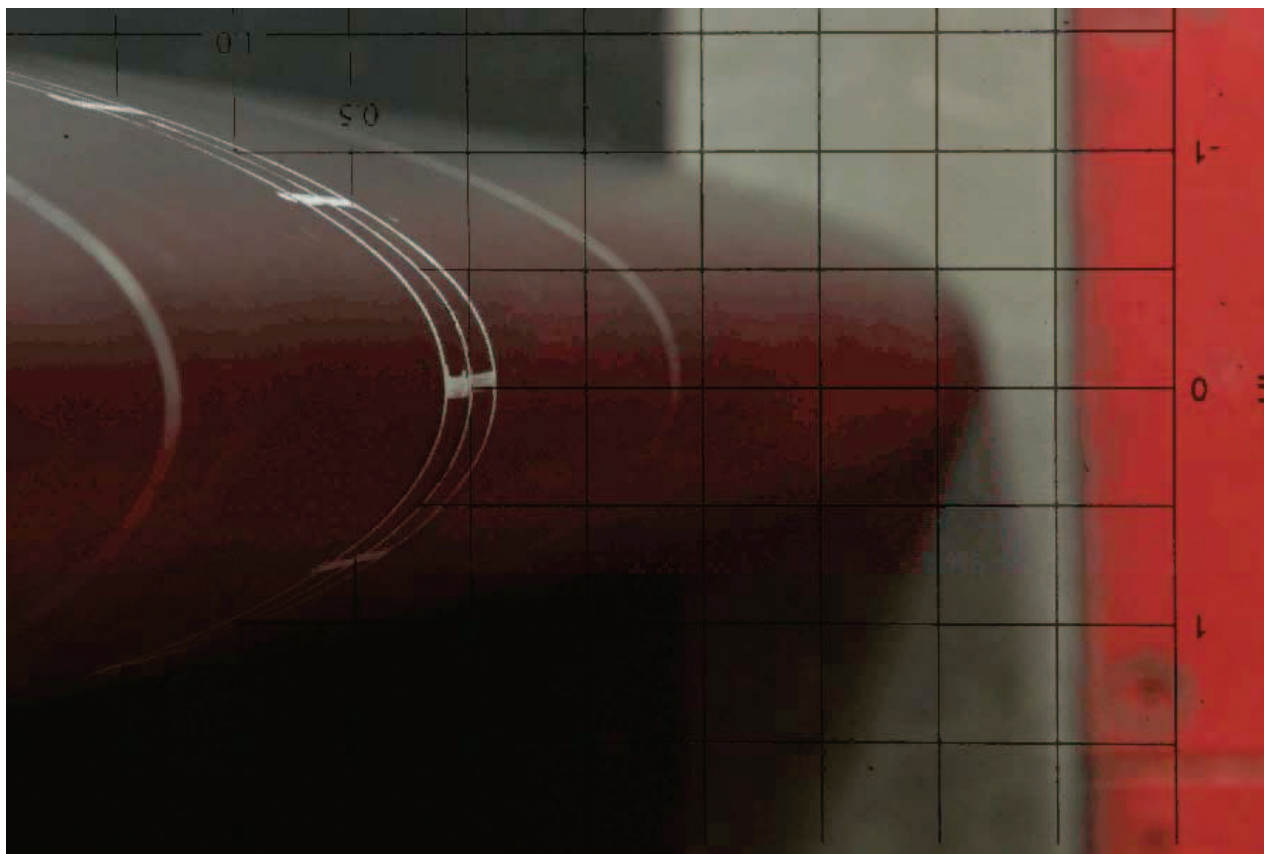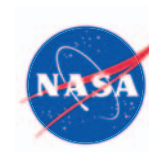## Ice Accretion Studies

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
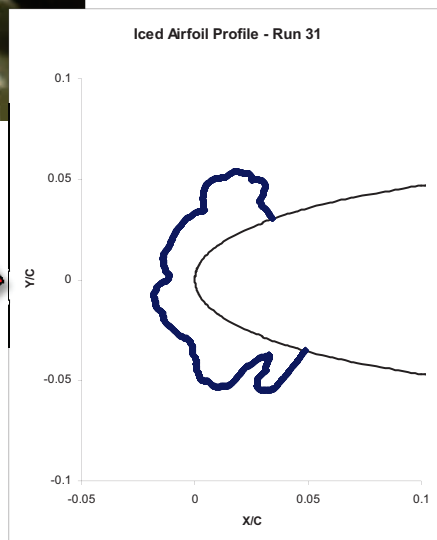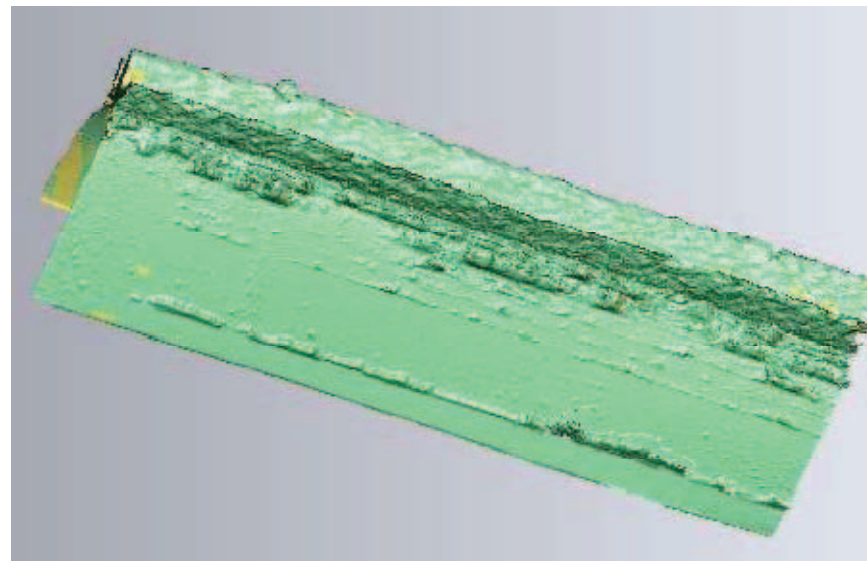

*IRT Test - ice shape growth*   ***Click to play movie***

Experimental Methods

Ice shape Measurement Methods

– Ice shape tracing

– Ice shape molds and castings

– Utilization of 3D scanner technology

Iced Airfoil Profile - Run 31

National Aeronautics and Space Administration

Experimental Methods

NASA/CP—2009-215797

Ice shape Measurement Methods

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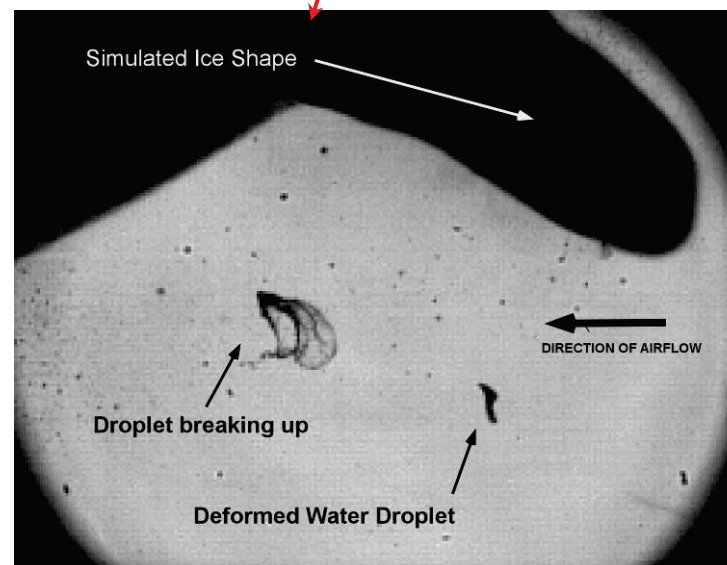- Utilization of 3D scanner technology

www.nasa.gov
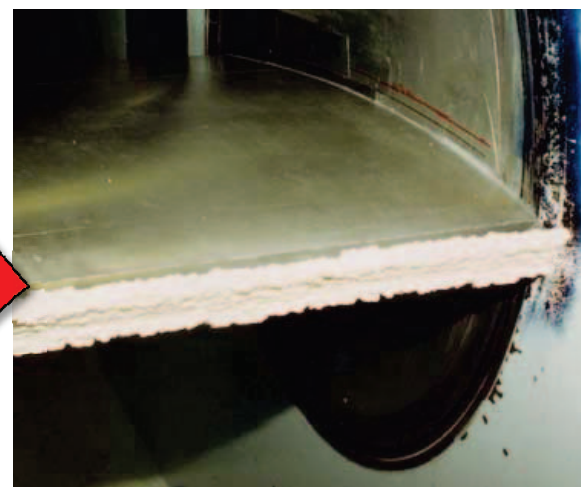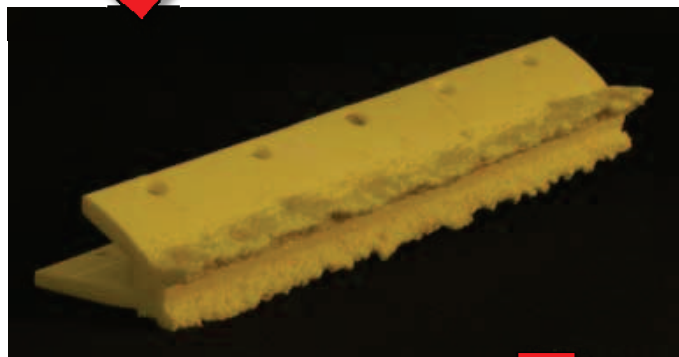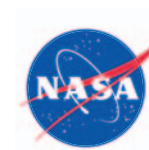
Experimental Methods

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

Simulated Ice Shape

DIRECTION OF AIRFLOW

Droplet breaking up
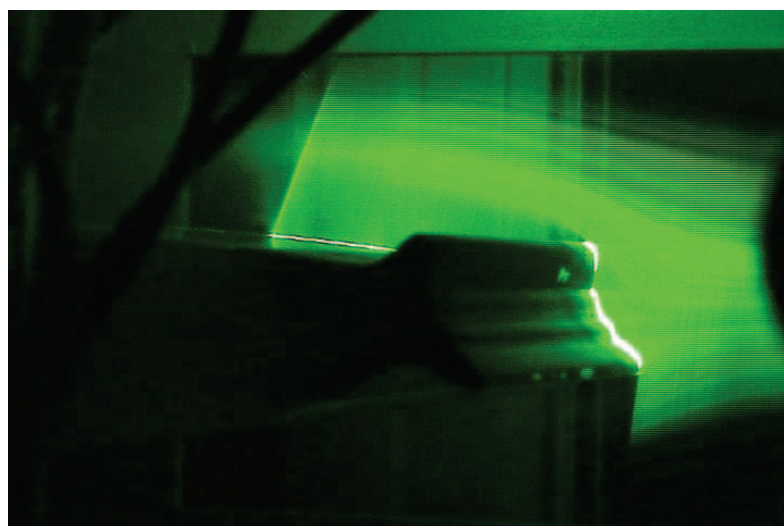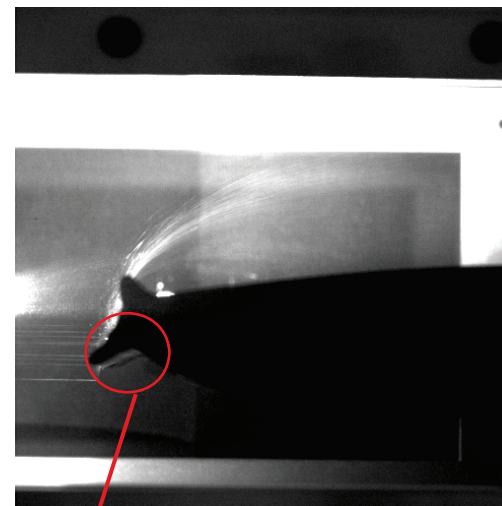
Deformed Water Droplet

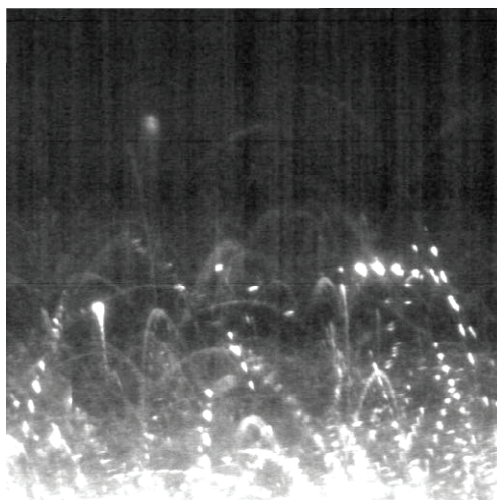**Click to play movie**

NASA/CP—2009-215797

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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
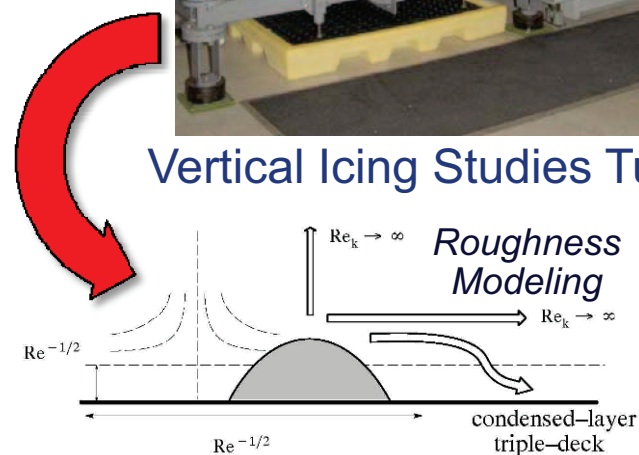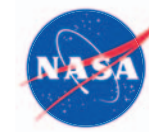
Scalloped Ice Shape Studies

Droplet Splashing Imaging

Vertical Icing Studies Tunnel
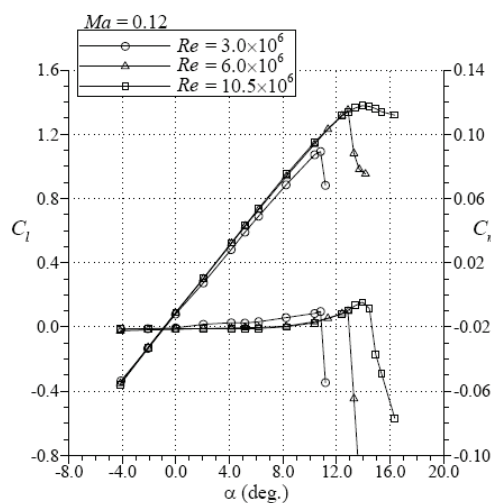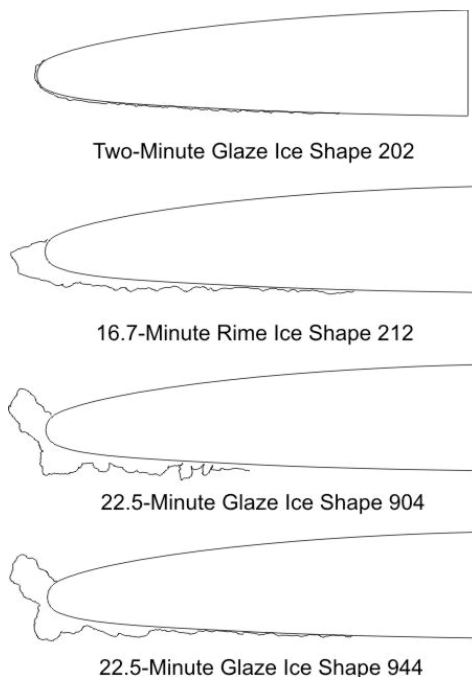
Roughness Modeling

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Experimental Methods

Aerodynamic Performance Measurements
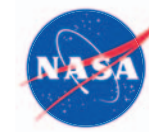
– Pressure and force measurements on airfoils and wings with leading edge artificial ice shapes

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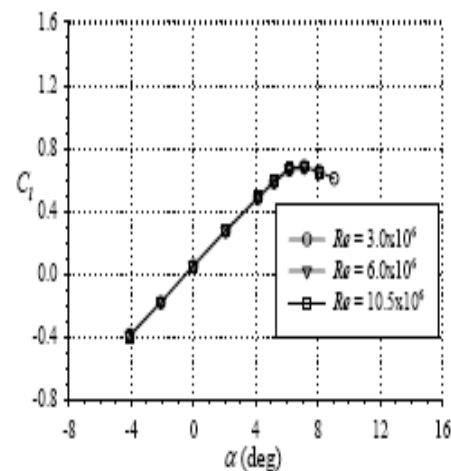
Reynolds Number Effects on 22.5-minute Glaze Ice Shape (944 casting) at $Ma = 0.12$

Experimental Methods
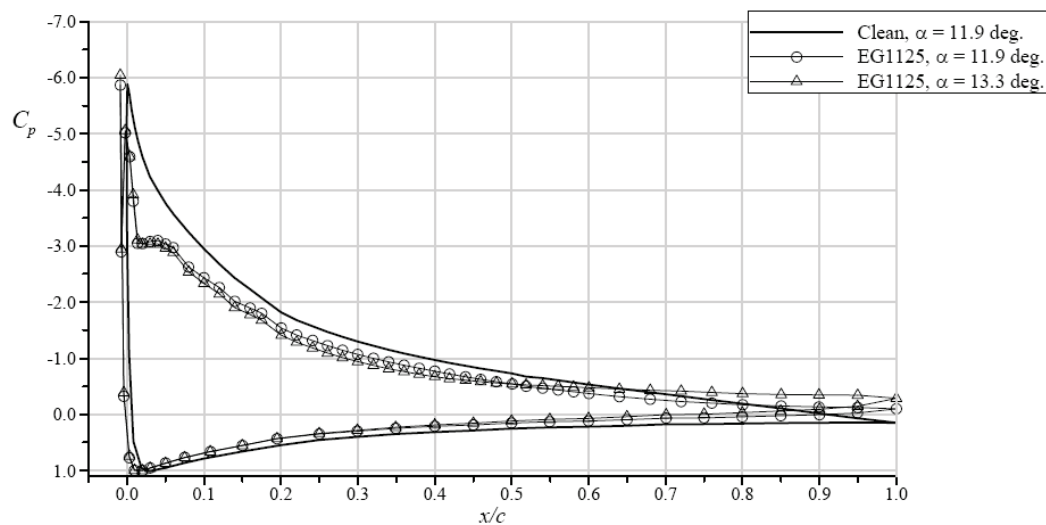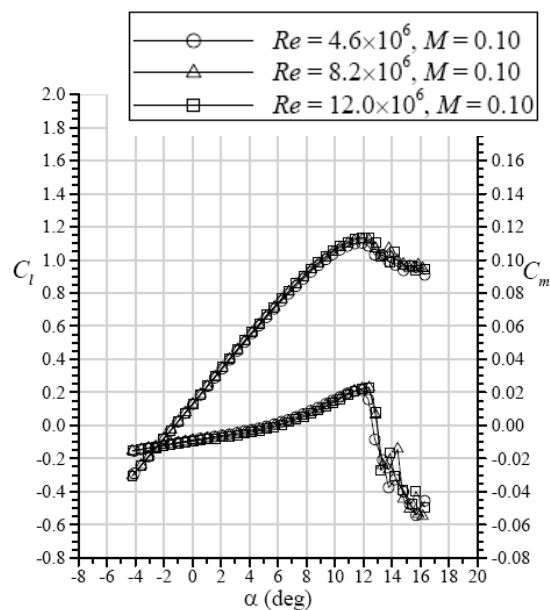
High Re Aerodynamic Performance Measurements at ONERA F1 Facility
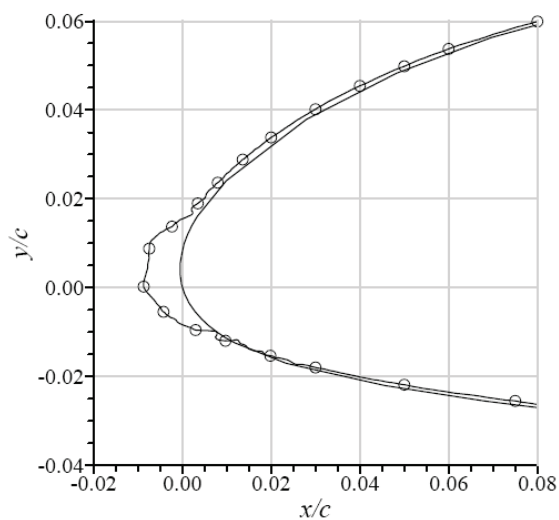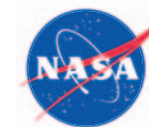
Experimental Methods

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
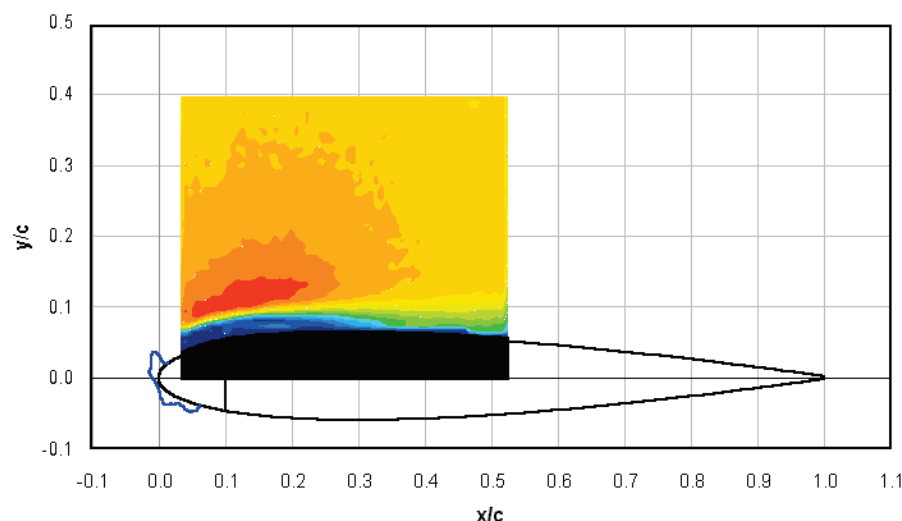
Contour plot of the average velocity field at mid-span for the NACA 0012 airfoil with 2D glaze ice simulation at *Re = 1x10^6 and α = 2.7º*
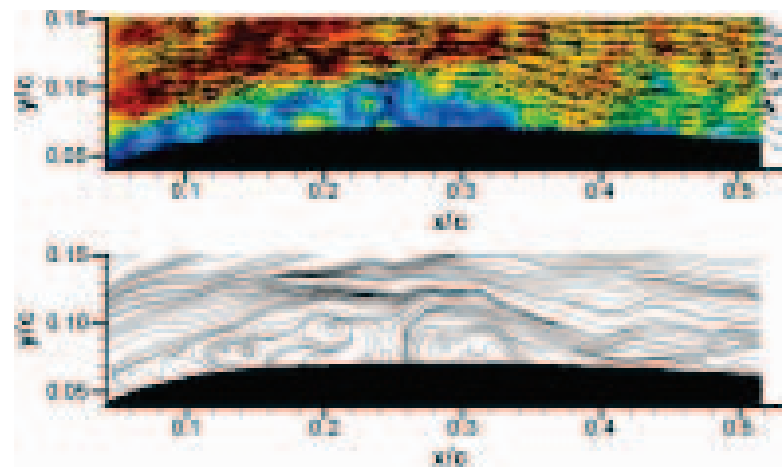
Contour vector and streamline plots of an instantaneous velocity field at mid-span for the NACA0012 airfoil with 2D glaze ice simulation at *Re = 1x10^6 and α = 2.7º*

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/m³	τ, min	β_0, %	$\beta_0 A_c$	n_0	We_L, 10^6
▭	36.0	5	100	160	1.50	9.7	95	1.6	0.43	1.2
──	10.5	11	200	40	1.00	2.4	93	1.8	0.40	1.4
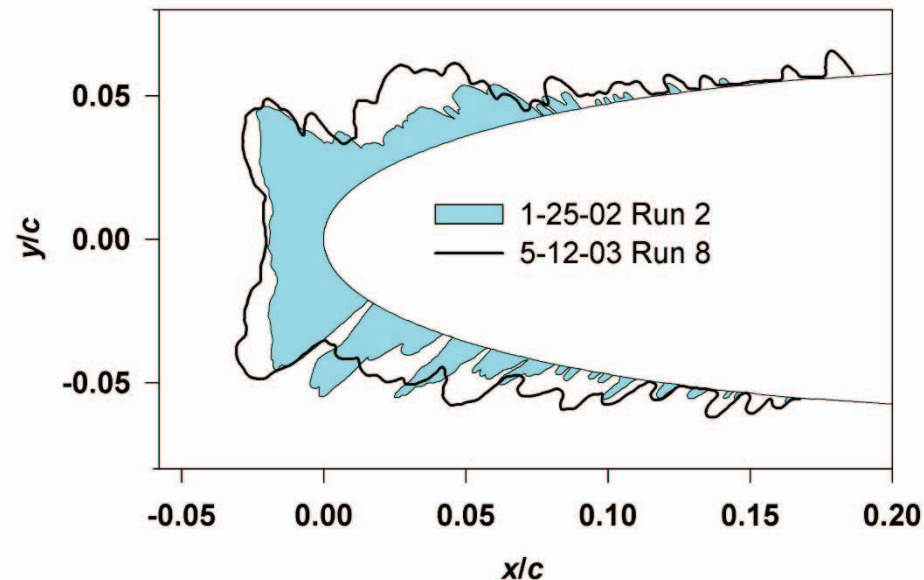
Scaling to App C for MVD's up to 160μm has been demonstrated

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

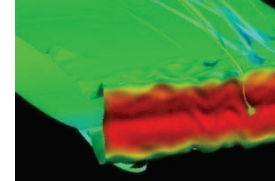# Historical Progress in Technology

Computational Methods		
1980s	1990s	2000s
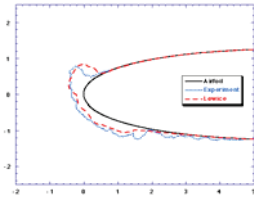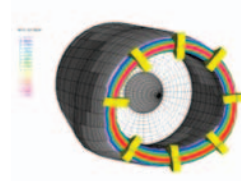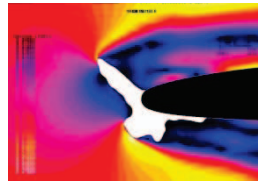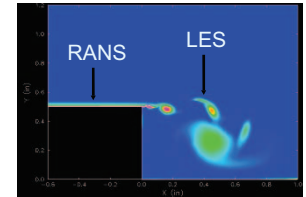
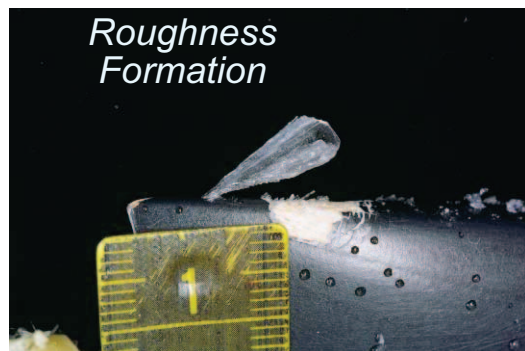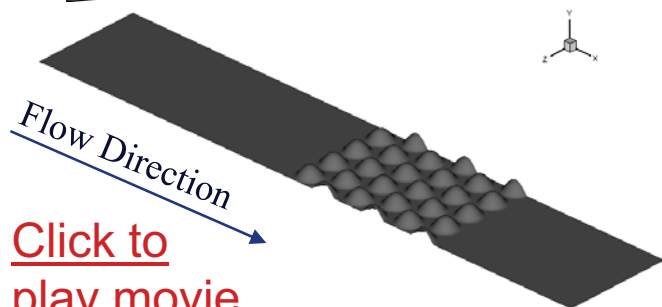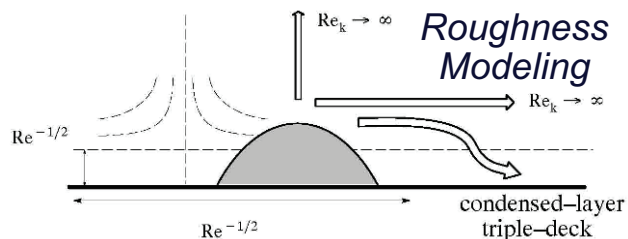| 1980s	1990s	2000s
• **LEWICE development** • **Early 2D performance analysis studies**	• **LEWICE3D development** • **Release of LEWICE 2.0** • **2D grid sensitivity and turbulence model evaluations** • **Early 3D performance analysis studies** • **Development of stand alone thermal IPS simulation methods**	• **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

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Roughness Formation

Feather growth

Water film movement

Flow Direction

Click to play movie

Re$_k$ → ∞

Re$^{-1/2}$

Roughness Modeling

Re$_k$ → ∞

Re$^{-1/2}$
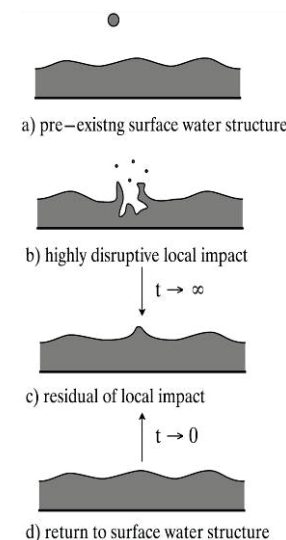
condensed–layer triple–deck

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

a) pre−existng surface water structure

b) highly disruptive local impact

t → ∞

c) residual of local impact

t → 0

d) return to surface water structure

Click to play movie
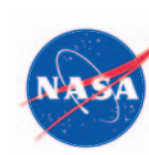
Ice Accretion Computational Modeling

LEWICE – 2D Ice Accretion Code

Ice Shape Tracing; Validation Database

Example of Ice Shape Prediction at
Average %Difference from Experimental Data
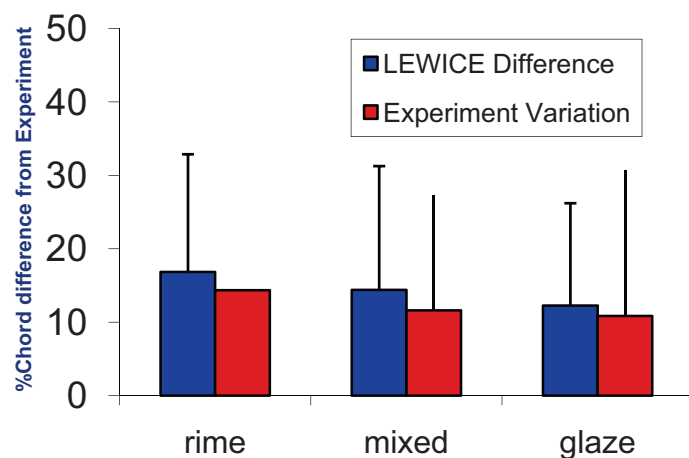
Ice Shape Comparison Results Comp. vs. Exp.
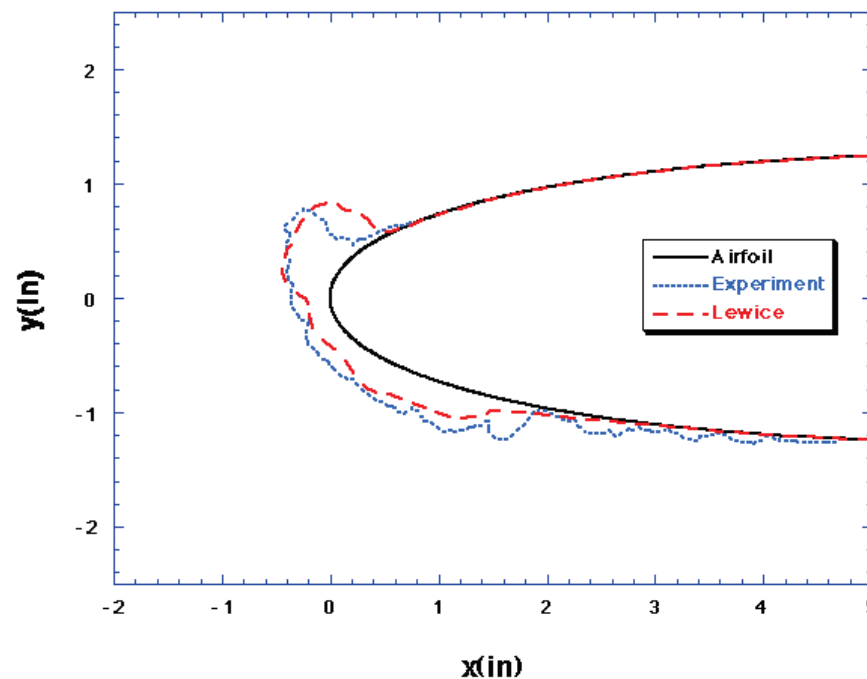
Ice Accretion Computational Modeling

LEWICE3D – 3D Ice Accretion Code
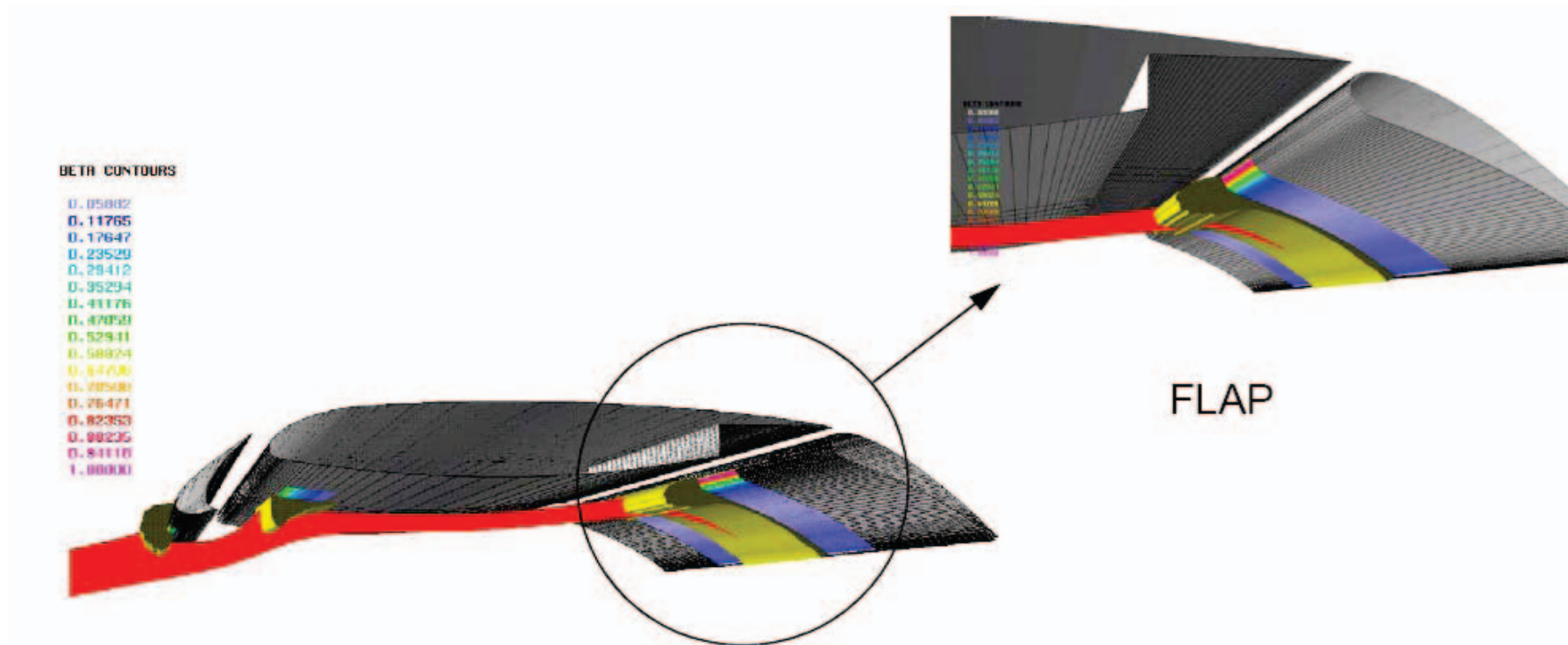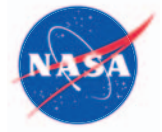
FLAP

Iced Aircraft CFD Modeling

Geometry preparation, blocking, gridding, link to flow solver, aero properties
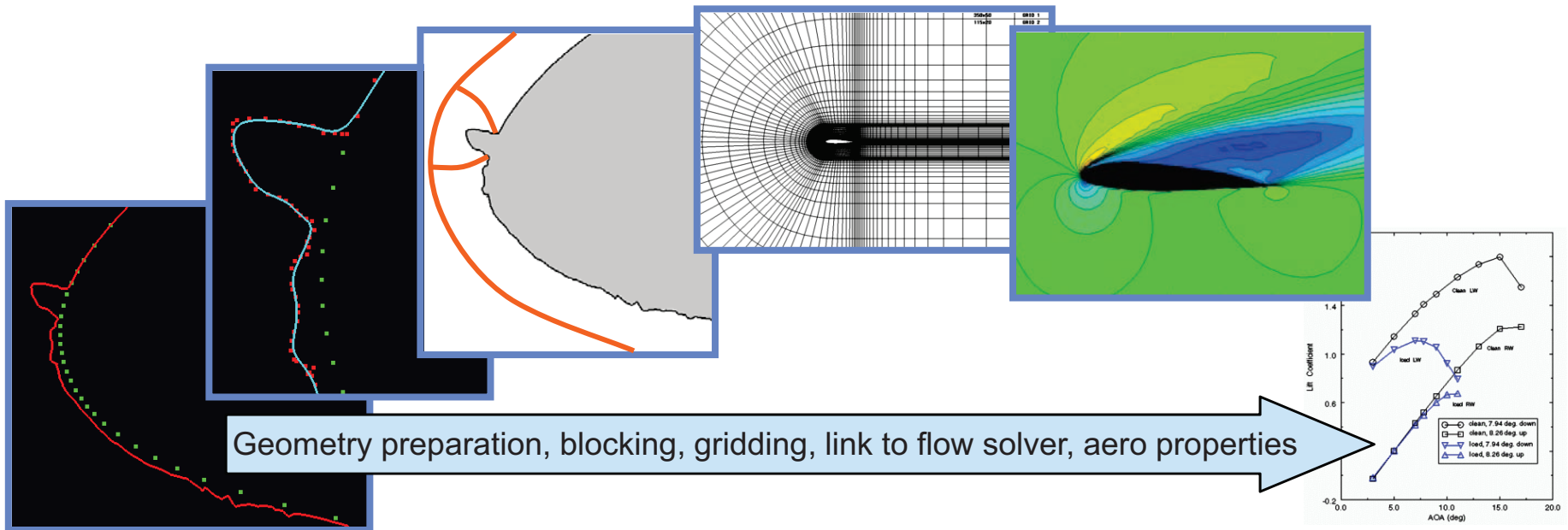
- Ice feature effects
- Identification of critical ice shapes
- Surface modeling and grid generation
- Turbulence modeling and multi-phase flow
- Time dependent/adaptive gridding
- CFD modeling for 3D surfaces
- Roughness effects (unsteady, multi-scale)
- 3D particle tracking through unsteady/separated flow
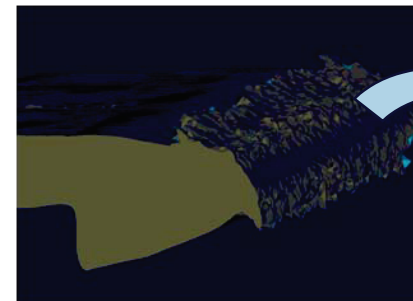
Scanned solid to CFD grid
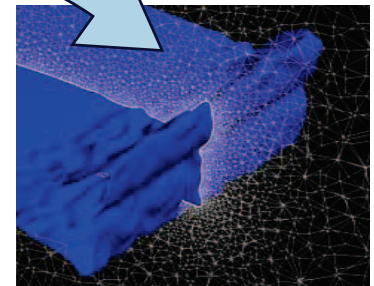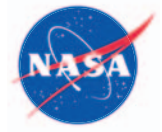
Iced Aircraft CFD

CFD Studies

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

2.) Turbulence modeling and time dependent/ adaptive gridding for icing topology
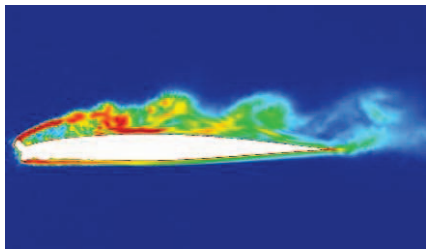
Turbulence generation behind a leading edge ice shape
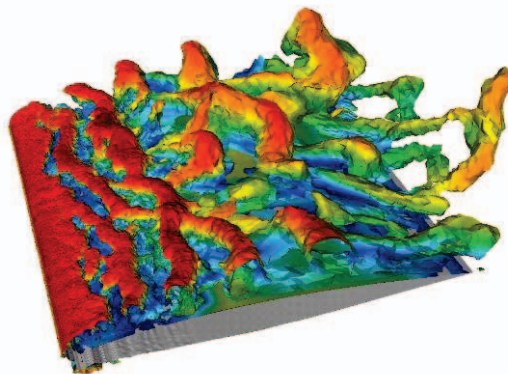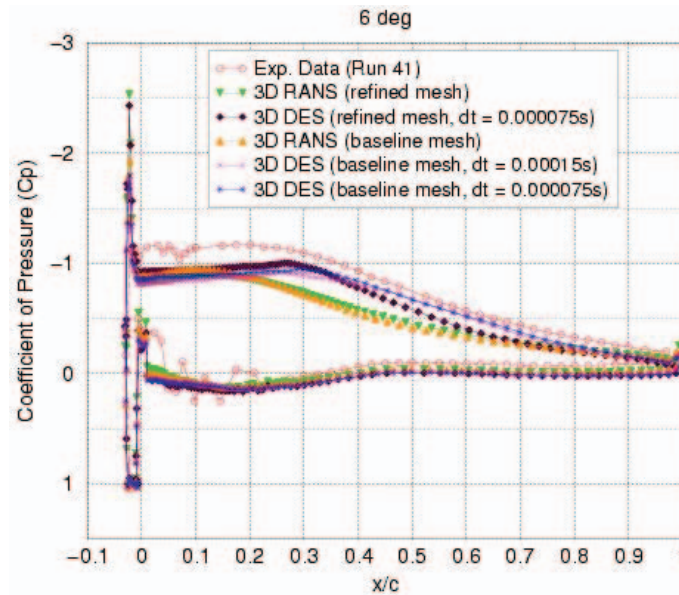
3.) CFD modeling for 3D surfaces
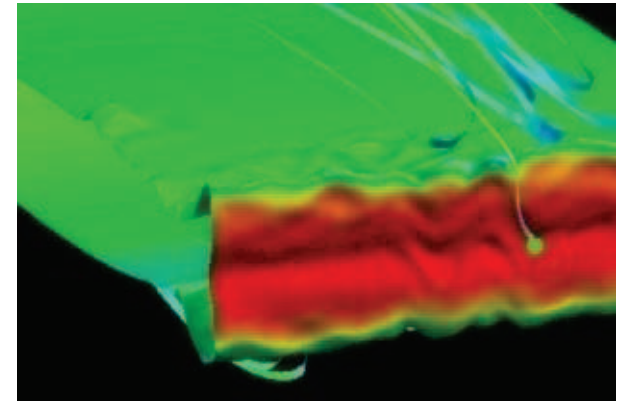
4.) Roughness effects (unsteady, multi-scale)
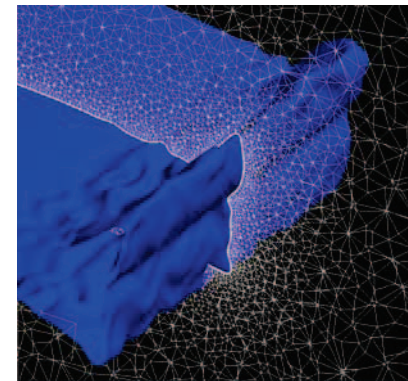
Historical Progress in Technology
Computational Methods - LEWICE

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
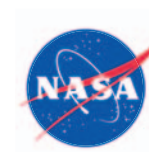
Historical Progress in Technology

Computational Methods – Performance Analysis

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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

Historical Progress in Technology

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Flight Dynamics		
1980s	**1990s**	**2000s**
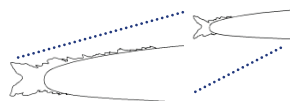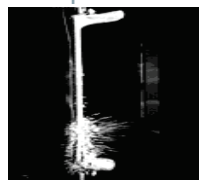
| 1980s	1990s	2000s
• **Initial testing of stability & control parameters on NASA Twin Otter** • **Classic longitudinal flight test techniques with artificial ice shapes** • **Application of digital inertial data system for stability and control derivative estimation for artificial ice and natural conditions** • **Tailplane Icing Project develops methods for evaluation of stability and control parameters for iced aircraft**	• **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.**	• **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.**

Icing Effects on Aircraft Controllability

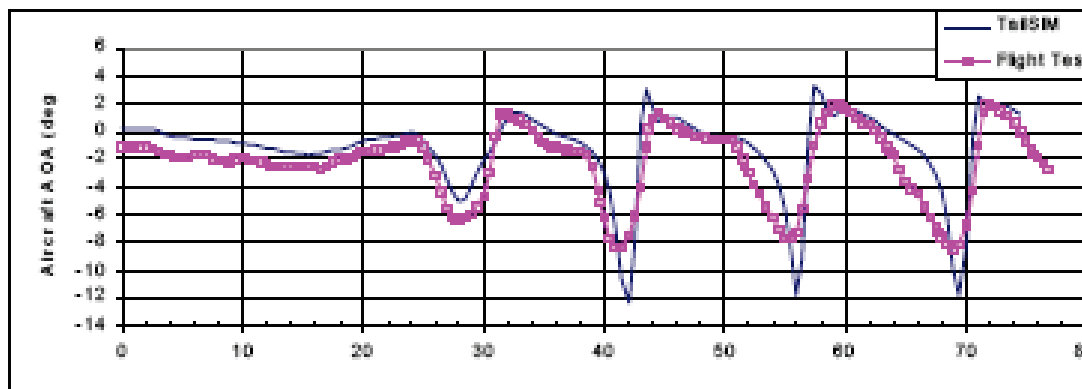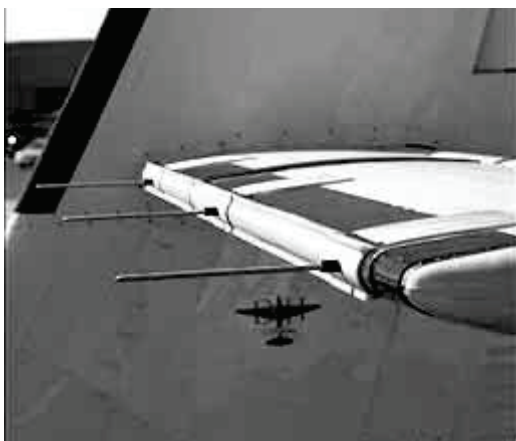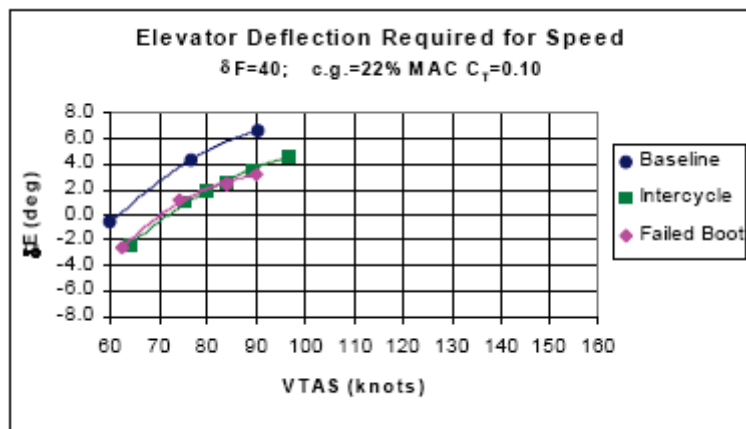## Preventing Iced Flight Dynamics Loss of Control

- 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
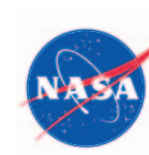
Fligth Dynamics

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

Elevator Deflection Required for Speed
$\delta F=40$; c.g.=22% MAC $C_L=0.10$

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
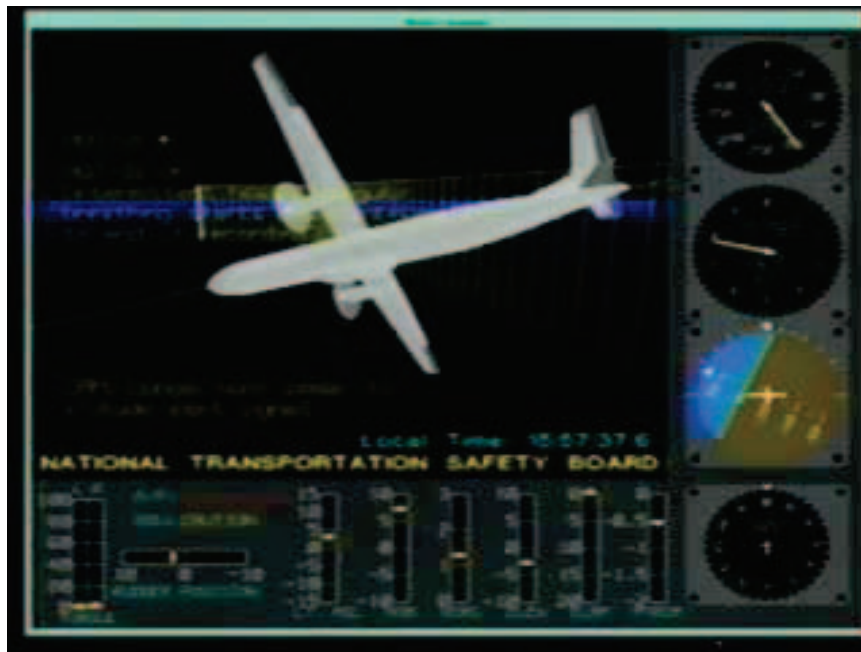

1994 - ATR-72, Roselawn, IN

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

Click to play movie
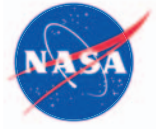
Research in Iced Flight Dynamics

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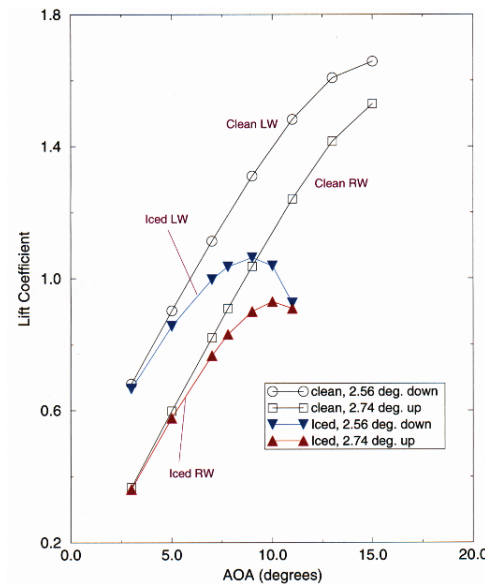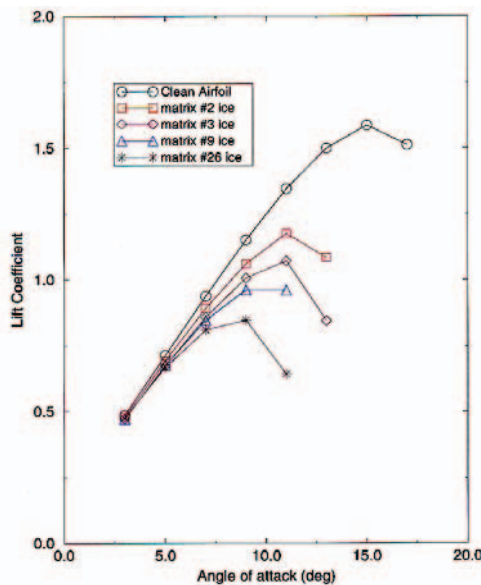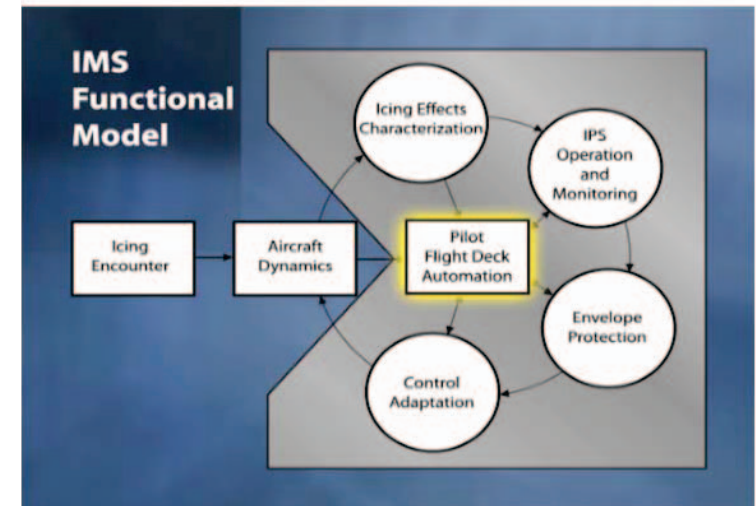
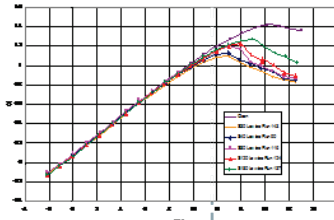Final NTSB report on Comair Flight 3272 released on November 4, 1998

- 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
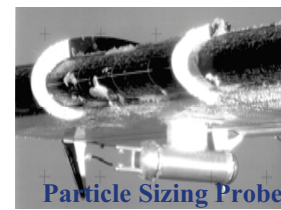
Historical Progress in Technology
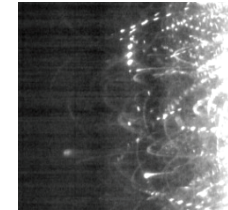
Experimental Databases		
1980s	**1990s**	**2000s**
• Ice shape profiles from various airfoils obtained in the IRT • Ice shape profiles and icing cloud conditions from in-flight measurements on the NASA Twin Otter • Iced airfoil performance characteristics using simplified artificial ice shape geometries	• 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	• 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

Particle Sizing Probe

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

National Aeronautics and Space Administration

NASA/CP—2009-215797

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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

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