NASA Airframe Icing Research Overview
Past and Current

Airframe Icing Workshop
NASA Glenn Research Center

Cleveland, Ohio
June 9, 2009
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

[Diagram showing:
• Historical timeline
• Highlights
• Development of major products]
## Historical Progress in Technology

### Experimental Methods

<table>
<thead>
<tr>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice shape tracing methods</td>
<td>3D laser scanner for ice shape measurement</td>
<td>Development of SLD simulation capability in IRT</td>
</tr>
<tr>
<td>Development of accurate ice shape casting technique</td>
<td>Significant progress in extension of scaling laws to greater range of sizes and conditions</td>
<td>Extension of scaling laws to SLD icing conditions</td>
</tr>
<tr>
<td>Scaling laws identified and tested</td>
<td>Investigations of Reynolds number effects on iced airfoil performance using cast ice shapes</td>
<td>Investigations of SLD droplet splashing, break-up and associated mass loss</td>
</tr>
<tr>
<td>De-icing fluid aerodynamic tests conducted in IRT</td>
<td>Tailplane Icing Project develops methods for evaluation of stability and control parameters for iced aircraft</td>
<td>Development of methods for sub-scale aero testing of complete aircraft with artificial ice shapes</td>
</tr>
<tr>
<td>Aircraft performance testing with artificial ice shapes using Twin Otter</td>
<td>Shed ice particle tracking with high speed cameras</td>
<td>Full scale iced airfoil performance testing at flight Reynolds numbers in ONERA F1 pressurized wind tunnel</td>
</tr>
<tr>
<td>Icing cloud droplet size and liquid water content probes tested in IRT and in flight</td>
<td></td>
<td>Swept wing ice shape generation and performance testing on representative business jet model</td>
</tr>
<tr>
<td>Development of methods for measurement of collection efficiency on clean airfoils</td>
<td></td>
<td>Extension of collection efficiency measurement methods to iced airfoil geometries</td>
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</tbody>
</table>

- *NASA/CP—2009-215797*
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

Stereoscopic imaging for ice shape documentation

LWC histogram for Twin-Otter flight in SLD
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
Experimental Methods

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

condensed—layer triple-deck
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

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
Contour plot of the average velocity field at mid-span for the NACA 0012 airfoil with 2D glaze ice simulation at $Re = 1 \times 10^6$ and $\alpha = 2.7^\circ$
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.
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


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

## Historical Progress in Technology

### Experimental Methods – Ground-based Testing

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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<tbody>
<tr>
<td>1989</td>
<td>Developed methods for testing aerodynamic penalties resulting from application of de-icing fluids</td>
</tr>
<tr>
<td>1985-1990</td>
<td>Developed ice casting methods for creation of realistic ice shape models to be used in dry-air wind tunnel performance testing</td>
</tr>
<tr>
<td>1985-Present</td>
<td>Developed methodology for collection efficiency measurements on airfoils, wings, engine inlets and other aircraft surfaces</td>
</tr>
<tr>
<td>1990-1995</td>
<td>Developed visualization methods for shed ice particle tracking</td>
</tr>
<tr>
<td>1995</td>
<td>Adapted laser sheet flow visualization methods for use in icing cloud; examined effects of ice growth on delta wing leading edge vortices</td>
</tr>
<tr>
<td>1990-Present</td>
<td>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</td>
</tr>
<tr>
<td>2003-2006</td>
<td>Development of methods for simulation of SLD icing conditions</td>
</tr>
</tbody>
</table>
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


2006 Addendum to Icing Scaling Manual to include SLD scaling
## Historical Progress in Technology

### Computational Methods

<table>
<thead>
<tr>
<th></th>
<th>1980s</th>
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<tr>
<td><strong>1980s</strong></td>
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<tr>
<td></td>
<td><strong>LEWICE development</strong></td>
<td><strong>LEWICE3D development</strong></td>
<td><strong>Release of LEWICE3D version 2</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Early 2D performance analysis studies</strong></td>
<td><strong>Release of LEWICE 2.0</strong></td>
<td><strong>Collaboration with Boeing on use of LEWICE3D for 787 analysis</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>2D grid sensitivity and turbulence model evaluations</strong></td>
<td><strong>Release of LEWICE 3.2.2; includes initial modifications for SLD</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Early 3D performance analysis studies</strong></td>
<td><strong>International release of LEWICE</strong></td>
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<td></td>
<td></td>
<td><strong>Development of stand alone thermal IPS simulation methods</strong></td>
<td><strong>Automated grid generation for LEWICE</strong></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Release of SmaggICE 2.0</strong></td>
</tr>
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<td></td>
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<td></td>
<td><strong>Unsteady DES methods for iced performance analysis</strong></td>
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<tr>
<td></td>
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<td></td>
<td><strong>Thermal IPS model in LEWICE 2.2</strong></td>
</tr>
</tbody>
</table>
Ice Accretion 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
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
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

Geometry preparation, blocking, gridding, link to flow solver, aero properties
CFD Studies

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

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

3.) CFD modeling for 3D surfaces

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

Turbulence generation behind a leading edge ice shape
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

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

#### Computational Methods – Performance Analysis

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
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<tbody>
<tr>
<td>1983 – 1991</td>
<td>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</td>
</tr>
<tr>
<td>1995 – 1999</td>
<td>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</td>
</tr>
<tr>
<td>2000 – present</td>
<td>First release of SmaggICE, computational tool to aid in development of grids for ice shape geometries</td>
</tr>
<tr>
<td>Current</td>
<td>Use 3D unsteady methods to identify stall behavior of iced aircraft</td>
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</tbody>
</table>
## Historical Progress in Technology

### Flight Dynamics

<table>
<thead>
<tr>
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<th>2000s</th>
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</thead>
<tbody>
<tr>
<td>Initial testing of stability &amp; control parameters on NASA Twin Otter</td>
<td>Refinement of analysis techniques and flight test techniques with artificial ice shapes</td>
<td>Subscale model testing of Twin Otter in Bahrle Applied Research spin tunnel</td>
</tr>
<tr>
<td>Classic longitudinal flight test techniques with artificial ice shapes</td>
<td>Tailplane Icing Project builds upon prior experience to quantify iced tailplane effects</td>
<td>Iced aircraft state assessment research at UTSI supported through NRA</td>
</tr>
<tr>
<td>Application of digital inertial data system for stability and control derivative estimation for artificial ice and natural conditions</td>
<td>Investigations of scale model tailplane performance parameters</td>
<td>Flight testing to develop parameter ID methods in support of Smart Icing Systems studies and Systems Technology, Inc. SBIR.</td>
</tr>
<tr>
<td>Tailplane Icing Project develops methods for evaluation of stability and control parameters for iced aircraft</td>
<td>Investigation of effects of tailplane icing using scaled and full-scale wind tunnel tests.</td>
<td>Development of Ice Contamination Effects Flight Training Device (ICEFTD) to train pilots on effects of ice accretion.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Development of iced aircraft flight simulation model of Twin Otter and Cessna business jet.</td>
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<tr>
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<td></td>
<td>Dynamic wind tunnel testing of iced S-3B Viking to obtain data for simulation model.</td>
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</table>
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
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
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

<table>
<thead>
<tr>
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<tr>
<td><img src="https://via.placeholder.com/150" alt="Image 1" /></td>
<td><img src="https://via.placeholder.com/150" alt="Image 2" /></td>
<td><img src="https://via.placeholder.com/150" alt="Image 3" /></td>
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</table>

- 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

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[www.nasa.gov](http://www.nasa.gov)
## Historical Progress in Technology

### Experimental Database Development

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1983 – present</td>
<td>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</td>
</tr>
<tr>
<td>1985 – 2001</td>
<td>Development of collection efficiency database in collaboration with Wichita State University</td>
</tr>
<tr>
<td>1996</td>
<td>Electro-thermal ice protection system model tested to provide database for validation of thermal ice protection system simulation software</td>
</tr>
<tr>
<td>1999-2002</td>
<td>Tailplane Icing effects on sub-scale &amp; full-scale business jet T-Tail</td>
</tr>
<tr>
<td>2002</td>
<td>Testing of swept wing model to determine effects of sweep on ice shape development and resulting performance losses</td>
</tr>
<tr>
<td>2007</td>
<td>Development of SLD ice shape database for validation of simulation tools</td>
</tr>
</tbody>
</table>
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