Engineering, Operations & Technology
Boeing Research & Technology

Icing Research at Boeing

4th Workshop on Aviation Safety:
Ice Formation in Aeronautical Structures: Simulation and Experiments
29 – 30 May 2014, Rio de Janiero

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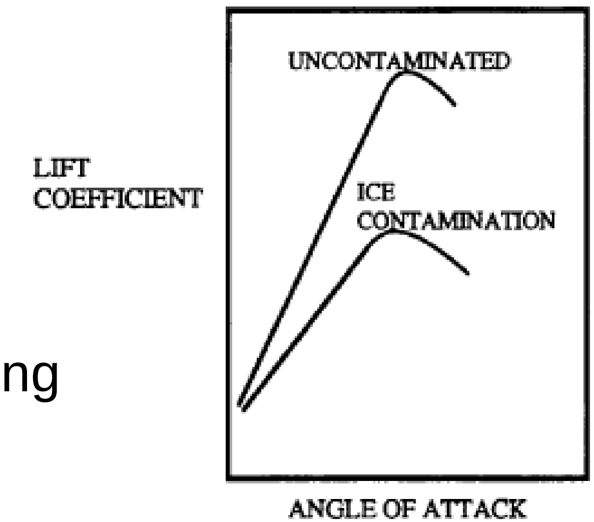
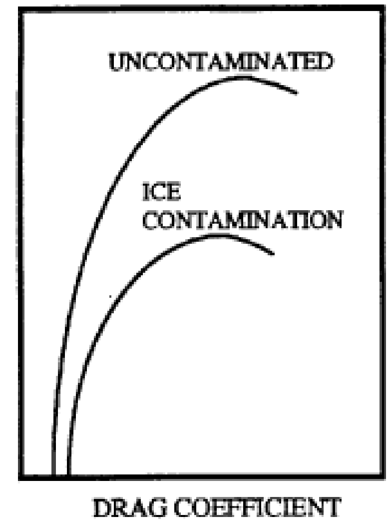
Agenda

- **Introduction**
  - Why is aerodynamics important in icing ?
- **Historical**
  - Early research
    - High-lift aerodynamics
    - In-spar frost and ice
- **Current Activity**
  - Rotorcraft Icing
  - Swept Wing Icing
  - Trajectory Analysis

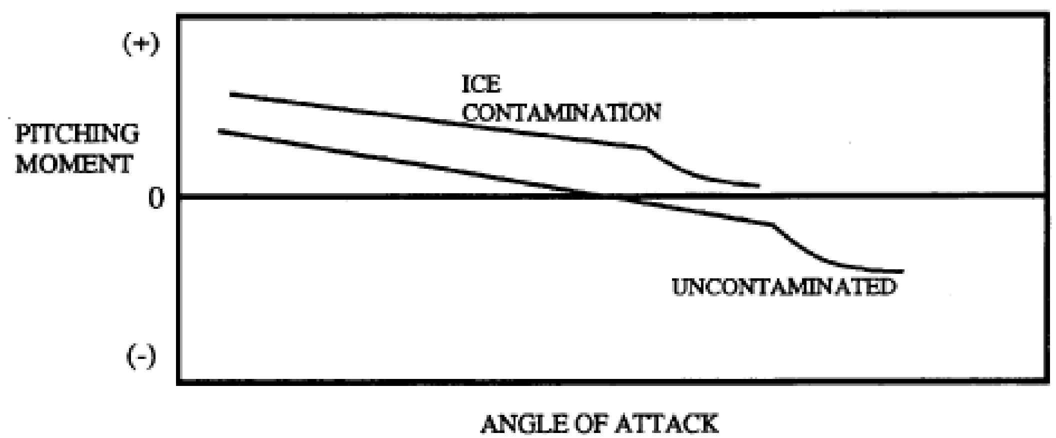
Introduction

- **Why is aerodynamics important in icing ?**
  - Significant lift loss
  - Loss of stall margin
  - Significant rise in drag
  - Drastic changes in pitching moment





- **Understanding the potential adverse impacts are important for both the designer and operator.**



Icing Research at Boeing dates back to the early days of the Company

Transcontinental and transatlantic flying over the northern route can never be entirely safe until a problem (icing) which has thus far baffled ingenuity has been solved.

—Commentary on attempts to solve icing problems, New York Times, April 9, 1931.

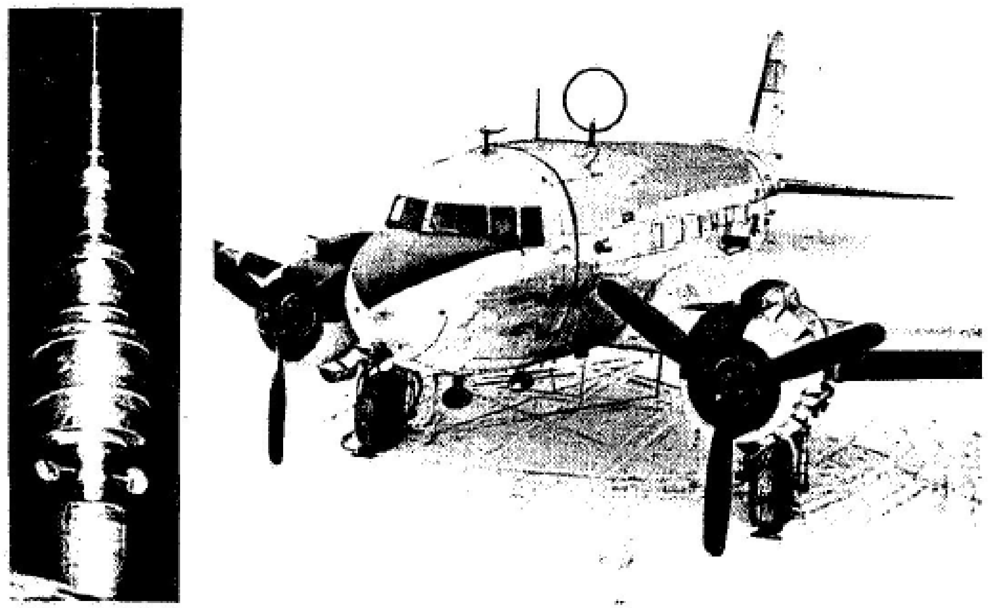
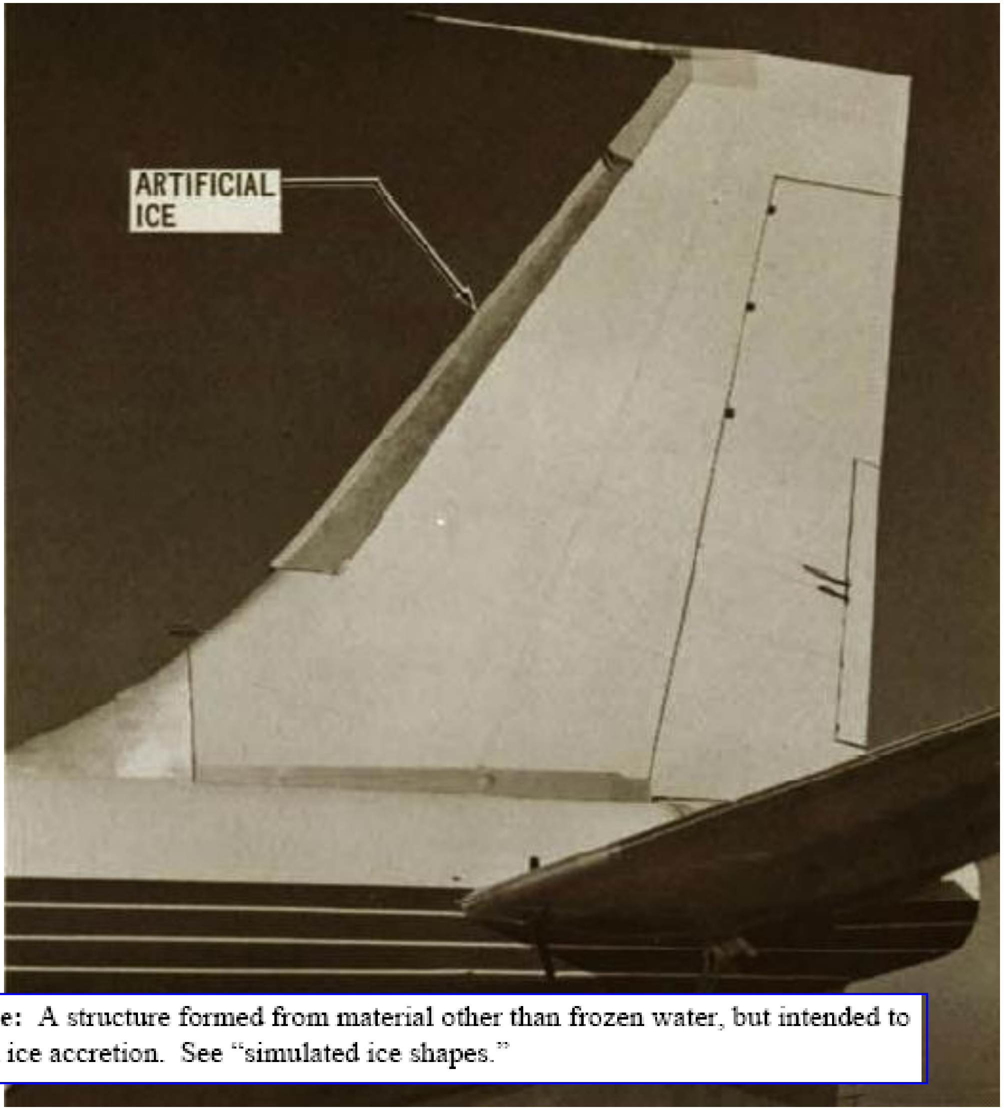


FIGURE 17.—Rotating multicylinder set extended through top of airplane fuselage.

NACA TR 1215

“An International Historic Mechanical Engineering Landmark: Icing Research Tunnel”, ASME publication, 20 May 1987

Icing Research at Boeing dates back to the early days of the Company



AC 20-73A: **Artificial ice:** A structure formed from material other than frozen water, but intended to represent an ice accretion. See "simulated ice shapes."

Boeing Airliner May-June 1962

BRAIT – Boeing Research Aero-Icing Tunnel

As the largest private operator of wind tunnels in the world, Boeing understands the importance of iced airfoil and iced-wing aerodynamics.

The Boeing Research Aero-Icing Tunnel (BRAIT), allows Boeing aerodynamics testing staff to create ice shapes and test de-icing systems on the ground, rather than in flight. This facility saves customers significant time and resources over actual in-flight testing, as it did during the Boeing 777 development and certification program

Test section: 4 by 6 ft
Sidewall mountings
Heated auxiliary air
Speed range: up to 250 knots (290 mph)
Minimum uniform c loud size: 3 by 4 ft
Temperature range: -25° to 50°F
Median droplet size: 15 to 40 microns
Liquid water content: .25 to 2.5 grams/cubic meter
Uniform temperature distribution: ±1.0°F
Velocity variation from mean: <±1°%
Test Section Turbulence level: < 0.5%

Early Research

- Early icing research at Boeing is well documented in the adjacent reference.
  - Aerodynamic Simulation Consideration
  - Effect of ice accretions
    - Initial ice-accretions (roughness)
    - Runback and ridge ice
    - Large in-flight accretions
    - Ground frost
- Conclusions
  - RN effects important for design considerations
  - Know your flow !

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Effects of ice accretions on aircraft aerodynamics

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Abstract

This article is a systematic and comprehensive review, correlation, and assessment of test results available in the public domain which address the aerodynamic performance and control degradations caused by various types of ice accretions on the lifting surfaces of fixed wing aircraft. To help put the various test results in perspective, overviews are provided first of the important factors and limitations involved in computational and experimental icing simulation techniques, as well as key aerodynamic testing simulation variables and governing flow physics issues. Following these are the actual reviews, assessments, and correlations of a large number of experimental measurements of various forms of mostly simulated in-flight and ground ice accretions, augmented where appropriate by similar measurements for other analogous forms of surface contamination and/or disruptions. In-flight icing categories reviewed include the initial and inter-cycle ice accretions inherent in the use of de-icing systems which are of particular concern because of widespread misconceptions about the thickness of such accretions which can be allowed before any serious consequences occur, and the runback/ridge ice accretions typically associated with larger-than-normal water droplet encounters which are of major concern because of the possible potential for catastrophic reductions in aerodynamic effectiveness. The other in-flight ice accretion category considered includes the more familiar large rime and glaze ice accretions, including ice shapes with rather grotesque features, where the concern is that, in spite of all the research conducted to date, the upper limit of penalties possible has probably not been defined. Lastly, the effects of various possible ground frost/ice accretions are considered. The concern with some of these is that for some types of configurations, all of the normally available operating margins to stall at takeoff may be erased if these accretions are not adequately removed prior to takeoff. Throughout this review, important voids in the available database are highlighted, as are instances where previous lessons learned have tended to be overlooked.

Early Research: Multi-Element Airfoils

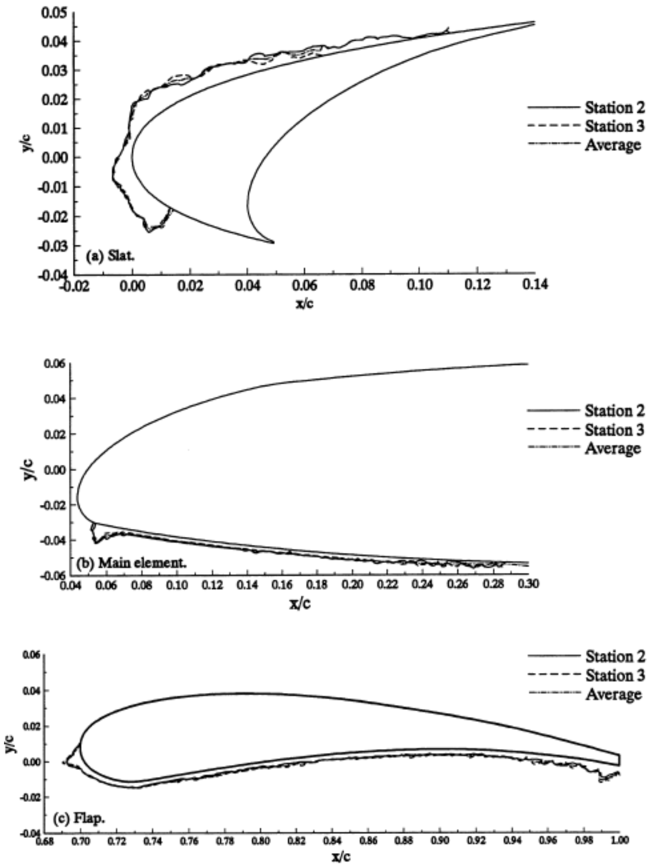


Figure 5 - Typical ice accretion spacial uniformity on high-lift model
(V = 198 mph, Tt = 30°, LWC = .6 g/m³, MVD = 20 μm, α = 4°, gap 1, t = 6 min)

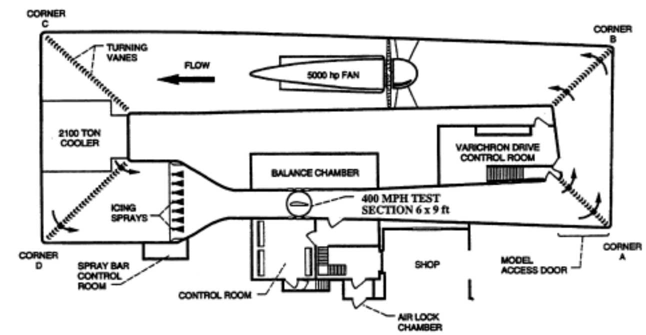


Figure 1 - Plan view of Icing Research Tunnel

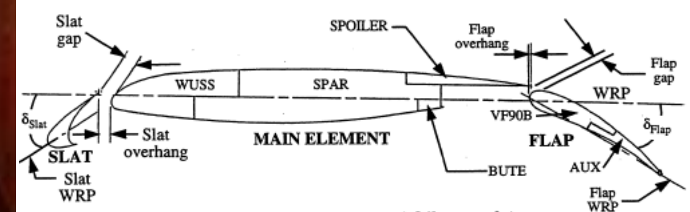


Figure 2 - Multi-element airfoil nomenclature

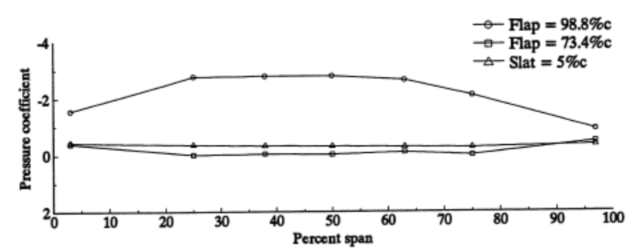
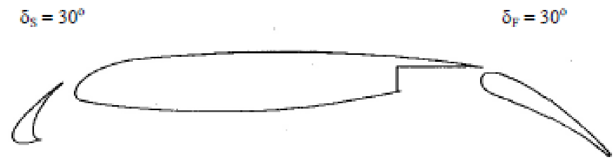


Figure 3 - Typical spanwise pressure distribution of the high-lift model

NASA TM 106620, AIAA 94-1869
NASA TM 106947, AIAA 95-1880

Early Research: Multi-Element Airfoils

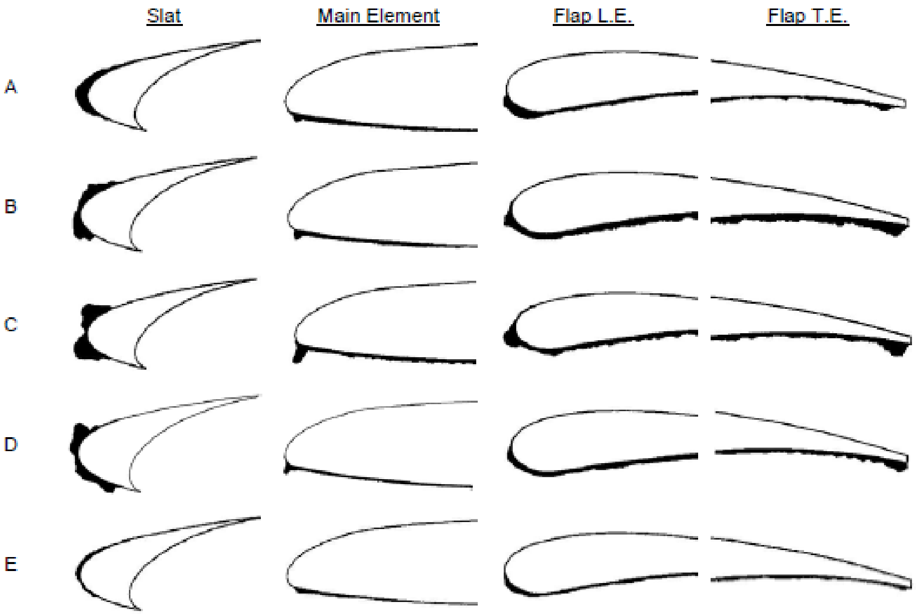


- **Ice accretions on a multi-element airfoil at the IRT**
  - **MDA 30P-30N**
  - **Representative TO, Approach and Hold conditions**
  - **3-year test campaign**

Ice Accretion Conditions

Ice Accretion	T_T (°C)	M_∞	LWC (g/m³)	MVD (μm)	Duration (minutes)	α (deg.)
A	-8.3	0.27	0.6	20	6	4
B	-1.1	0.27	0.6	20	6	4
C	-1.1	0.27	1.2	20	6	4
D	-1.1	0.27	0.6	20	6	8
E	-8.4	0.16	0.66	14	4	0

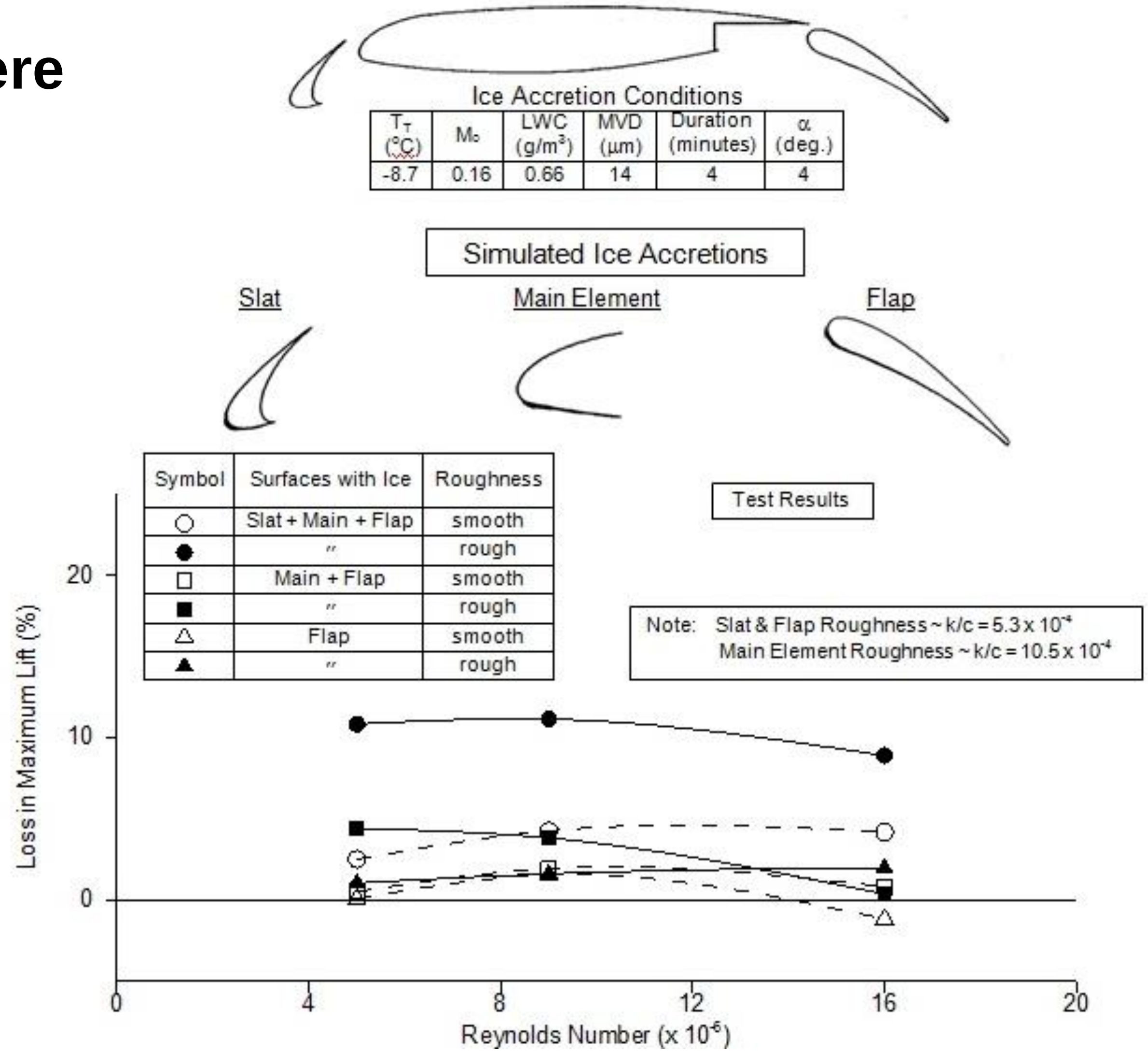
Ice Accretions



Sources:
- Shin J, Wilcox P, Chin V, Sheldon D. Icing tests on an advanced two-dimensional high-lift multi-element airfoil. AIAA Paper 94-1869, 1994.
- Miller D, Shin J, Sheldon D, Khodadoust A, Wilcox P, Langahls T. Further investigation of icing effects on an advanced high-lift multi-element airfoil. AIAA Paper 95-1880, 1995.

Early Research: Multi-Element Airfoils

- **Ice shapes from IRT were replicated for aerodynamic testing at the LTPT**
  - Significant performance losses
    - – Lift, max lift, drag, stall margin, …
  - RN sensitive



Sources:
- Khodadoust A, Dominik C, Shin J, Miller D. Effect of inflight ice accretion on the performance of a multi-element airfoil. Proceedings of AHS/SAE International Icing Symposium, 1995.

Early Research: Under-Wing Ice

Under-wing ice contamination on a Boeing 767-300 aircraft (photo credit: N*Ice – Frankfurt).

Early Research: Under-Wing Ice

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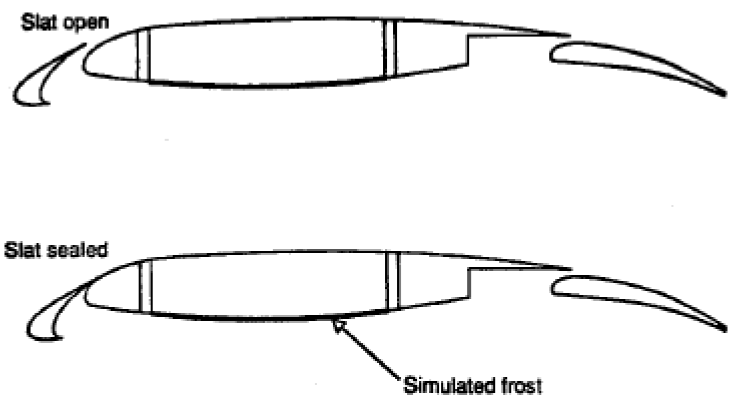


Fig. 1 Transport airfoil model in takeoff configuration.

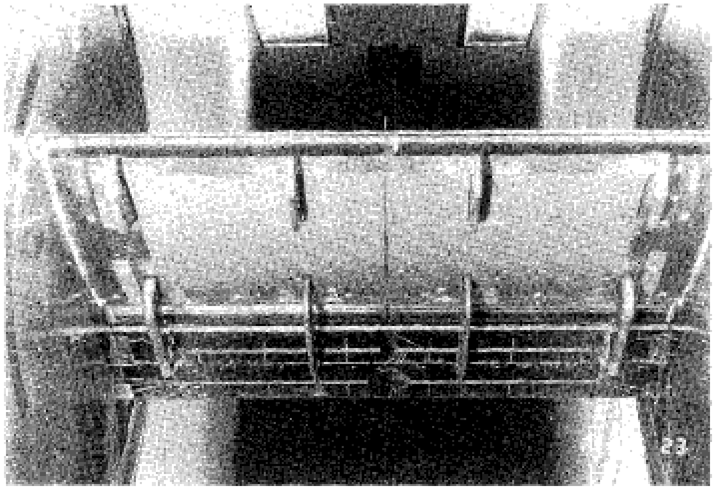


Fig. 2 Model in the tunnel with underwing frost simulation installed on the lower surface from 12 to 60% chord.

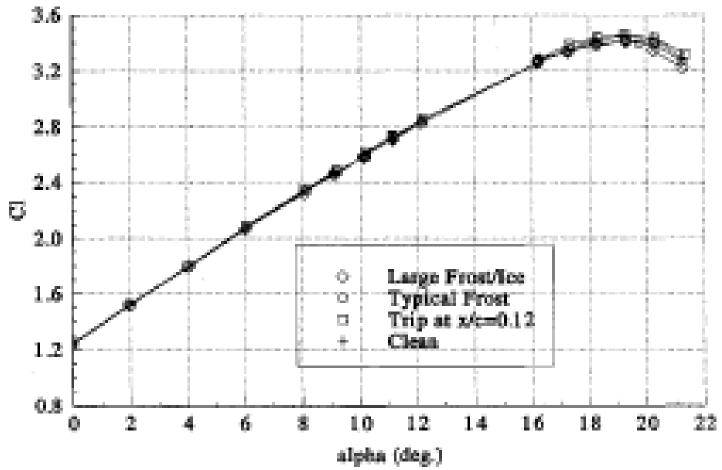


Fig. 13 Effect of simulated frost on lift at $Re = 9 \times 10^6$, slat-open, and roughness starting at $x/c = 0.12$.

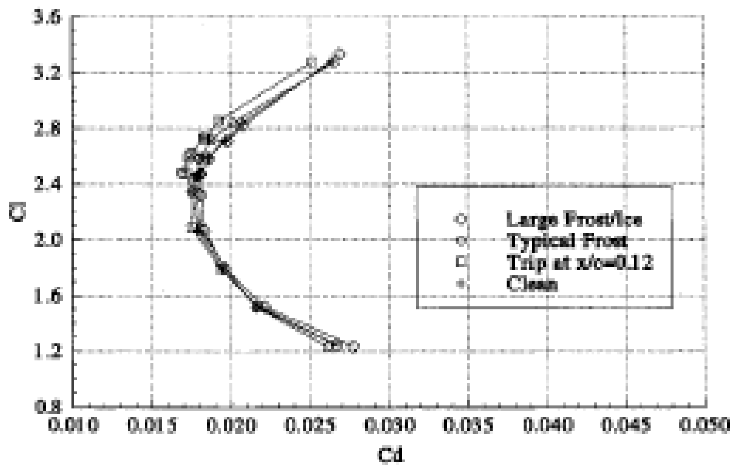


Fig. 14 Effect of simulated frost on drag at $Re = 9 \times 10^6$, slat-open, and roughness starting at $x/c = 0.12$.

Journal of Aircraft, V. 31, No 6, Nov-Dec 19

Rotorcraft Icing Research

Rotorcraft icing is characterized by disparate scales which requires attention to details and long-running analysis

- Characteristic length of a rotor blade… feet
- Characteristic length of ice… fraction of an inch
- Time-scale of a rotor revolution… fraction of a second
- Time-scale of ice accretion… several minutes

Ice growth on an rotor blade section measured in the NASA IRT

It is very difficult to base an icing analysis purely on first-principle physics

Rotorcraft Icing Research

- **Continuing a strong tradition, current icing research is targeted towards producing validated analytical tools for the prediction of**
  - Rotor and fuselage ice accumulation
  - Ice shedding from a rotating/oscillating blade
  - Deice and anti-ice system performance including transient heat transfer
  - Performance impact due to ice accretion.

- **Viewed as a major safety concern for rotorcraft, the research is coordinated among industry, Government, and academia**

Rotorcraft Icing Research

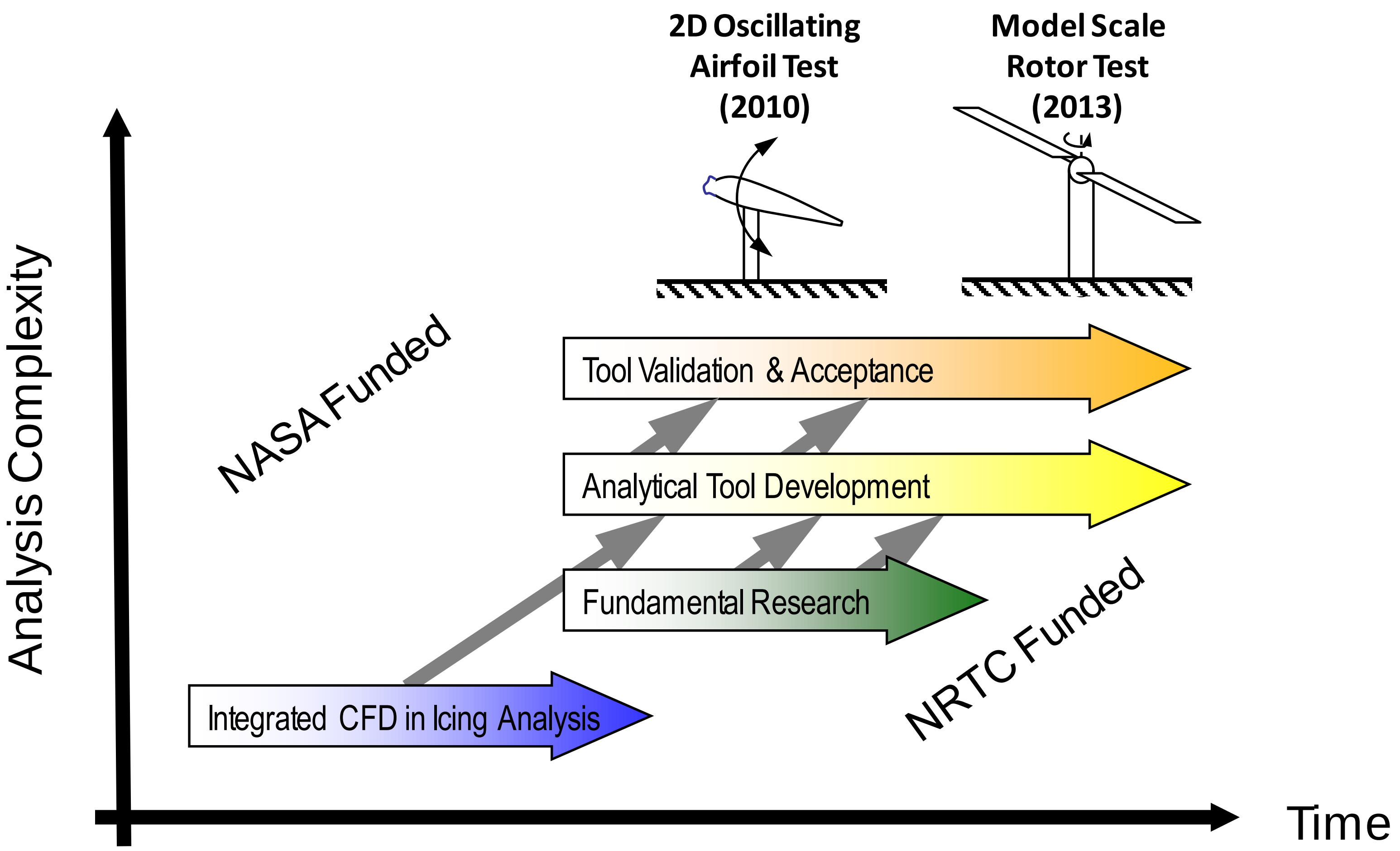
- **The collaboration has lead to two major icing tunnel test in the NASA Glenn Icing Research Facility**

  - May 2010 – Oscillating airfoil test with the key conclusion that ice shapes accreted on oscillating airfoils are essentially independent of frequency.

  - August 2013* – Model-scale rotor where data was collected for ice shapes, rotor performance, ice shedding, heater performance, shed ice trajectory, shed Impact

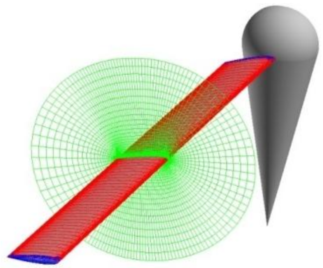
* This year's recipient of the Howard Hughes Award. The test team is recognized by the AHS for the contributions towards the understanding of fundamental aspects of rotorcraft icing and for the validation of icing analysis tools

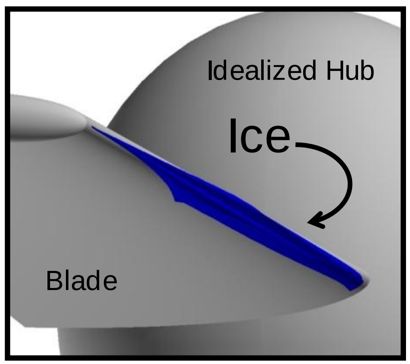
Rotorcraft Icing Research: Technical Approach

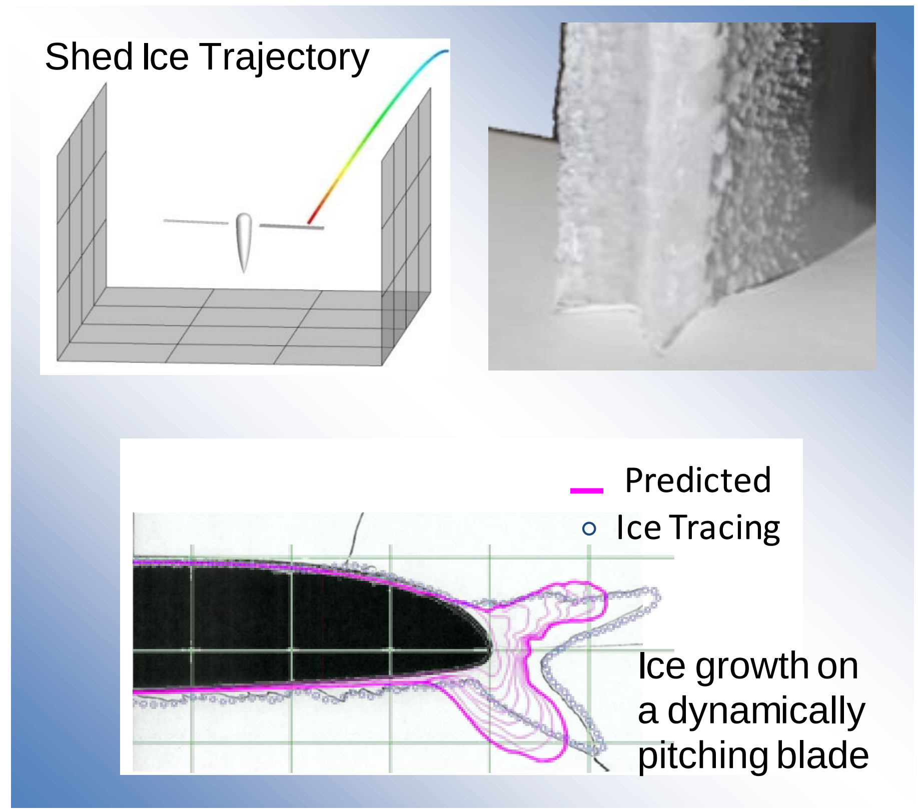


Rotor Icing Analyses with OVERFLOW

OVERFLOW is loosely coupled with LEWICE3D to support ice growth performance degradation, and shedding analysis for rotor systems





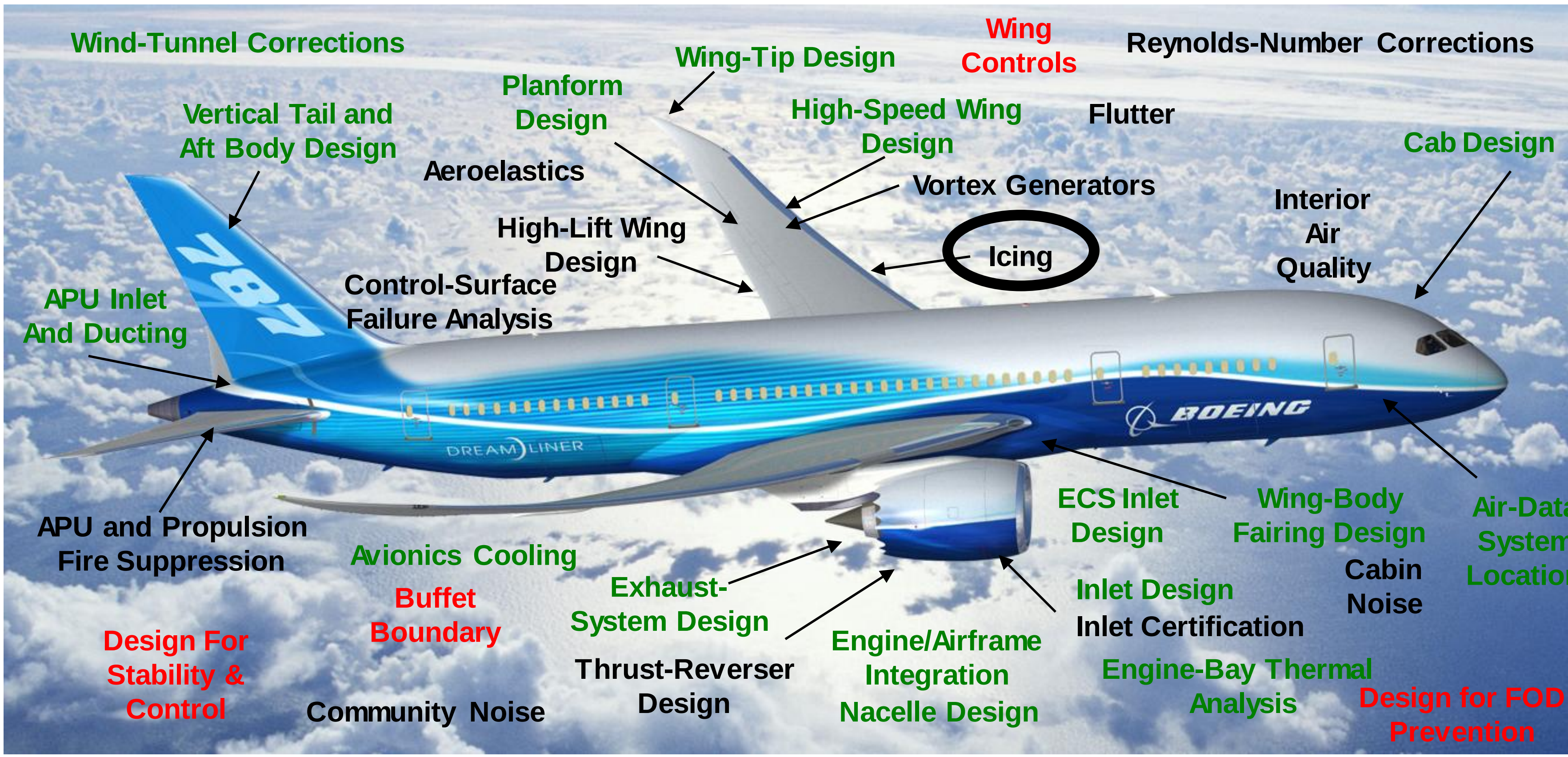


The rotor processes and analyses were funded by the Vertical Lift Consortium, formerly the Center for Rotorcraft Innovation and the National Rotorcraft Technology Center (NRTC), U.S. Army Aviation and Missile Research, Development and Engineering Center (AMRDEC) under Technology Investment Agreement W911W6-06-2-0002, entitled National Rotorcraft Technology Center Research Program. The authors would like to acknowledge that this research and development was accomplished with the support and guidance of the NRTC and VLC. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the AMRDEC or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

NRTC/VLC Project: ***High Fidelity Icing Analysis and Validation for Rotors*** **(WBS No. 2012-B-11-T1.1-P2)**

CFD Contributions to Aircraft Design

Substantial CFD Utilization **Some CFD Utilization** **Limited CFD Utilization**



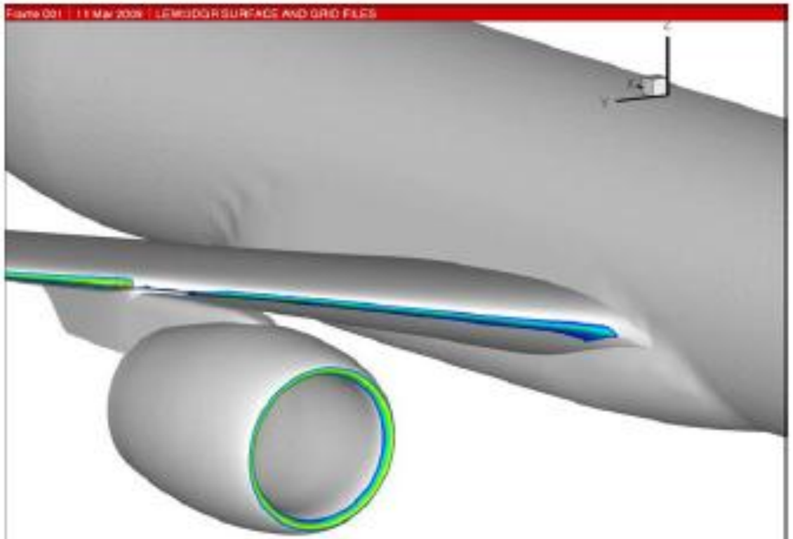
Enablers: High Performance Computing,
Physics-based Design/Analysis/Optimization

Computational Ice Shape Generation

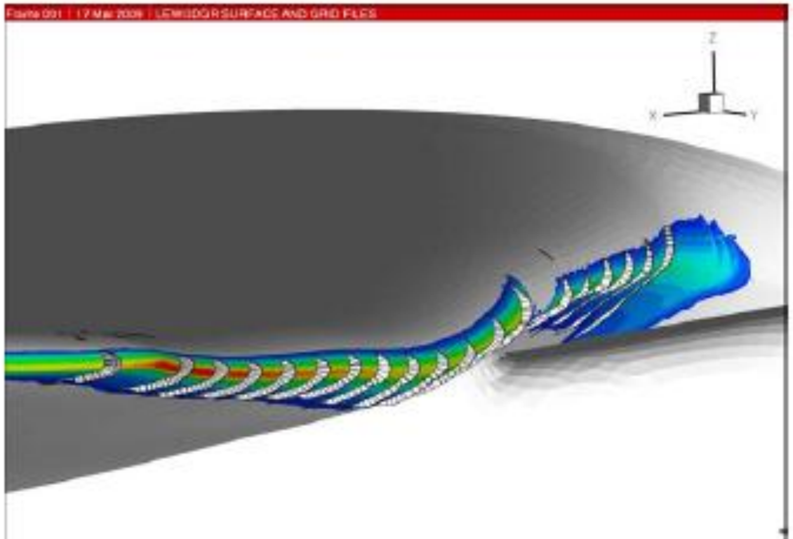
- **Why is it important ?**
  - Airframe ice shapes corresponding to critical flight conditions were needed for 787 low speed wind tunnel testing to measure the impact on aircraft handling characteristics and maximum lift
  - LEWICE3D, a code developed by NASA, greatly reduced the need to interpolate / extrapolate ice shapes to generate wind tunnel model parts.
  - Using LEWICE3D drastically reduced the time needed to generate ice shapes.
- **What are the technical challenges ?**
  - LEWICE3D computes water droplet trajectories through a converged CFD flow-field to generate a 3D droplet collection efficiency distribution on the airframe. This is a large computation, needing parallelization in order to be feasible.
  - Finding sufficient experimental swept wing ice shape data to further refine the ice shape generation model and methodology was problematic.

Computational Ice Shape Generation

- **What are we doing ?**
  - Flight conditions considered critical for airframe icing were selected
  - NS solvers CFD++ or OVERFLOW were run with these conditions to generate the flow-field for input into LEWICE3D
  - LEWICE3D generated a collection efficiency and ice shape cuts
  - Ice shape cuts were used to produce lofts for stereo lithography production into wind tunnel model parts.



Water Droplet Collection Efficiency



Ice Shape Cuts on Wing Leading Edge

Boeing's Goals for Icing

- **From an aerodynamics perspective**
  - Eliminate icing tunnel testing for generation of ice shapes used for Aerodynamic analysis
  - Streamline the icing process
    - Preparation / execution for aero configuration development
    - Minimize schedule flow for ice shape development
    - Establish standard methods / approaches for ice shape determination with regulatory agencies
  - Improve the effectiveness of the entire process
    - Understand the applicability and uncertainty of the information generated by the tools
    - Ensure that the ice shape features that matter are captured.

Current Ice Accretion Modeling Tools

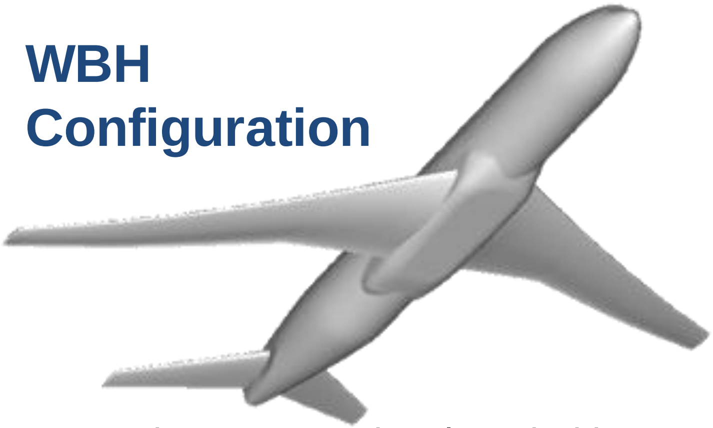
- **LEWICE3D captures 3D icing information**
  - Impingement limits, water catch, and some shape characteristics
  - Spanwise characteristics which allow for creation of 3D ice shapes
- **LEWICE3D allows for rapid generation of ice shapes throughout the entire Appendix C icing envelope**
  - Provides for a broad look at many ice shapes
  - Supports Product Development cycles for Aero/Systems requirements and design, and wind-tunnel test configuration ice shape development
- **LEWICE3D cannot be used as a black box. With <u>an understanding of the icing envelope</u>, you can used the code to determine the range of ice shapes required for an exhaustive analysis of aerodynamic performance and handling qualities.**

CRM: An Alternative to Proprietary Geometry

General Description

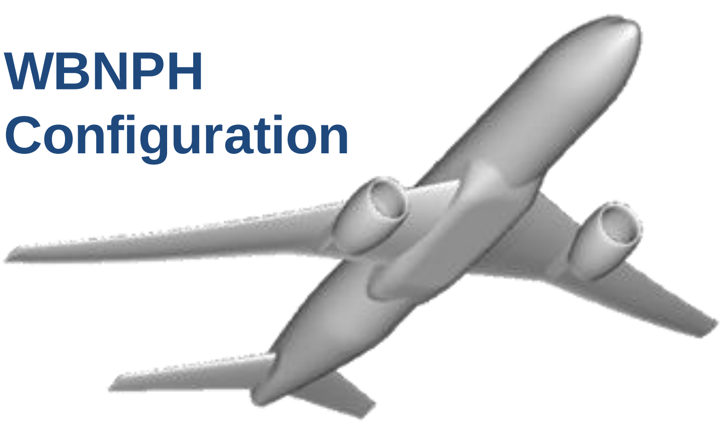
- **NASA Common Research Model (CRM) is a commercial transport class configuration**
- **Contemporary high-performance transonic supercritical wing design**
- **Aerodynamic characteristics well behaved with and without the nacelle/pylon group**
- **HPR flow-through nacelle with a natural unforced MFR typical of engines at cruise**
- **Design: 0.85M , CL=0.5 , Re=40 million**

WBH Configuration



- A generic geometry, developed with contributions from Boeing, NASA and other industry.
- Representative of SOA modern transport.

WBNPH Configuration



Aircraft Geometry Selection

- **Common Research Model Semispan**
  - Designed by Boeing as a baseline model for CFD Drag Prediction Workshop
  - Typical of wide body (B777) airliner
- **Wing parameters**
  - $\Lambda = 35°$, $\lambda = 0.275$, AR = 9

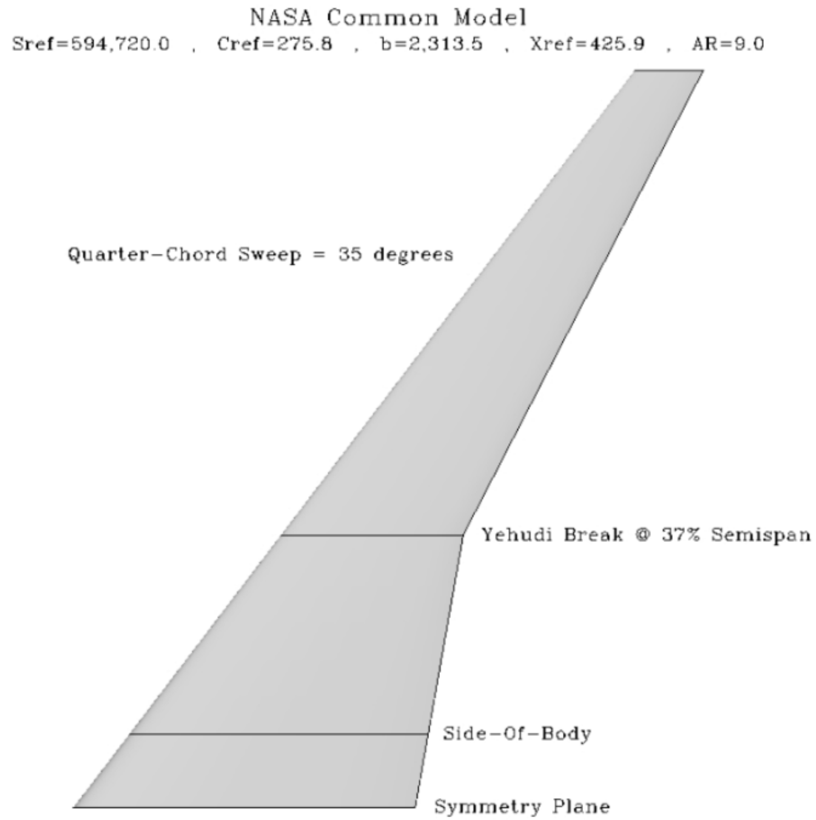
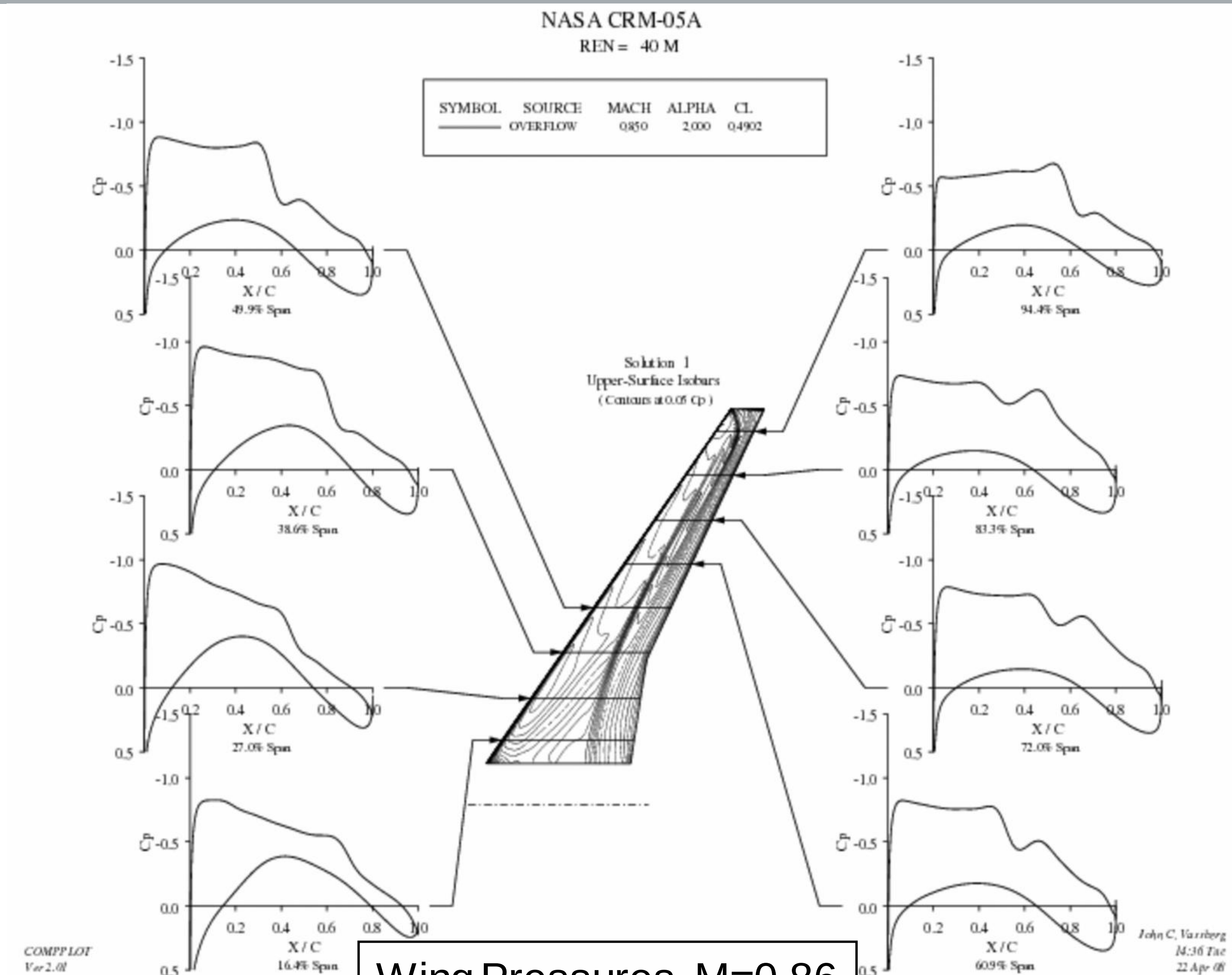


Figure 1: Full-Scale Planform of the CRM Wing.

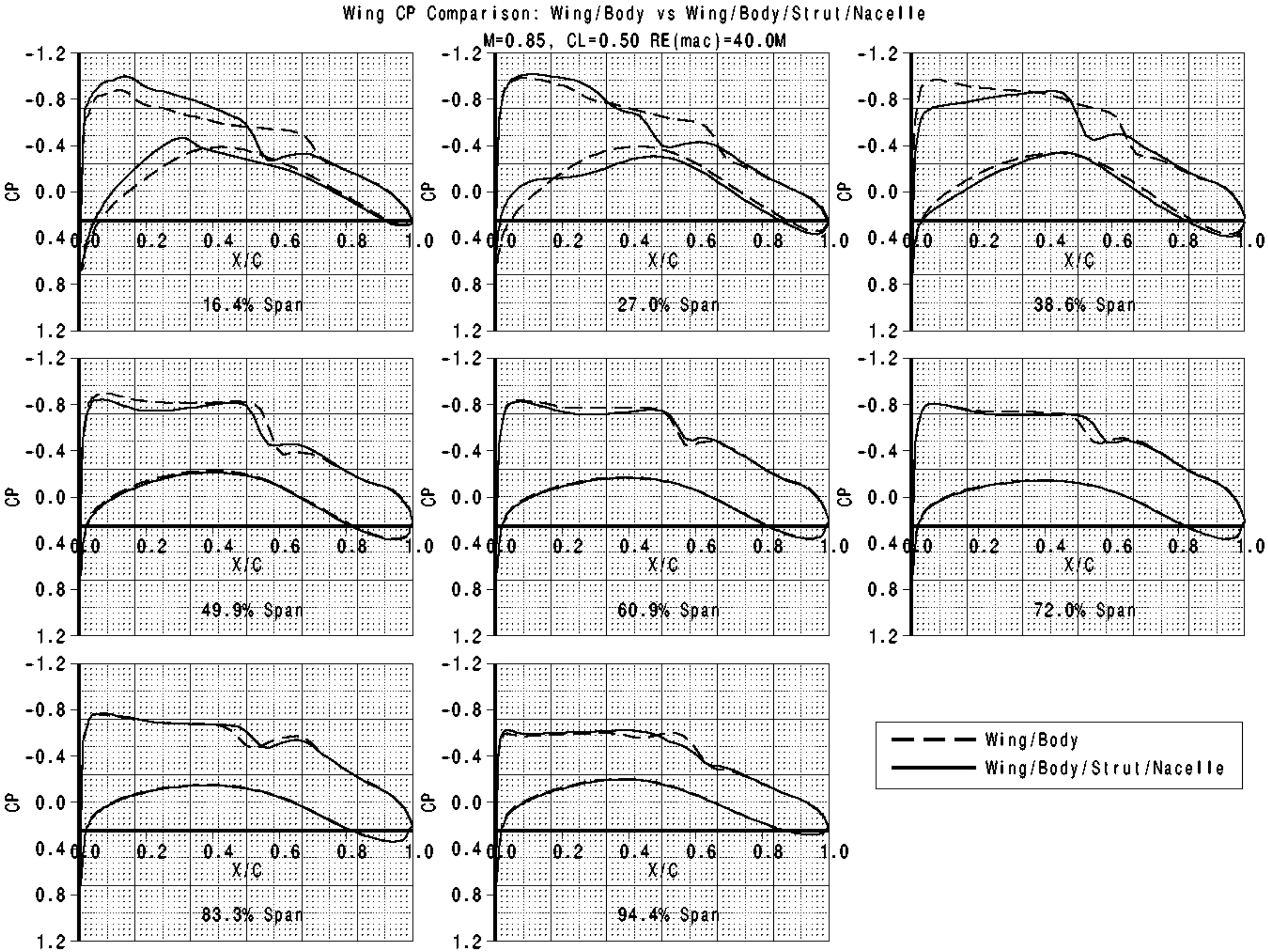
J.C. Vassberg, M.A. DeHaan, S.M. Rivers, and R.A. Wahls.
"Development of a Common Research Model for Applied CFD Validation Studies," AIAA Paper 2008-6929.

The CRM Wing is Representative of Modern Transport Aircraft

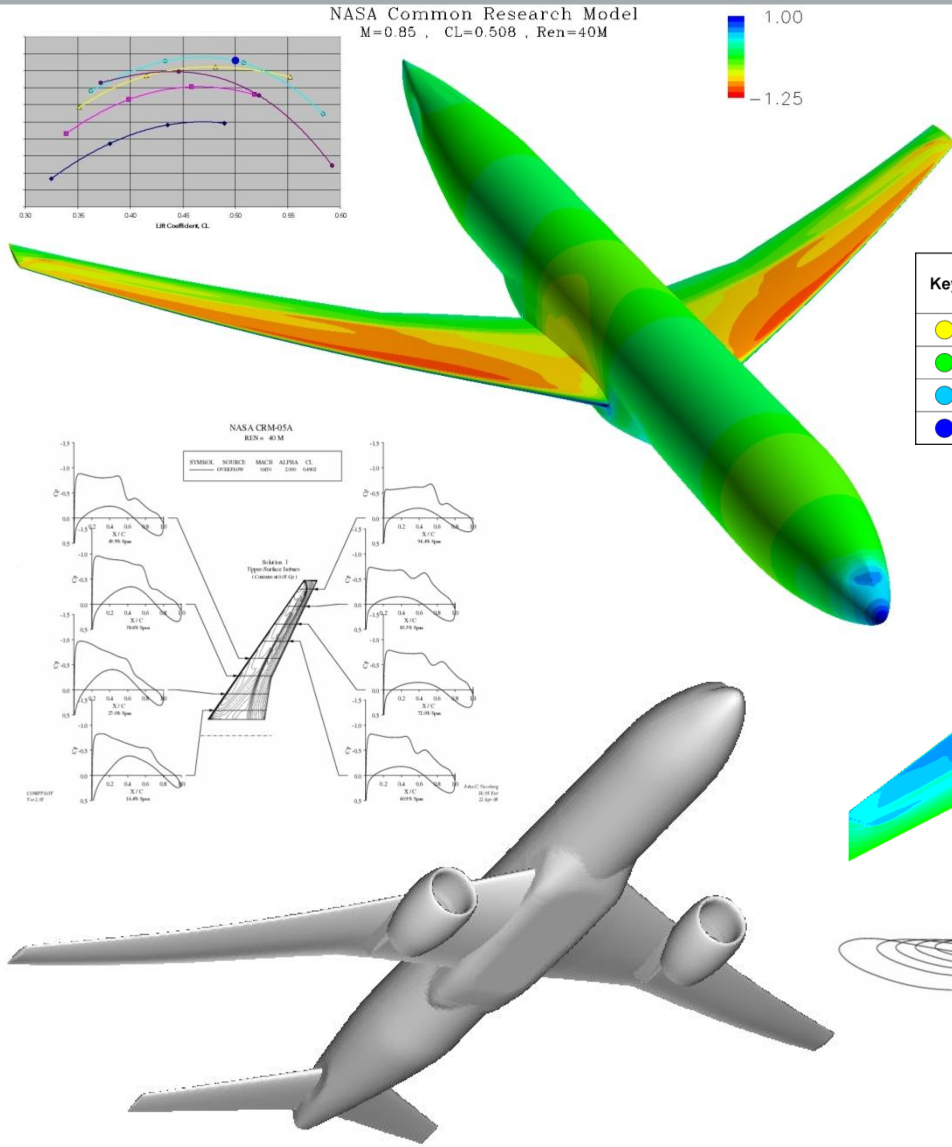


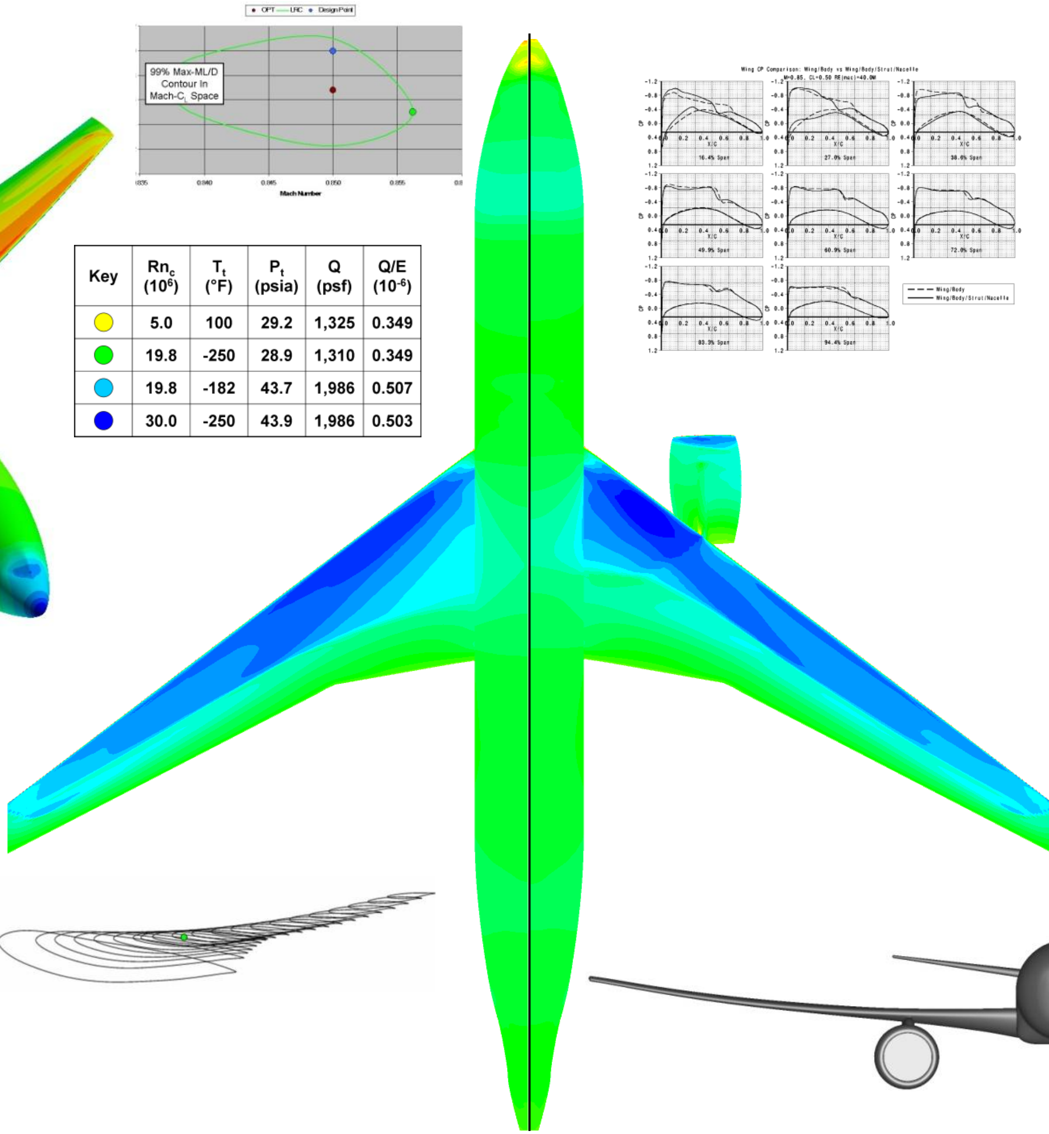
Wing Pressures, M=0.86

Nacelle/Pylon Effect



The CRM has been offered as a generic testbed for validation of emerging prediction methods





Key	Rn_c (10^6)	T_t (°F)	P_t (psia)	Q (psf)	Q/E (10^{-6})
Yellow	5.0	100	29.2	1,325	0.349
Green	19.8	-250	28.9	1,310	0.349
Light blue	19.8	-182	43.7	1,986	0.507
Blue	30.0	-250	43.9	1,986	0.503

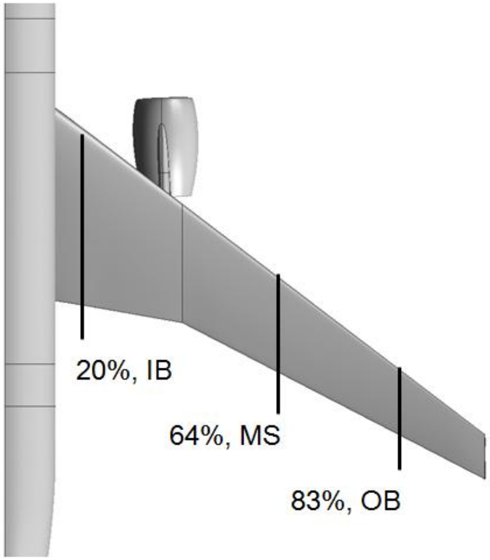
Common Research Model (CRM) Interest

- **Groups Interested in a CRM**
  - Drag Prediction Workshop
    - Subject Geometry for DPW-IV and DPW-V
  - COMSAC
  - Various WT Facilities
    - NTF, Ames 11-ft, JAXA, ETW

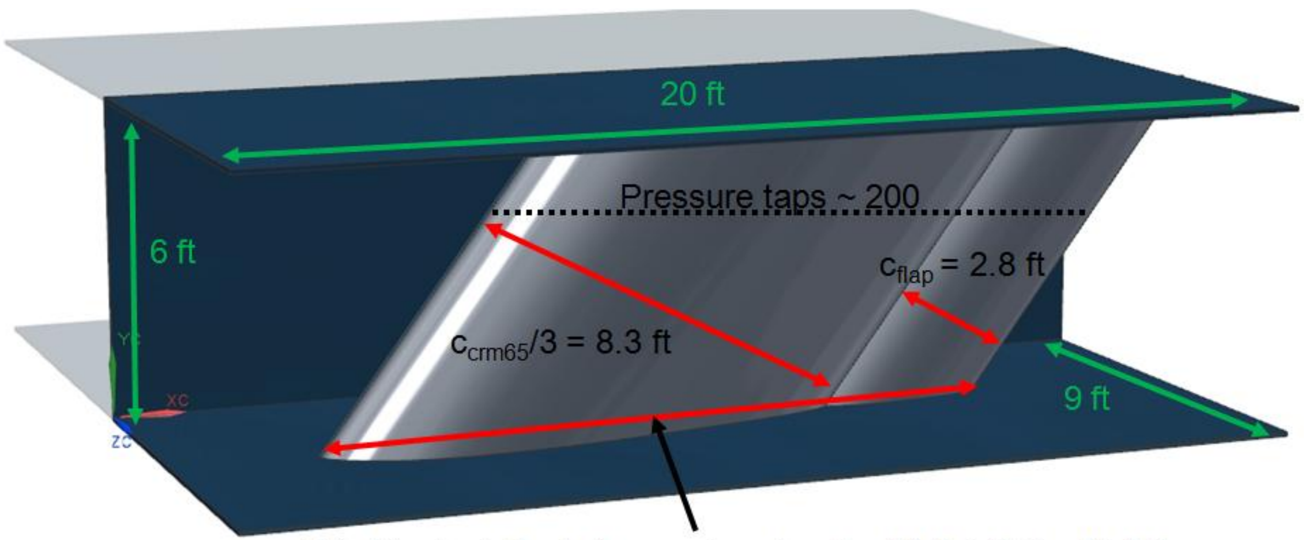
- **Large Cross-section of Government and Industry**
  - Air Force, Boeing, Cessna, Gulfstream, Hawker-Beechcraft, Lockheed-Martin, NASA, Navy, Northrup-Grumman, Pratt & Whitney

- **NASA Swept Wing Icing NRA**

NASA Swept Wing Icing NRA: Background



- **Purpose of the study**
  - Develop an improved approach over current method, for determining ice shapes for swept wings
- **Use the Common Research Model (CRM) wing, as the test bed.**
  - Develop test articles based on cruise wing profile at three stations.
  - Truncate the airfoils (to preserve leading edge geometry size)
  - Use a slotted flap on the trailing edge, to simulate the pressure distribution on the original airfoil.

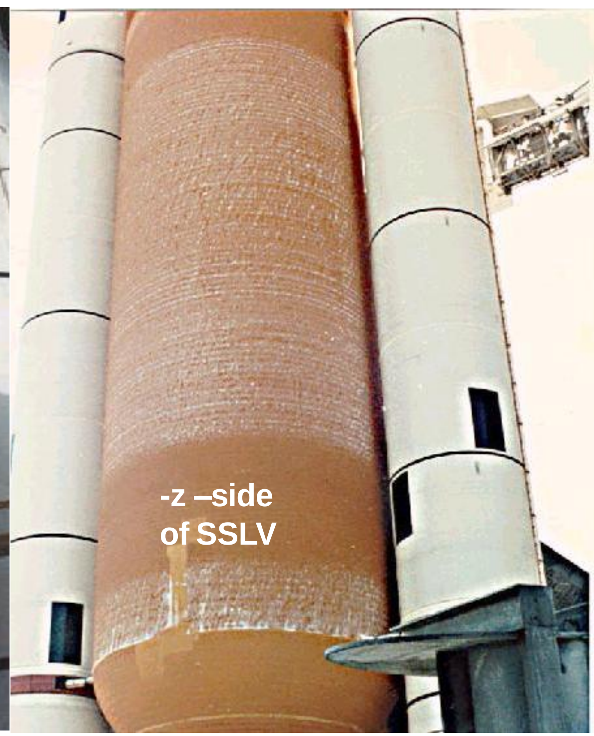


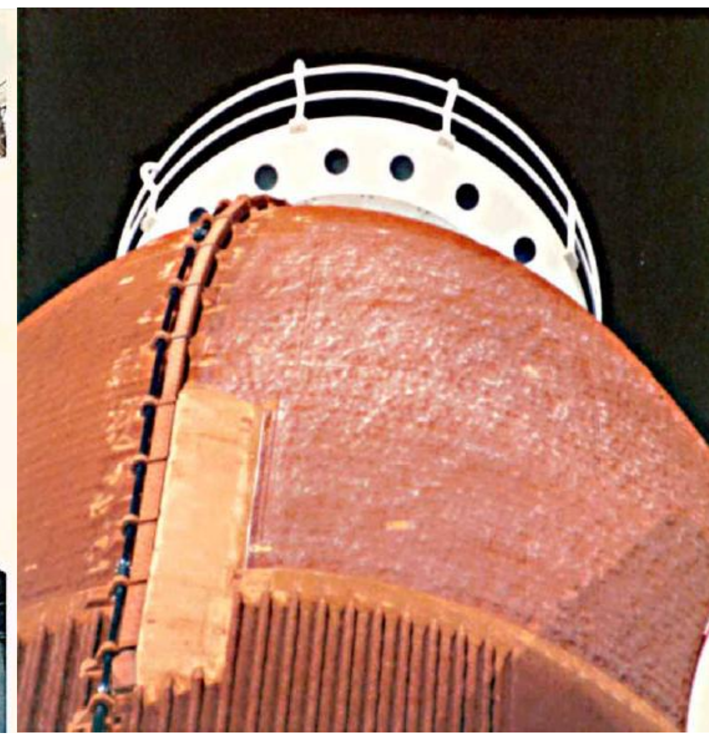
Total (main + flap) streamwise chord = 10.4 + 3.5 = 13.9 ft

h / c = 9 / 13.9 = 0.65

Spacecraft Icing During Launch

- Reduction in ET skin temperature due to super-cooled liquid hydrogen and liquid oxygen pumped into the ET fuel storage chambers.
- Combination of ambient humidity, temperature and relative wind conditions causes moisture and condensation to form on ET acreage.
- Conditions have resulted in formation of frost on the ET acreage.

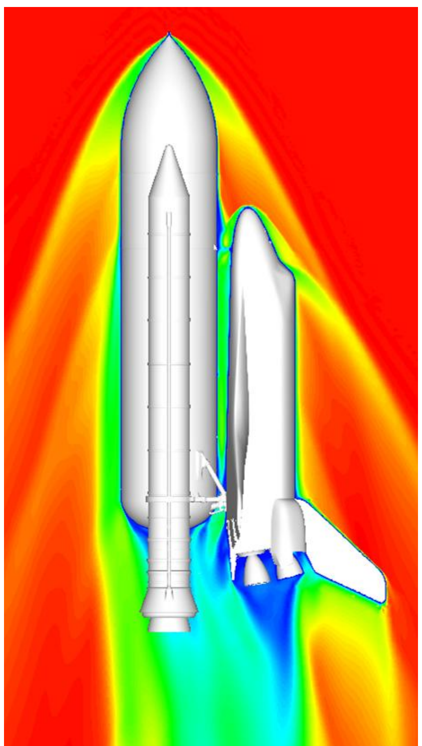




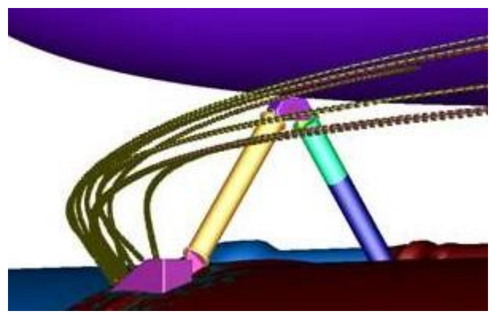
Background – NASA Debris Code

- NASA JSC developed a new Debris code in the aftermath of the Columbia accident
- Trace debris trajectory based on local flow & vehicle acceleration

Overflow solution

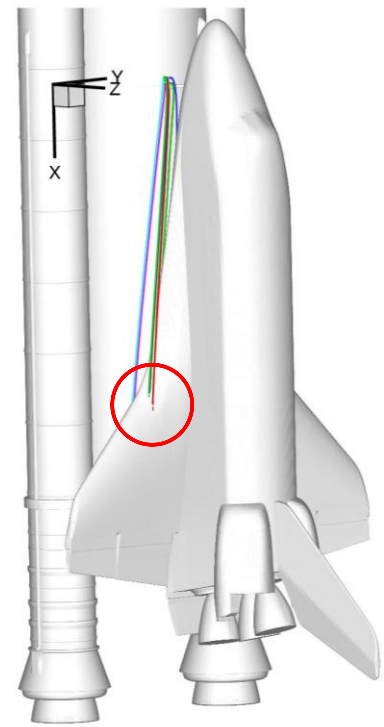


Debris source,
Initial conditions



Debris Code

Trajectory & impact



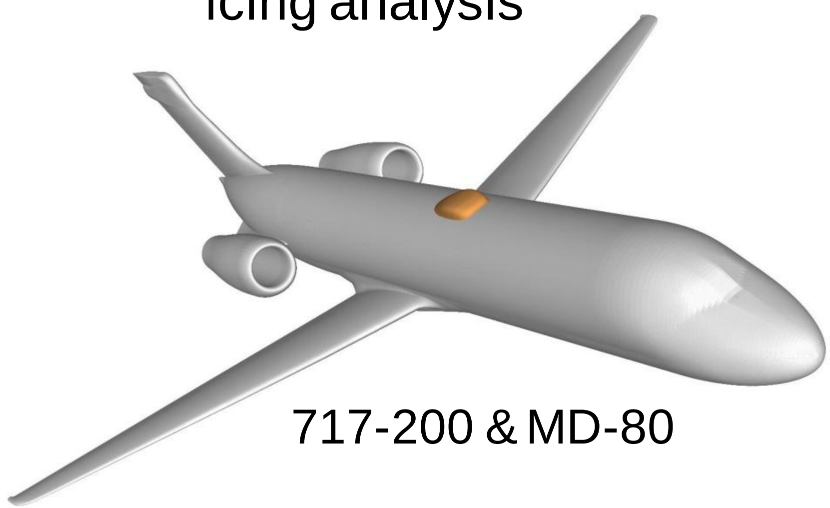
NASA Debris Code: an Alternative Trajectory Analysis Approach

- ❑ Efficient search algorithms in this tools allow for rapid Turn-around of trajectory analysis predictions

- ❑ Implemented a drag model for micron-sized water droplets into the NASA Debris code

- ❑ Applied droplet tracing to several airframes for icing analysis

  - Connexion antenna icing analysis

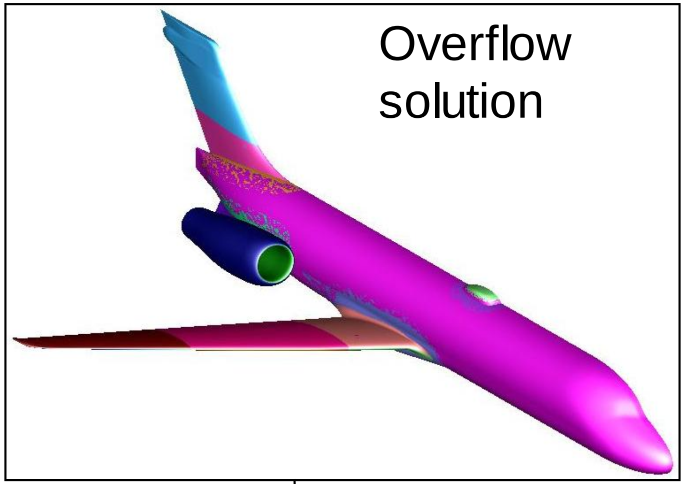


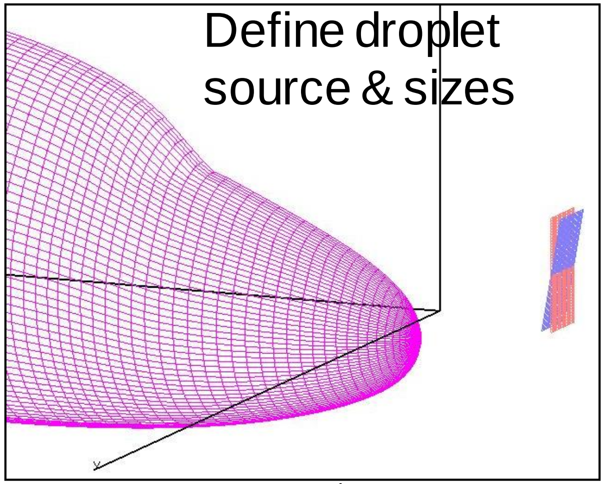
717-200 & MD-80

  - 747-LCF water droplet analysis

Example : Connexion Antenna Icing Analysis

- ❑ Track water droplet trajectories using Overflow solutions
- ❑ Simulate 717-200 and MD-80 at representative icing conditions



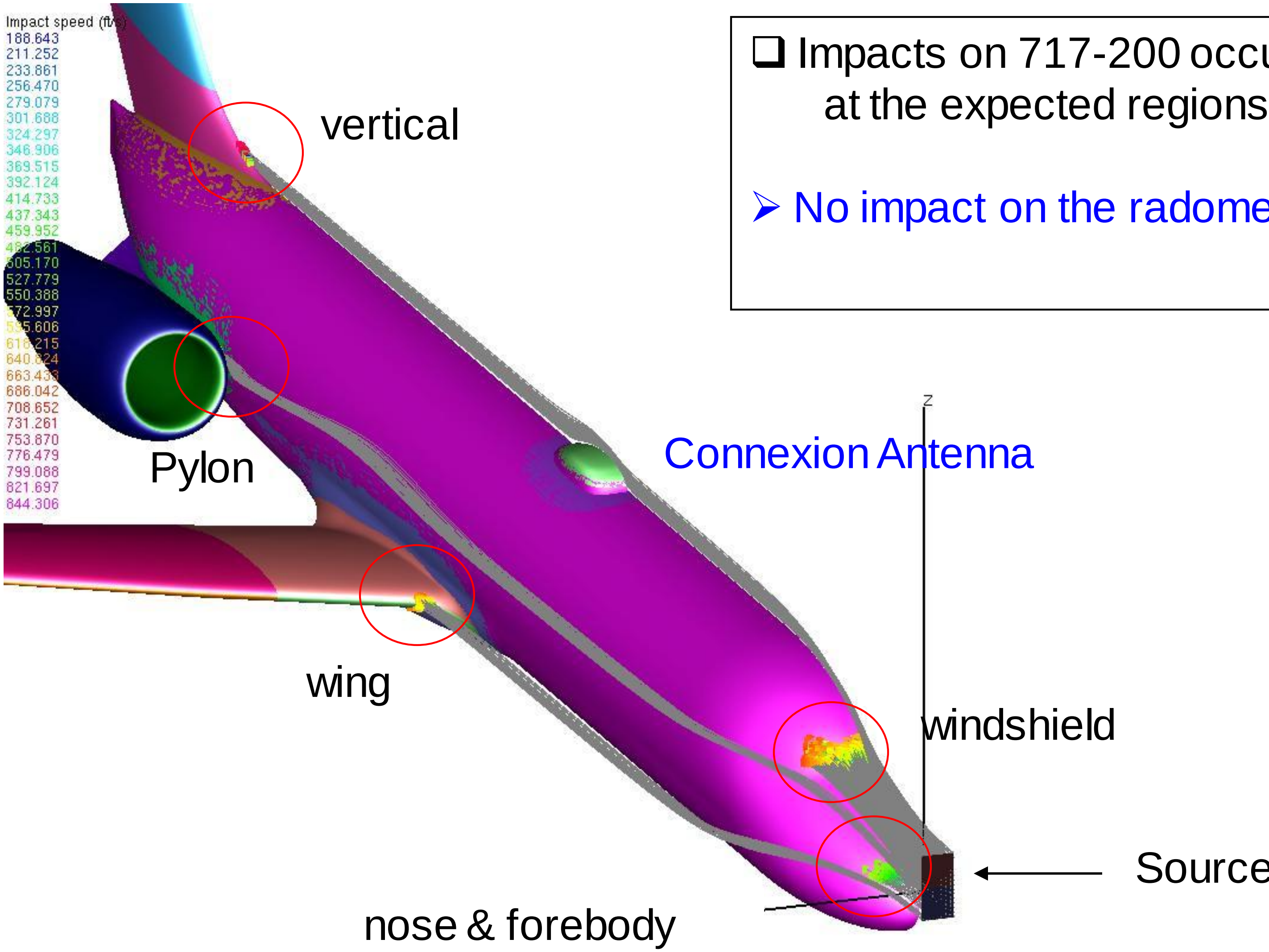


Modified Debris Code

Evaluate antenna impingement

717 Droplet Trajectories & Impingement

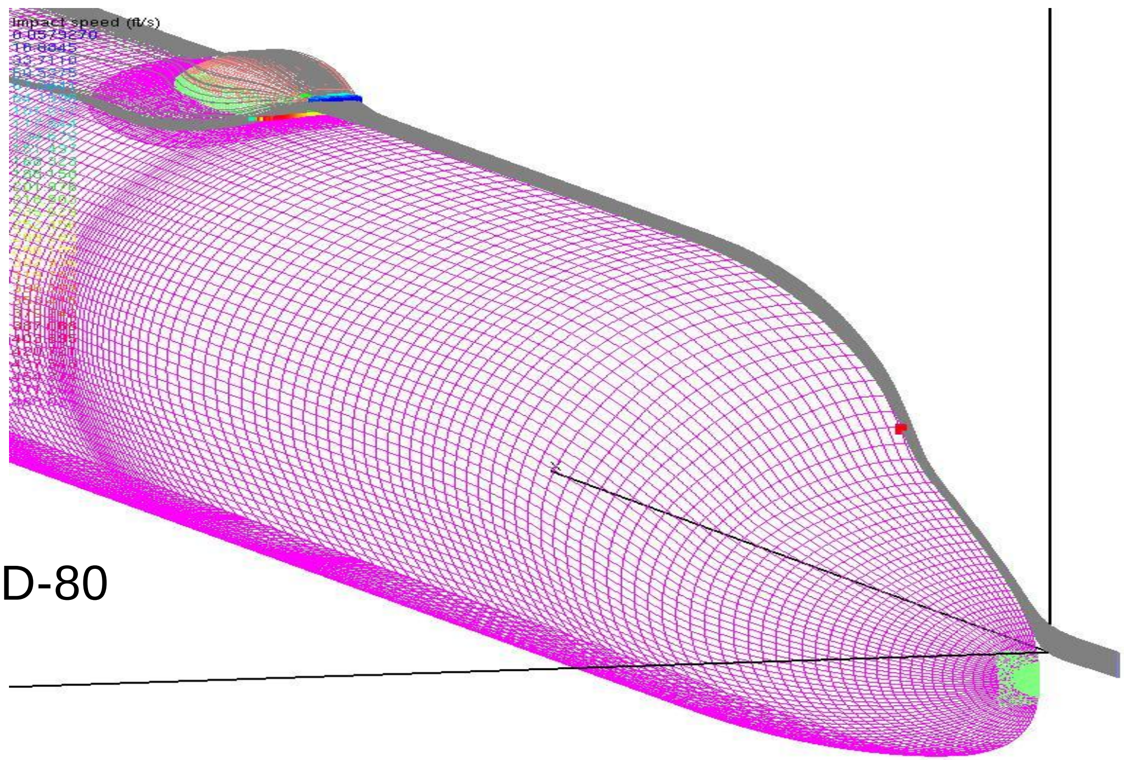
- ❑ Impacts on 717-200 occur at the expected regions
  - ➢ No impact on the radome



MD-80 Liquid Water Catch

- ❑ Total liquid water "caught" by antenna fairing is small

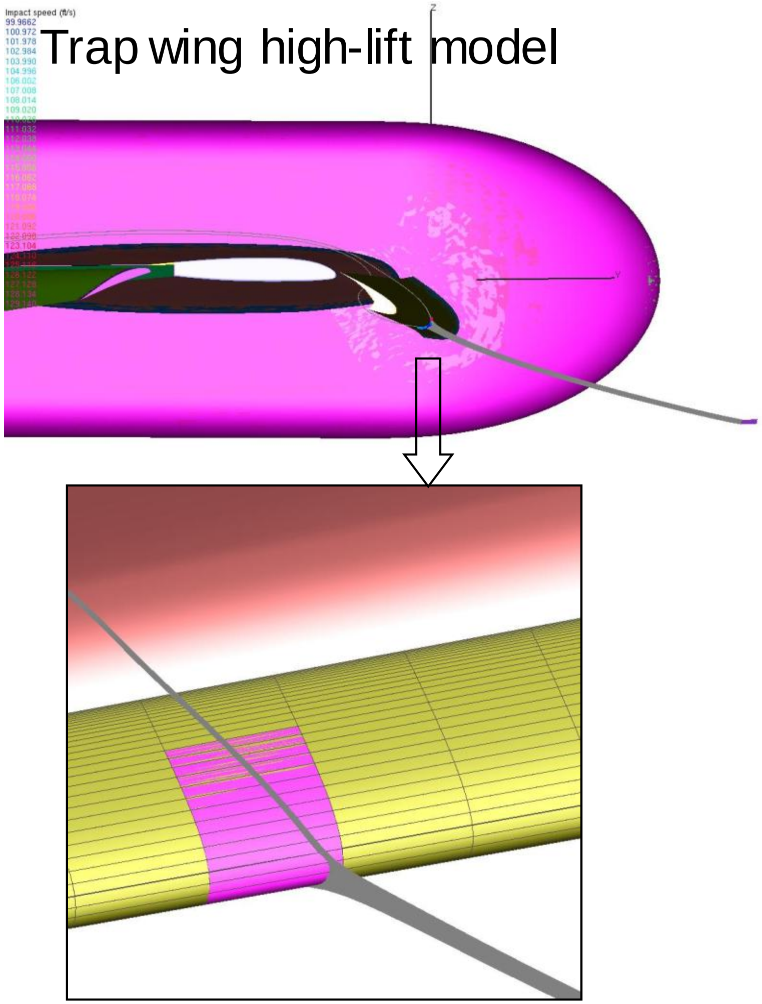
- ❑ Only the smallest droplets (6.2 microns) impinge
- ➢ Droplet tracing is used interactively with radome redesign



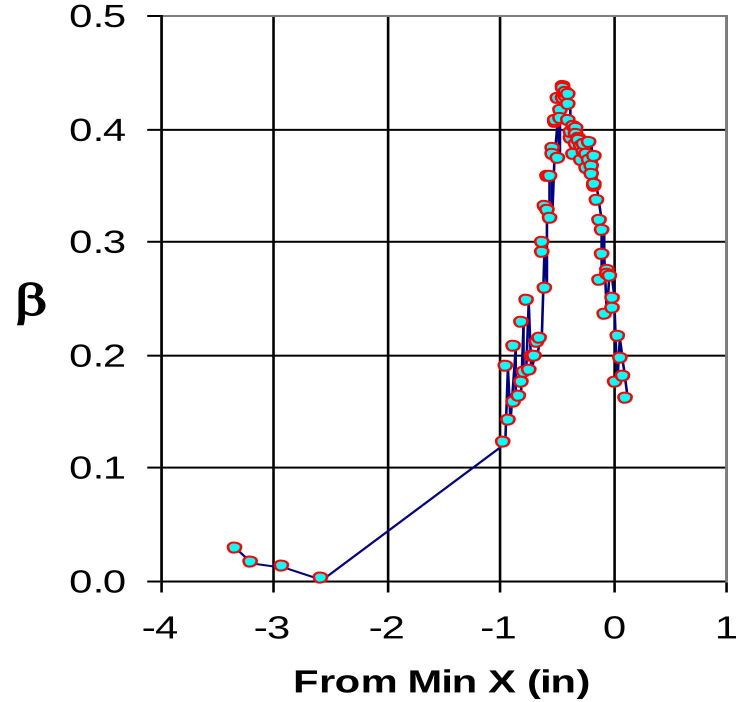
MD-80

Water Collection Efficiency (β) Calculation

- β is calculated based on the ratio of area density change



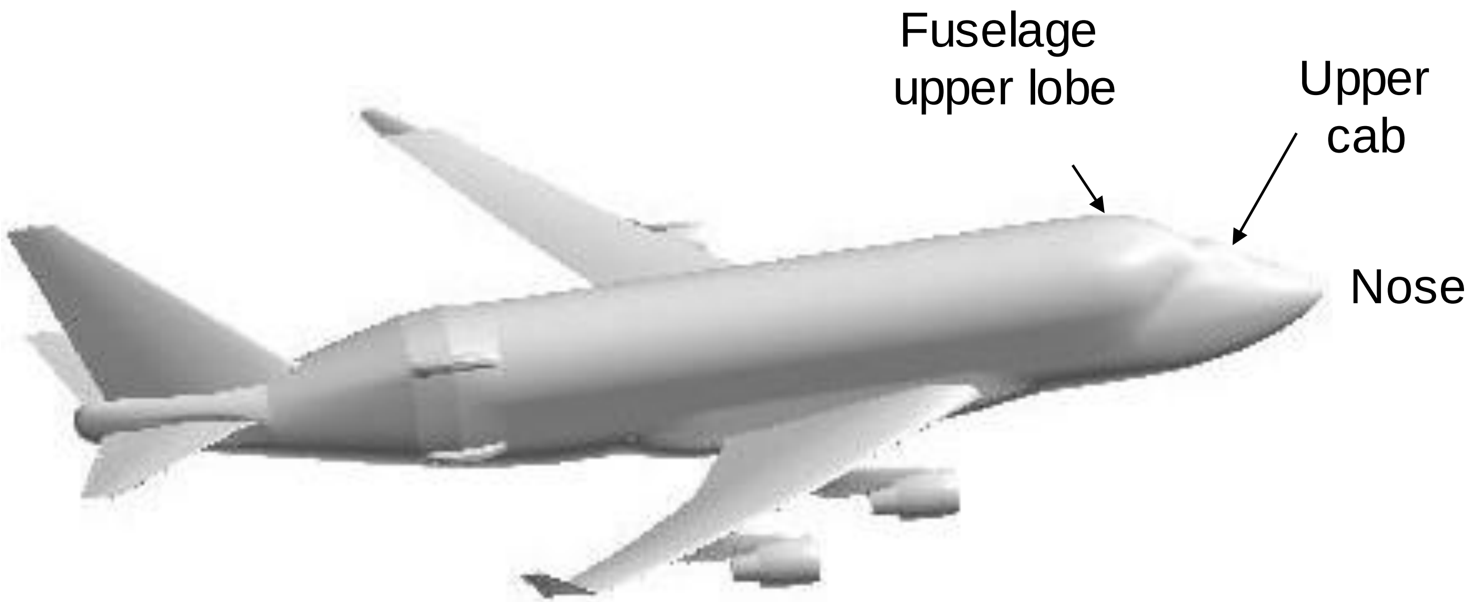
$$\beta = \frac{dS_{release}}{dS_{hit}}$$



Example : 747-LCF Water Droplet Analysis

- The debris tracing code was used to determine if the upper lobe of the 747-LCF fuselage would accrete ice

- A holding case was selected at AoA=2.5 deg as a worst case

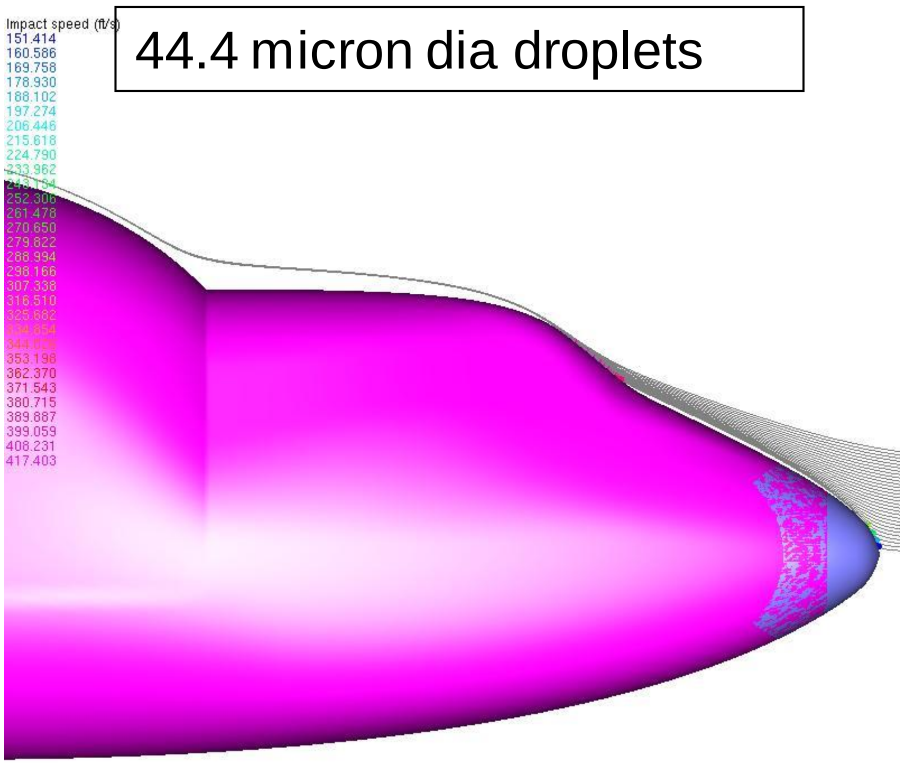


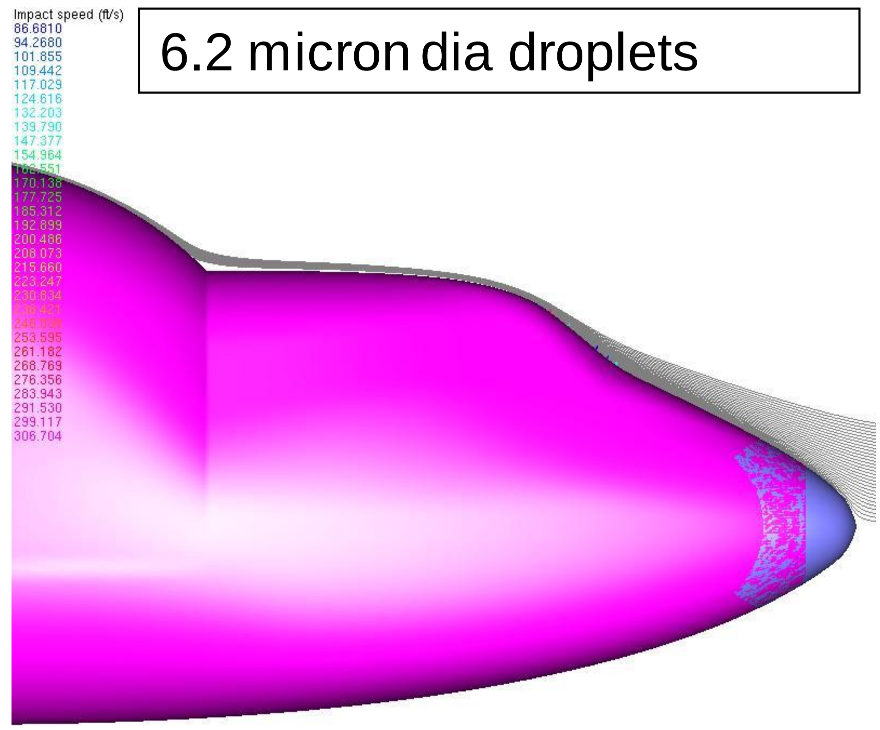
747-Large Cargo Freighter

747-LCF Water Droplet Traces (M=.5, α=2.5°)

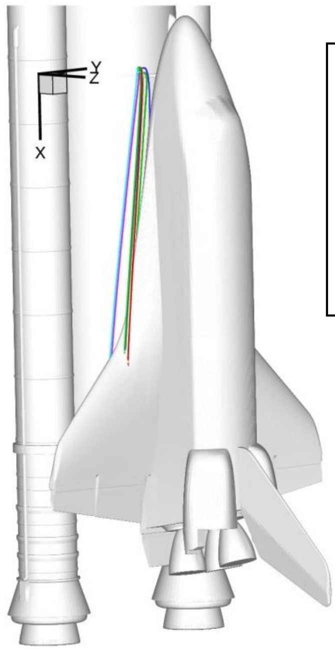
- No droplets of either size hit the brow fairing

- Small droplets are closer to brow fairing than large droplets





Using the Modified NASA Debris Code for a Range of Products

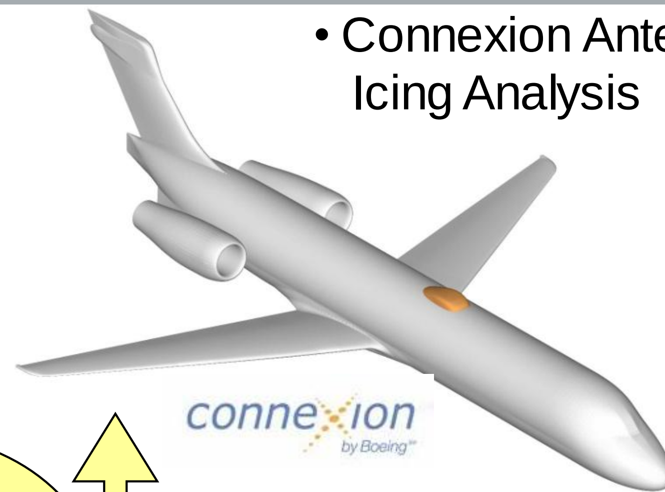


NASA Debris Code

Water Droplet Tracing

BCA

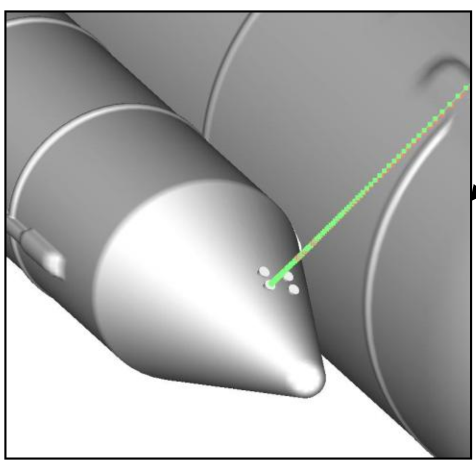
BDS



- Connexion Antenna Icing Analysis

717-200
MD-80

- 747-LCF Water droplet Analysis



BSM debris

Summary, Conclusion

- **Boeing has been involved in icing research since the early days of the company**

- **Boeing understands the importance of ice accumulation on flight (and aerodynamic) surfaces.**
  - Implications to performance, handling qualities and flight safety

- **Boeing takes exhaustive steps for analysis and understanding of aerodynamic performance effects of icing.**

- **Boeing is working with NASA, academia, other industry and rule-making organizations, to help implement analysis-based certification approaches for icing**