SLD Simulation Capabilities with LEWICE

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CFD Methods for SLD Simulation Workshop

Scottsdale, AZ October 19-20, 2006

Outline

- **SLD Requirements**
- **SLD Icing Physics**
- **SLD Modeling in LEWICE**
- **Reproducing SLD Cloud Conditions in the IRT**
- **Numerical Simulation of Ice Shapes from a Bimodal Large Droplet Icing Cloud**

SLD Requirements

SLD Requirements

BACKGROUND

- **Requirements (or metrics) need to be defined to provide a "target" for SLD simulation in quantified terms**
  - **Essential features or characteristics that need to be simulated**
  - **How accurately characteristics need to be simulated**
- **These requirements will be developed by means of sensitivity studies, either experimental or computational**
- **Requirements take into account recommendations from the IPHWG on Appendix X**

OBJECTIVES

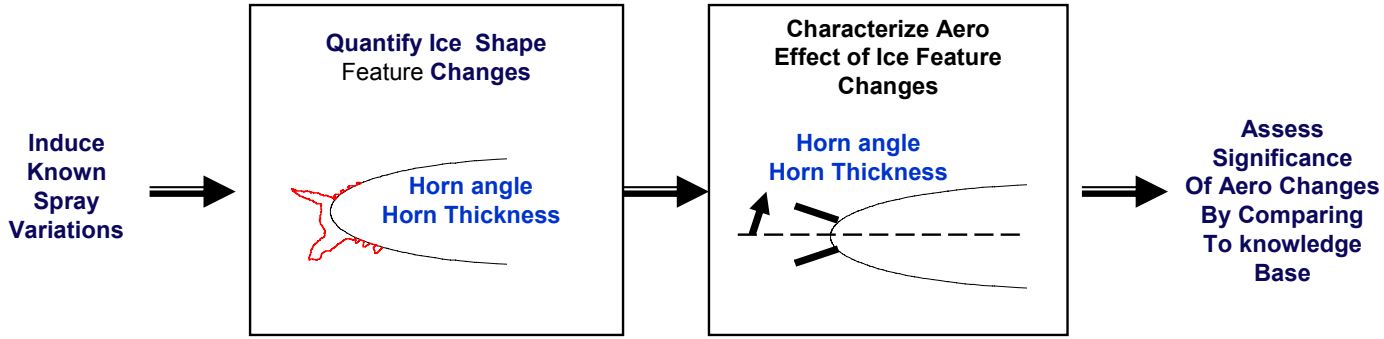
- **Identify the metrics that have to be met to assure adequate simulation of the SLD environment from an engineering perspective**
- **Provide assessment of how accurately these elements must be simulated**

SLD Requirements

APPROACH

- **Conduct sensitivity tests in SLD conditions to estimate threshold where LWC, drop size, temperature errors have noticeable effect on the generated ice shape**
  - **Attempt to develop / identify methodology to link aero effects to ice feature changes**
- **Conduct SLD Instrumentation Workshop to identify what current state-of-the-art is for water content and drop size instrumentation**
  - **Estimates of measurement error**
  - **Operational issues affecting accuracy**
  - **Identify research investments to mitigate measurement issues**
- **Get feedback from user community on SLD requirements at SLD Tools Workshop**
  - **Incorporate feedback into development of draft requirements document**
- **Develop draft requirements document which includes parameters to be simulated, and required accuracies**
  - **Consolidate results from tests & workshops**

SLD Sensitivity Studies



OBJECTIVE - **Determine the variation in icing cloud parameters necessary to produce a measurable change in resulting ice accumulation**

APPROACH

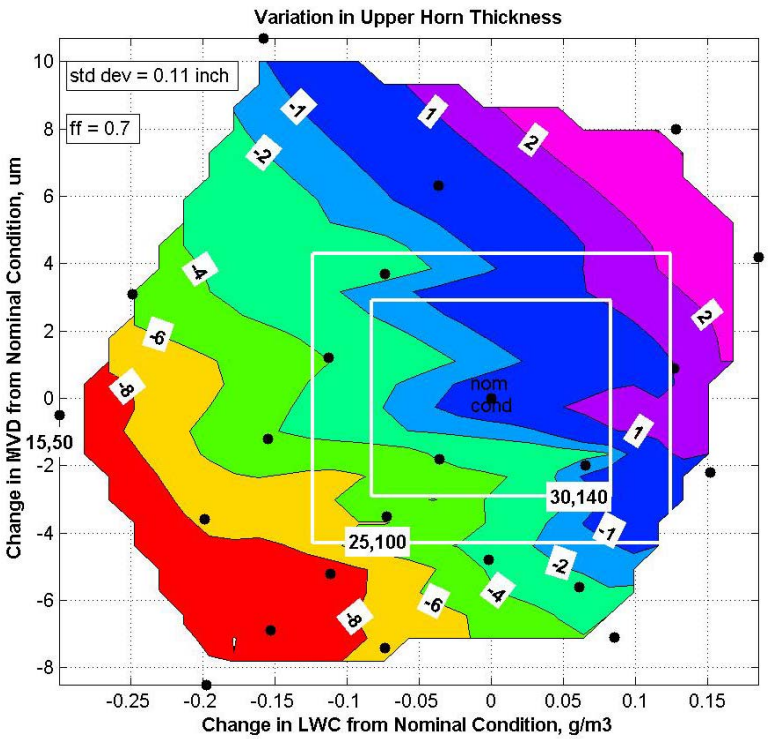
- **Identify nominal SLD icing conditions (freezing fractions of 0.3 and 0.7)**
- **Determine the variant conditions (i.e. the amount of variation from the nominal LWC, MVD, temperature)**
- **Measure and compare ice shape parameters for nominal and variant conditions**
  - **Geometric parameters**
  - **Ice mass**

STATUS

- **3 sensitivity tests completed**
- **Results reported in AIAA-2005-0073, AIAA-2006-0469**
- **Methodology to define accuracy still under development (attempting to couple MVD, LWC changes to ice shape to aero effects)**

SLD Sensitivity Studies

Contour Plot Showing Effect Of Change in MVD & LWC On Upper Horn Thickness

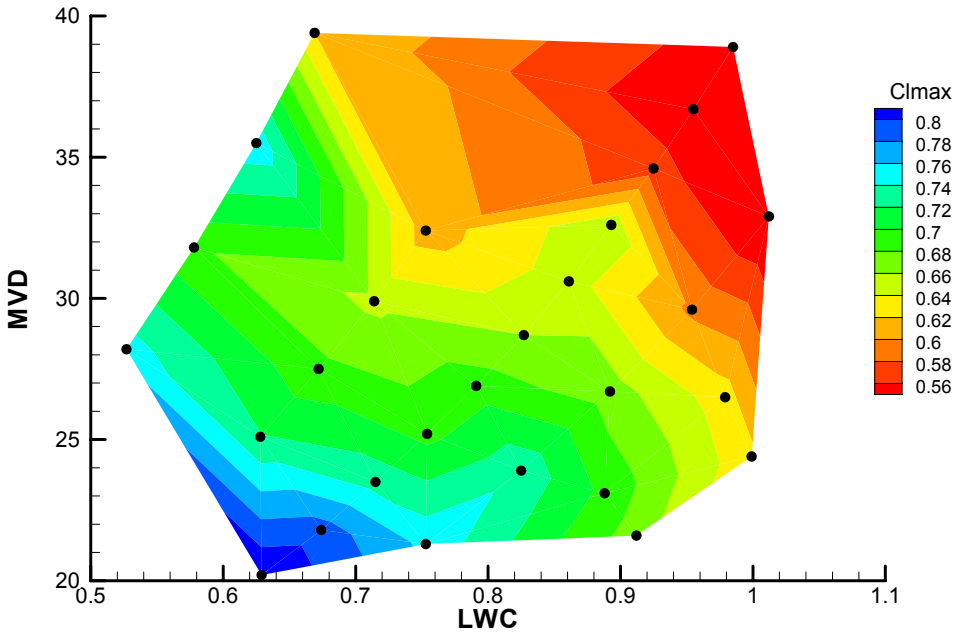


T_{tot}=7.9°F, T_s= -1.6°F, η_0=0.75, V=200 knots, AOA=2.5deg, 15 min spray

- Contour plot method used in 2004 / 2005 sensitivity tests has potential to characterize the effect of small changes in LWC, MVD on ice shape
  - Provide link between changes in spray cloud and ice shape changes
  - Preliminary estimate of minimal change LWC, MVD to produce change in ice shape
- 2006 test entry to confirm methodology

SLD Sensitivity Studies

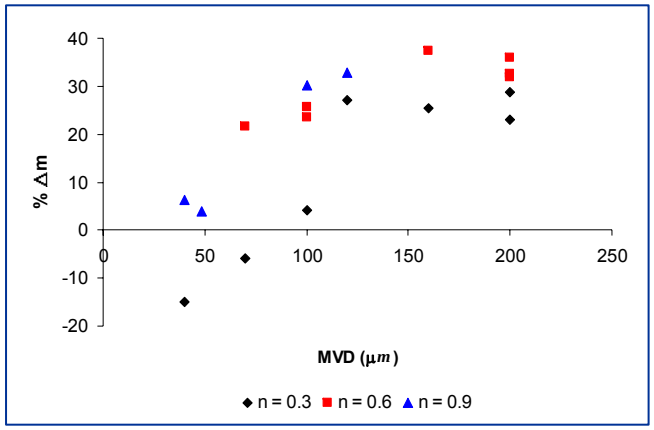
Contour Plot Showing Effect Of Change in MVD & LWC On Cl_{max}

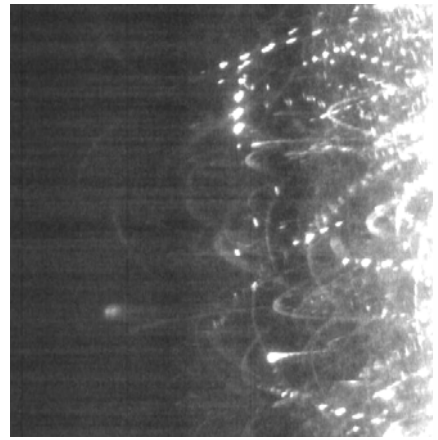


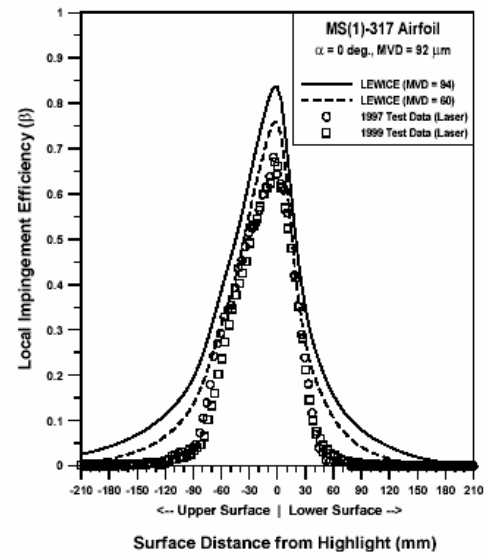
- **Follow-on aero testing performed at UIUC**
- **Contour plot method used in 2004 / 2005 sensitivity tests has potential to characterize the effect of small changes in LWC, MVD on aerodynamic effects**
  - **Provide link between changes in spray cloud, ice shape changes, and aero effects**
  - **Preliminary estimate of minimal change LWC, MVD to produce change in aerodynamic characteristics**
  - **Results are not yet published**

SLD Icing Physics

SLD Icing Physics







Background

Identify the physical processes of ice accretion that are impacted by the presence of super-cooled large droplets. Quantify the important physical characteristics of the identified processes. Develop a database of information for development of models to be used in simulation software.

SLD Icing Physics

Approach

- **Investigate icing physics processes that are characteristic of SLD**
- **Develop a thorough understanding of SLD icing physics**
- **Provide data that will be useful in identifying necessary changes to icing facilities or to measurement equipment**
- **Provide data that will be useful in development of SLD models to be used in ice accretion codes**

WSU Droplet Break-up Analysis

Location Wichita State University

Principal Investigator Jason Tan & Michael Papadakis

Objective

- Identify droplet dynamic issues relevant to SLD icing
  - Droplet deformation & breakup prior to impact
  - Droplet splash/deposition/bounce
  - Near-wall effects
  - Supercooling large droplets
  - LWC measurement of large MVD spray cloud

Status

- AIAA papers: 2003-0391 & 0392, 2004-0410, 2006-463

Cranfield Droplet Splashing Research

Location - Cranfield University

Principal Investigators - David Hammond, NASA, WSU

Objective

- **Characterize large droplet impact / splash**
  - **Quantify the incoming/splashed drop size, velocity, and angle**
  - **Measure the mass resulting from the splash process**

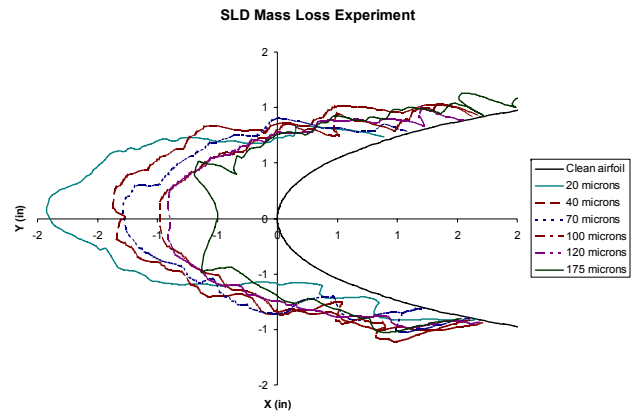
Approach

- **Use a low turbulence vertical tunnel to accelerate droplets of known size toward a target plate having a controlled water film**
- **Quantify drop size, velocity, angle of impact splash with high speed imaging methods**
- **Correlate droplet impact/splash parameters with mass splashed from target plate water film**

Status

- **Test completed July-August 2004**
- **Results analyzed: AIAA 2005-0077, 2006-0466**

Ice Mass Measurements on Airfoils



Location Glenn Icing Research Tunnel

Principal Investigator Mark Potapczuk

Objective

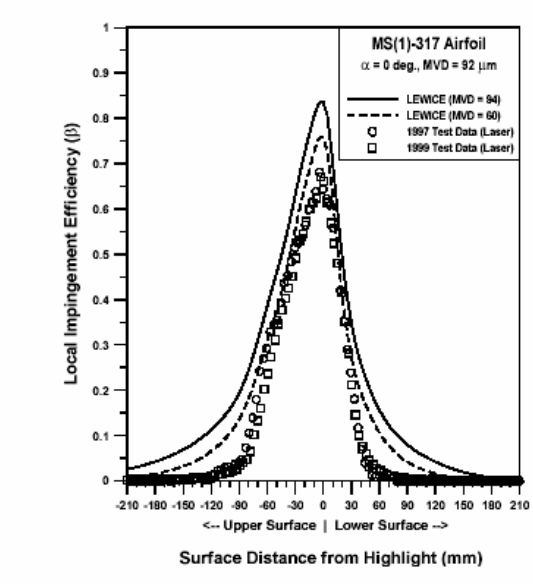
- Determine whether large droplet encounters result in mass loss
- Directly measure the mass of ice deposited on a well-defined target geometry under Appendix C and SLD conditions
  - Method 1: maintain K_0, A_c, and velocity over range of drop sizes
  - Method2: maintain A_c, β_o, and freezing fraction over range of model sizes and drop diameters
- Determine ice shapes with LEWICE assuming no splashing
- Compare ice shape tracings to LEWICE results and compare measured and calculated ice mass values
- AIAA paper 2003-0387

Clean Geometry SLD β Study

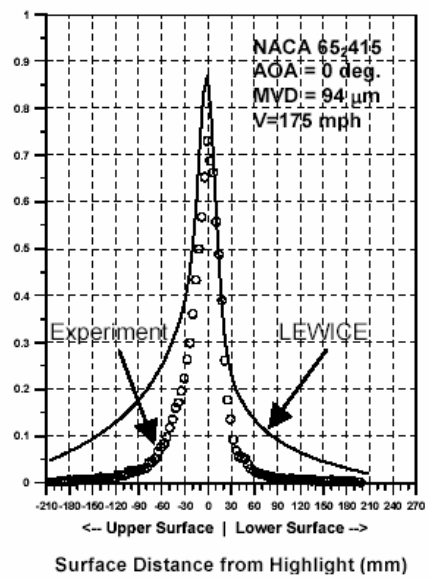
Location NASA Glenn Icing Research Tunnel

Principal Investigator Michael Papadakis

Objective Measure collection efficiency in SLD



SLD impingement on an MS-317 airfoil (LEWICE vs. experiment)



SLD impingement on a NACA 65_2415 airfoil (LEWICE vs. experiment)

SLD Ice Shape β Study

Location NASA Glenn Icing Research Tunnel (US)

Principal Investigator Michael Papadakis

Objective

Measure collection efficiency in airfoils with existing ice shapes

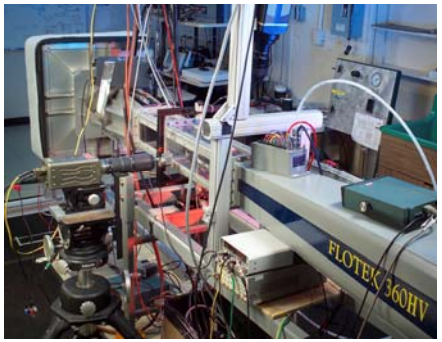
Approach

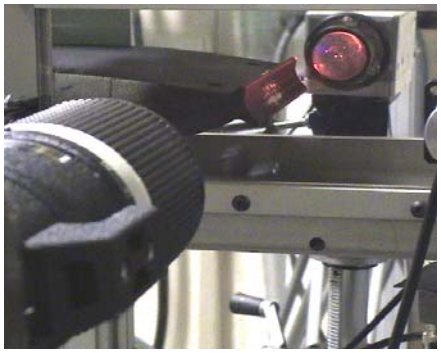
Use existing blotter strip method for collection efficiency measurement on ice shape models

Status:

- Tests completed
- FAA contractor report completed Dec. 2005

WSU/NASA DrIFT Experiment



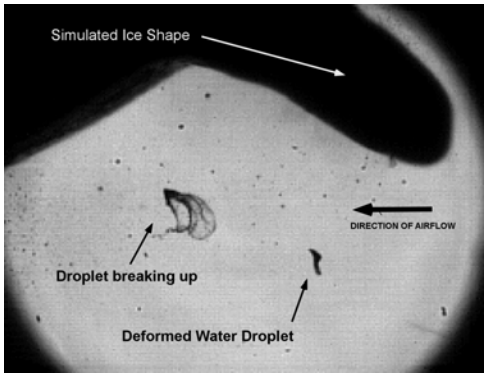


Location Droplet Imaging Flow Tunnel (DrIFT)

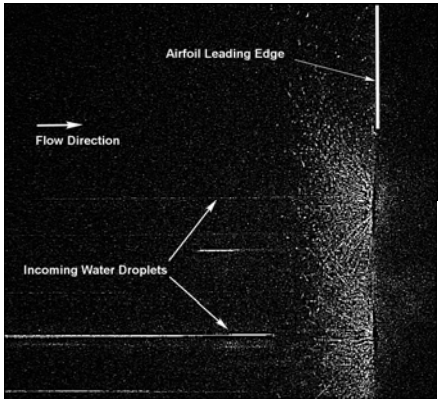
Principal Investigators
Michael Papadakis, Jason Tan, Dean Miller

Objective
Investigate imaging methods to study droplet dynamics

Approach
- **WSU re-design/fabricated tunnel inlet to facilitate droplet dynamics experiments**
- **Mono-dispersed droplet stream (44, 70,107, 160, 350 μm) aimed at test articles**
  - **Iced and un-iced NACA-0012 airfoil**
  - **Multi-element airfoil**
- **NASA high speed imaging techniques used to study droplet splash and breakup**
  - **Phantom camera with optical backlighting**
  - **Gated intensified camera with laser sheet**



Status
- **Testing conducted in July and Sept 2005**
- **Qualitative imagery of droplet impact and breakup obtained**
- **Data currently being analyzed**



SLD Modeling in LEWICE

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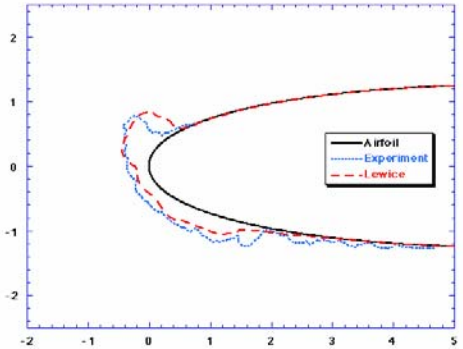


Background

Develop an interim model for SLD ice growth that can be added to LEWICE. Develop a framework for introduction of updated SLD icing physics into models as they become available.

SLD Modeling in LEWICE

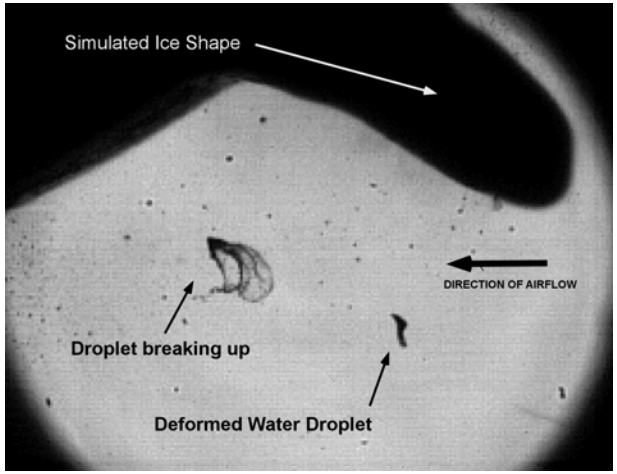
Approach

- **Utilize the data from the SLD Icing Physics studies to develop mathematical models that can be used in computational tools such as LEWICE**
- **Incorporate the models into the code and compare output to SLD ice shape database**
- **Document changes to LEWICE as models are developed**

Develop Droplet Breakup Model

Location Glenn Research Center

Principal Investigator William Wright



Objective

- Allow SLD droplet break-up to influence ice shape development

Approach

- Incorporate droplet dynamics model into LEWICE and investigate influence on ice shape development

Status

- Model has been incorporated into LEWICE 3.2.2
- Thorough testing of model has been completed
- Upgrades to model can be included as more break-up testing and modeling is conducted
- DVD of experimental ice shape and prediction comparison available
- AIAA-2004-0412 ,AIAA-2005-1243 , AIAA-2006-0464

Develop Droplet Splashing Model

Location: Glenn Research Center

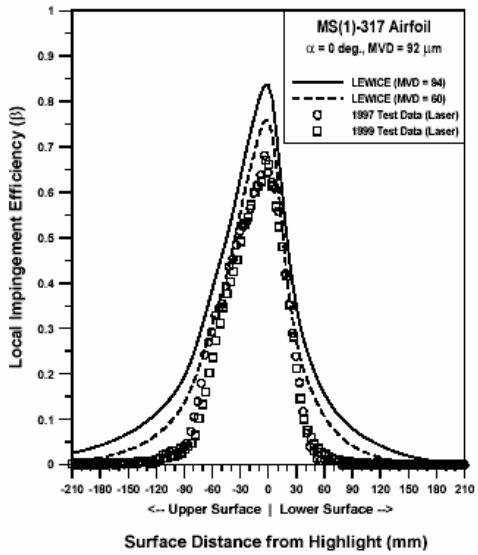
Principal Investigator: William Wright

Objective

- **Allow SLD droplet splashing to influence ice shape development**

Approach

- **Incorporate droplet splashing model into LEWICE and investigate influence on ice shape development**



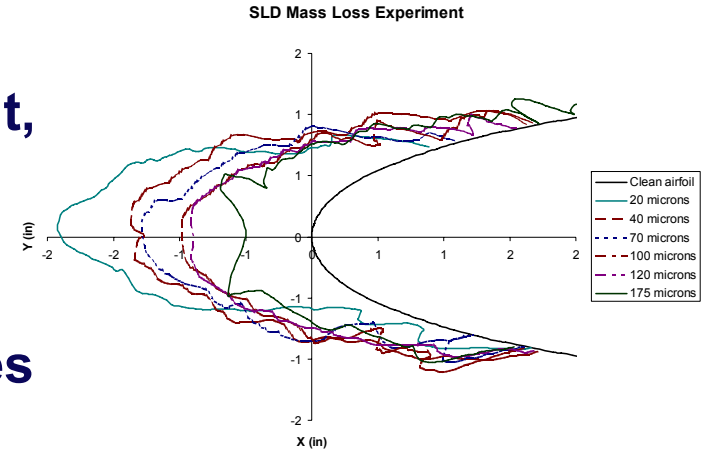
Status

- **Model has been incorporated into LEWICE 3.0**
- **Thorough testing of model has been completed**
- **Upgrades to model can be included as more splashing testing and modeling is conducted**
- **DVD of experimental ice shape and prediction comparison available**
- **AIAA-2004-0412, AIAA-2005-1243, AIAA-2006-0464**

Compare LEWICE Model to Mass Loss Data

Location Glenn Research Center

Principal Investigator William Wright, Mark Potapczuk



Objective

- Identify strengths and weaknesses of SLD model

Approach

- Run LEWICE for conditions used in development of SLD ice shape database and compare ice shapes

Status

- Some initial comparisons have been conducted
- Mass agreement improved with droplet splashing model added

Droplet Trajectory and Impact

- All physical effects modeled
  - Turbulence
  - Saffman lift
  - Bassett force (buoyancy)
  - Gravity
  - Drop deformation
  - Drop breakup
  - Drop splashing
  - Splashed drop trajectory
- Impingement limit search for collection efficiency

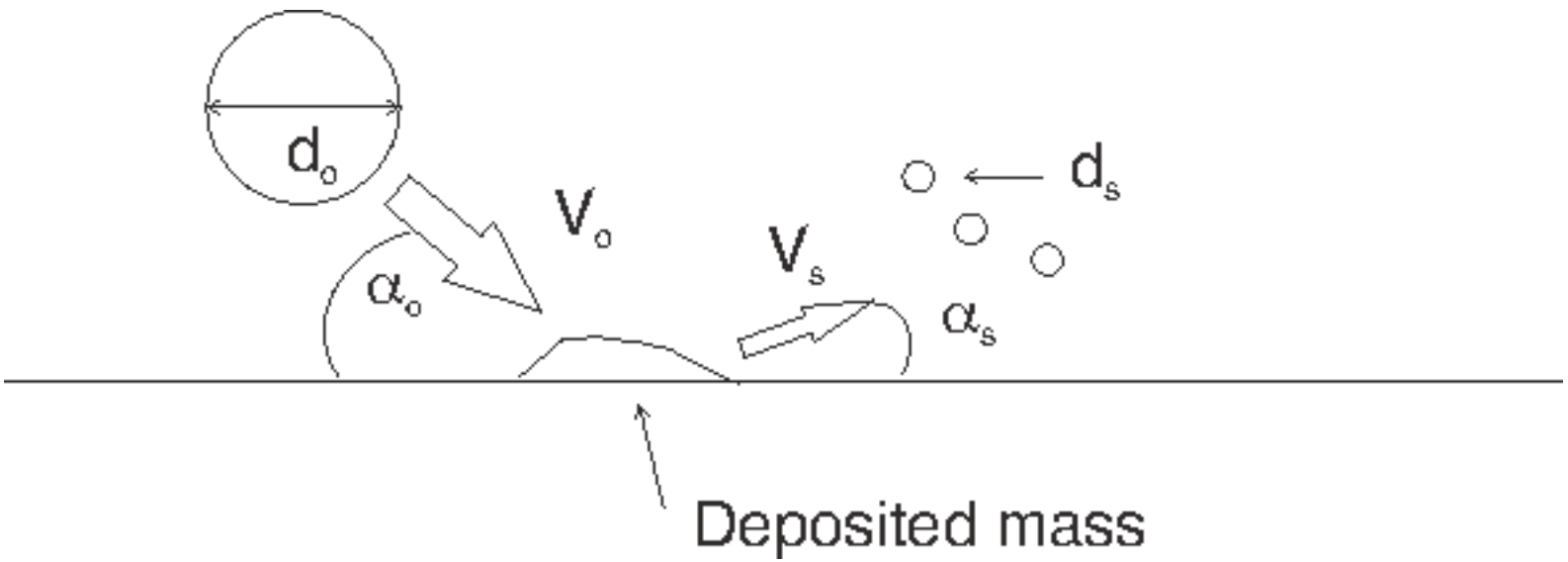
Drop Breakup Model

- Drop breaks completely if $We_a > 13$
  - Conservative assumption (drops take 2-3 cm to break completely)
- Secondary drop size determined by empirical relationship
- No experimental data available for validation

$$\frac{d_s}{d_o} = 6.2\left(\frac{\rho_w}{\rho_a}\right)^{1/4} \mathrm{Re}_d^{-1/2}$$

Splashing Model Requirements

- Fraction of impinging mass ejected
- Size, velocity, angle of ejected drops
- Tracking/re-impinging of ejected drops



Current Model

- Track one splashed drop for each incoming drop
  - Use MVD of splashed distribution
- Add splashed mass if drop re-impinges
- Drop-drop and drop-film interactions assumed part of correlation
- Asymptotic effects imposed when extrapolating

Empirical Splashing Model (Part 1)

$$\frac{d_s}{d_o} = 8.72e^{-0.0281K}$$

$$\frac{V_{x,s}}{V_{x,o}} = 1.075 - 0.0025\alpha_o$$

$$\frac{V_{y,s}}{V_{y,o}} = 0.3 - 0.002\alpha_o$$

$$\boxed{\frac{m_s}{m_o} = 0.7\left(1 - \sin\alpha\right)\left(1 - e^{-0.0092*\left(K_{L_n} - 200\right)}\right)}$$

Empirical Splashing Model (Part 2)

Splash Threshold: $$K_{L_n} = \frac{K^{0.859}}{(\sin\alpha)^{1.25}}\left(\frac{\rho_l}{LWC}\right)^{0.125} > 200$$

$$K = Oh * \mathrm{Re}^{1.25} = \frac{\mu_w}{\rho_w \sigma d}\left(\frac{\rho_w V_n d}{\mu_w}\right)^{1.25}$$

Validation Data (Impingement)

- NASA/WSU Impingement Database
  - 19 geometries (7 ice shape geometries)
  - 10 different MVDs (11 μm - 236 μm)
  - 0 ≤ AOA ≤ 8
  - 32” - 57” chord
  - 175 mph (152 kts)

LEWICE Impingement Runs

- All conditions were computed with 4 options:
  - Potential flow, no splashing (PF-NS)
  - Potential Flow, splashing (PF-S)
  - Naviér-Stokes, no splashing (NS-NS)
  - Naviér-Stokes, splashing (NS-S)
- All cases use 27-bin drop size
- Grids for Naviér-Stokes generated with ICEG2D option
  - Grid refinement performed on high AOA cases only
- WIND 5.0 used as Naviér-Stokes solver
  - Spalart-Allmaras turbulence model used
  - 27 solutions needed for impingement cases

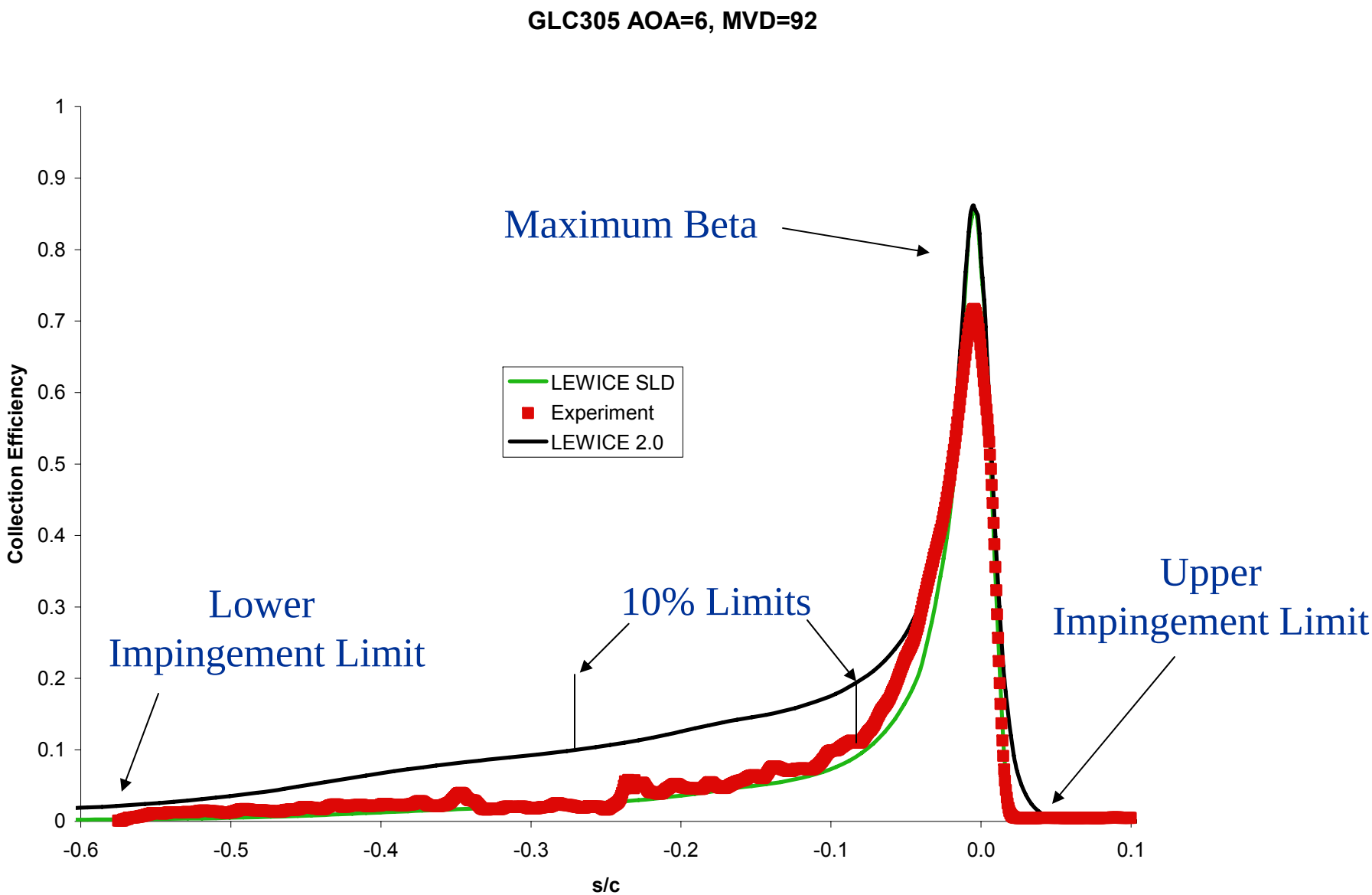
Impingement Parameters Compared

- Maximum Beta
  - Results also compared to scaling method
- Total Water Catch

$$\dot{m} = LWC * V * W * \int \beta ds$$

- Upper and Lower Impingement Limits
  - Measured from leading edge as a percent chord
- Upper and Lower Location where $\beta = 0.1$
  - Occasionally used for sizing de-icing equipment

Typical Splashing Results



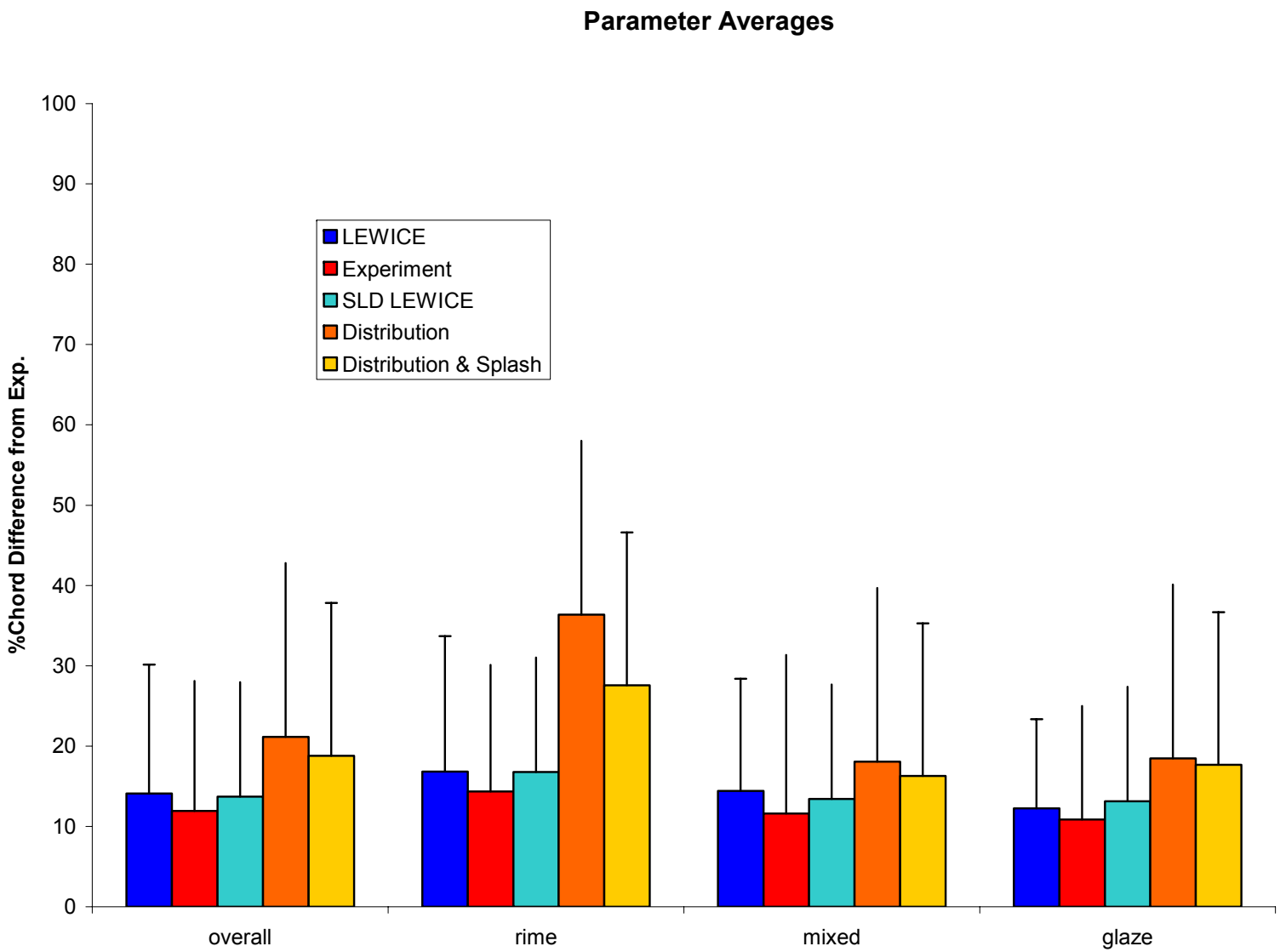
Validation Data (Ice Shapes)

- 3017 IRT Ice Shapes
- 3049 LEWICE Runs
  - 944 Appendix C conditions
  - 682 SLD conditions ran with three options
    - Monodisperse MVD
    - 27 bin distribution (no splash)
    - 27 bin distribution (with splash)
  - 9 Different geometries
  - Time: 0.5 to 69.7 min (scaled condition)
  - Chord: 1.5 (cylinder) to 78 in
  - Velocity : 65 to 323 kts ($0.19*10^6 < Re < 14.6*10^6$)
  - LWC: 0.3 to 2.8 g/m^3
  - MVD: 12 to 305 μm
  - Temperature (total): -20 to 34 °F

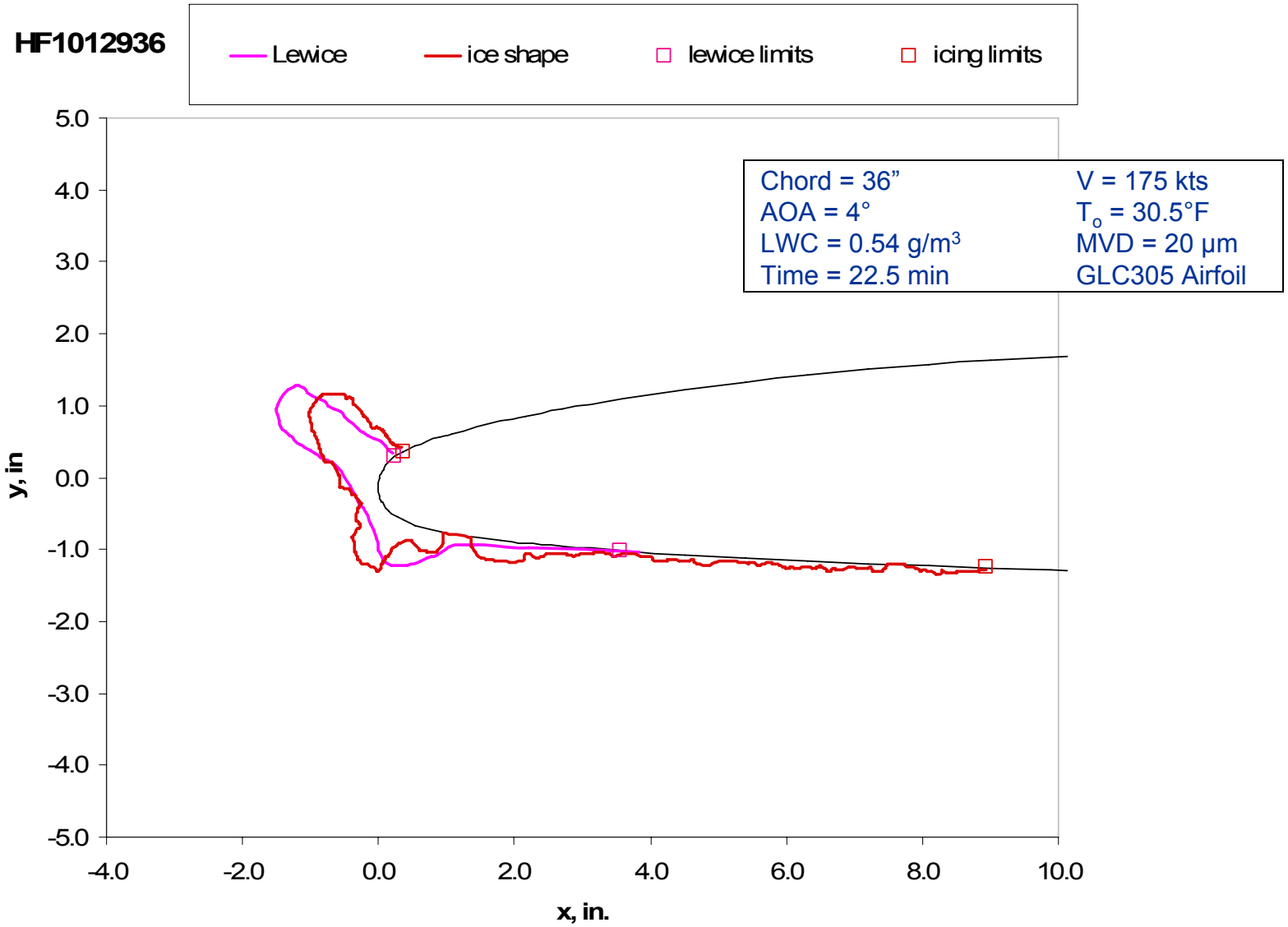
Icing Parameters Compared

- Icing Limit
  - Upper & lower
- Horn Height
  - Upper & lower
- Stagnation freezing fraction
  - Leading edge minimum thickness
- Horn Angle
  - Upper & lower
- Iced Area
- Ice Weight (if measured)

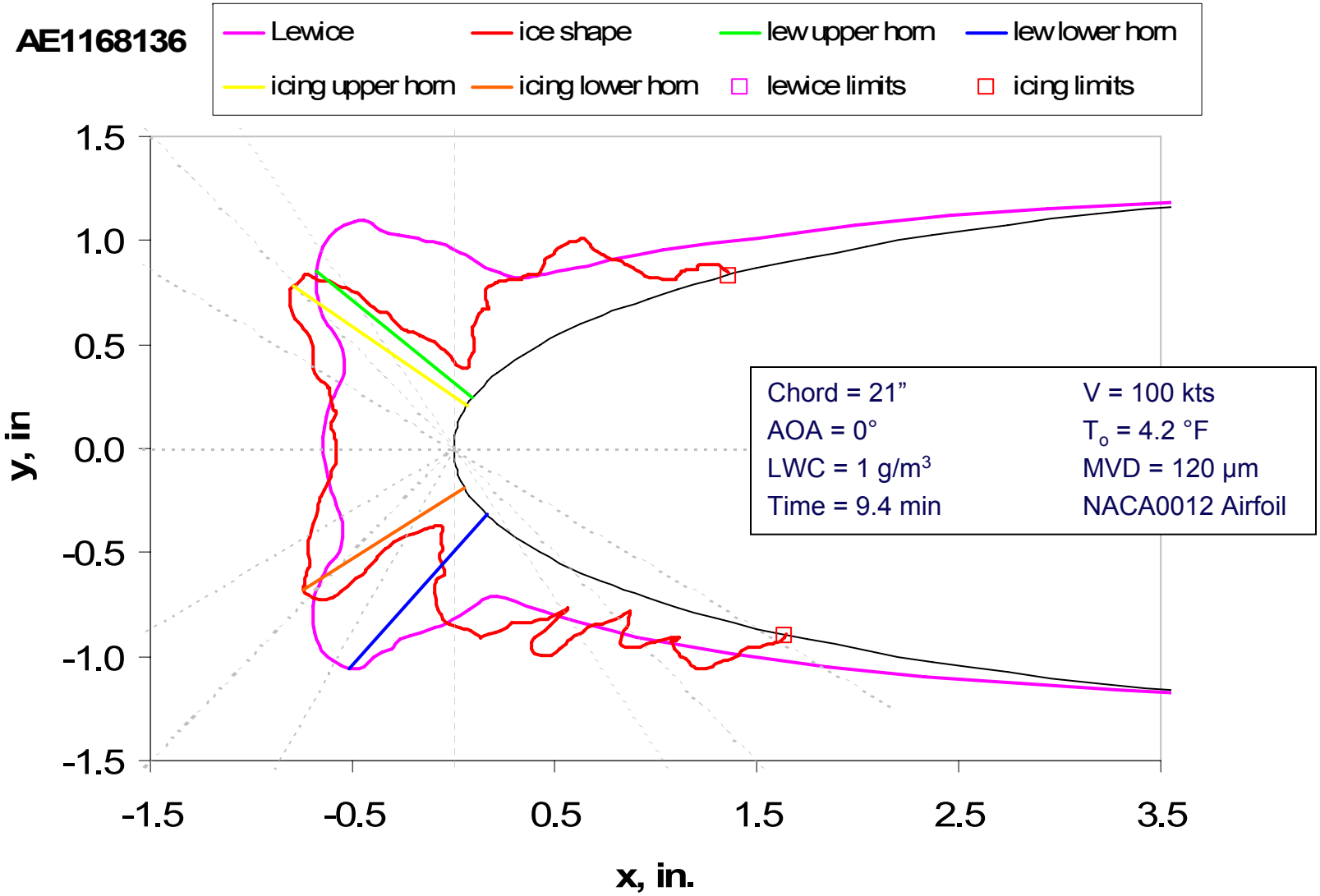
Overall Comparison



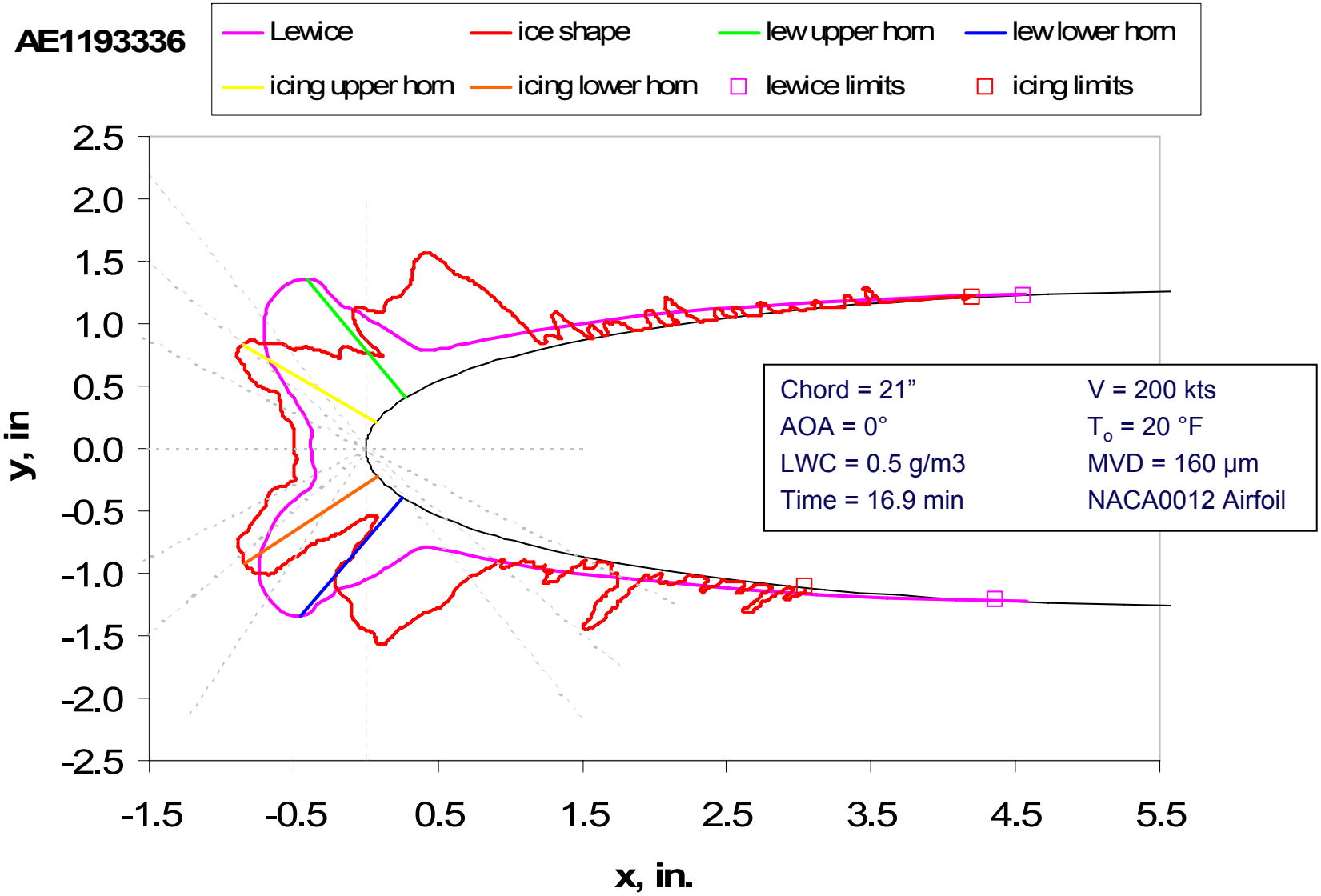
Typical Icing Results



Typical SLD Results

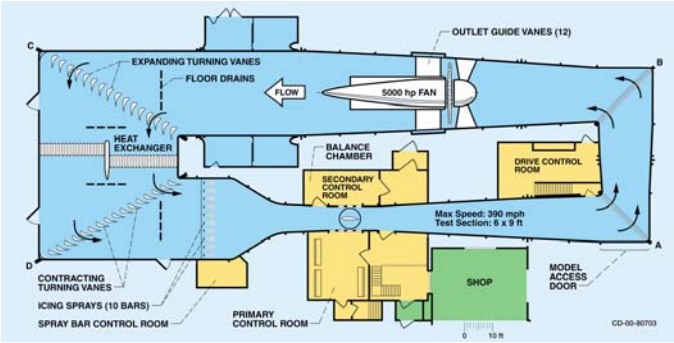


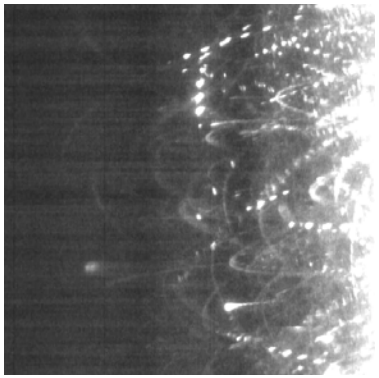
Need Feather Model?



Reproducing SLD Conditions in the IRT

Reproducing SLD Conditions in the IRT





Background

- **Determine the characteristics of SLD icing conditions that must be reproduced in a ground based icing facility.**
- **Identify the range of SLD conditions that can be produced using the current capabilities of the IRT.**
- **Develop methods for reproducing characteristics of in-flight SLD icing conditions that cannot be simulated currently.**
- **Document those characteristics that cannot be reproduced in the facility in its current configuration.**

Reproducing SLD Conditions in the IRT

Approach

- **Assess current capability to produce SLD**

  What set or range of icing conditions can be produced in an icing tunnel with current spray system technology

- **Investigate and document constant or time varying icing conditions in natural SLD encounters**

  Examine the data from SLD in-flight encounters and characterize the cloud and flight conditions for an SLD ice shape

- **Develop SLD cloud simulation method**

  Create operating conditions in the IRT that produce a cloud similar to that found in natural SLD encounters by altering spray times and conditions

- **Document Range of LWC and MVD vs. Appendix X**
- **Document drop size distribution vs. Appendix X**

Develop SLD Cloud Simulation Method

Location Glenn Research Center

Principal Investigators Dean Miller, Mark Potapczuk, Robert Ide, & John Oldenburg

Objective

- Attempt to generate a Bi-Modal SLD spray cloud in an icing tunnel

Approach

- Sequentially spray a small drop (20 µm MVD) condition, then a large drop (130 µm MVD) condition
  - Maintain freezing fraction for both conditions
  - Vary order / time of spray conditions
  - Generate a "sequenced" ice shape
  - Document ice shape with ice tracings and photographs
- Compare "sequenced" SLD ice shape to ice shape generated from "non-sequenced" 20 µm MVD or 130 µm MVD icing spray

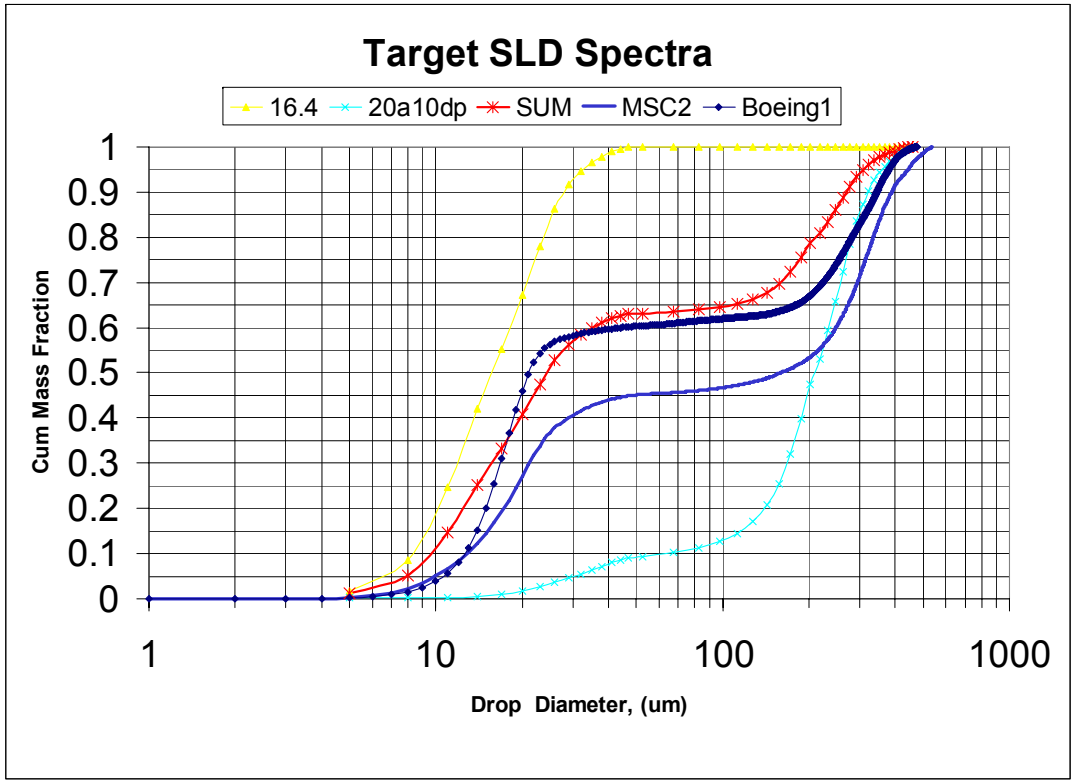
Status

- 2 tests completed, reported in AIAA-2005-0076, AIAA-2006-0462
- Currently investigating another alternate technique

Develop SLD Cloud Simulation Method

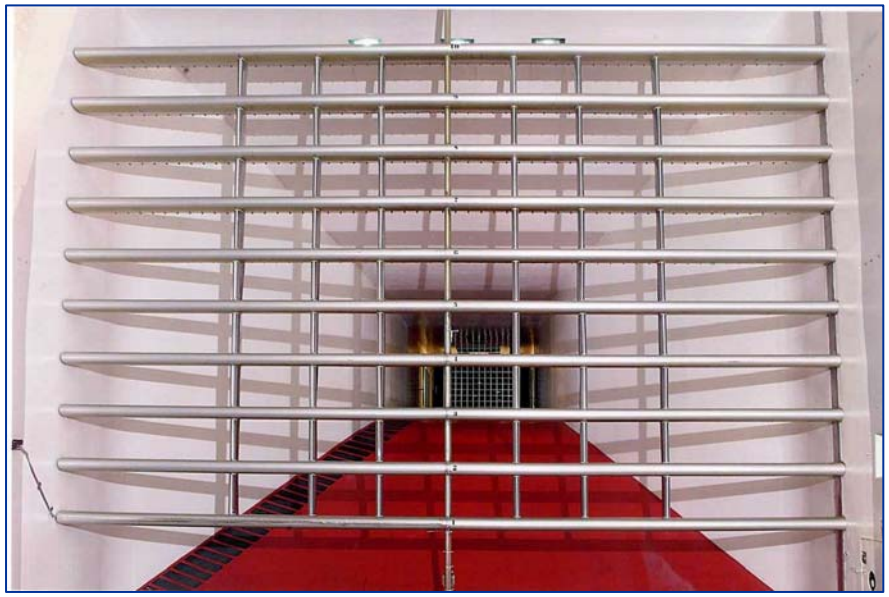
- Alternate method under development
  - Sequencing not required
  - Utilizes existing IRT nozzles
  - Adds hydraulic (water only) nozzle
- Preliminary results suggest can match bi-modal cases with “flat area” in cumulative LWC curve
- Prototype nozzles under evaluation
  - Engineering issues to be resolved

Cumulative LWC From Simultaneous Spray (Mod-1 & Hydraulic Nozzle)



SLD Cloud Uniformity in the NASA IRT

Principal Investigators - Jack Oldenburg and Mark Potapczuk



Objectives

- Icing Research Tunnel (IRT) enhancements to improve SLD uniformity allowing a broader range of icing test possibilities under SLD conditions.
- Future SLD experiments will produce more reliable and robust data than has been previously available.

Description

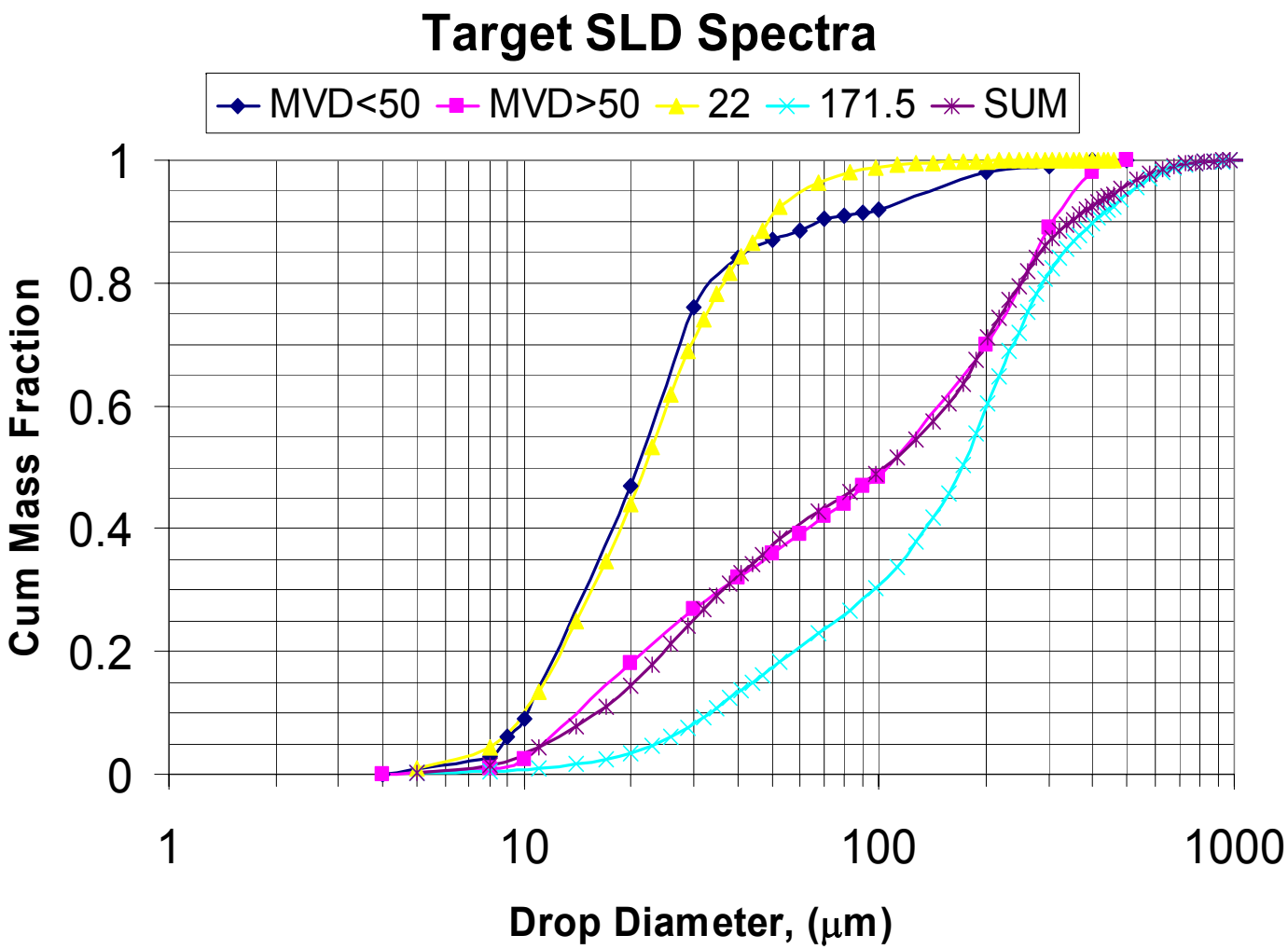
- Six columns of vertical airfoil shaped struts were added to the IRT spray bars
- Improved LWC uniformity.
- Increased the performance capabilities of the tunnel
- Increased the confidence level of the cloud operational characteristics
- Enhancements to SLD uniformity will allow a broader range of icing test possibilities

Status

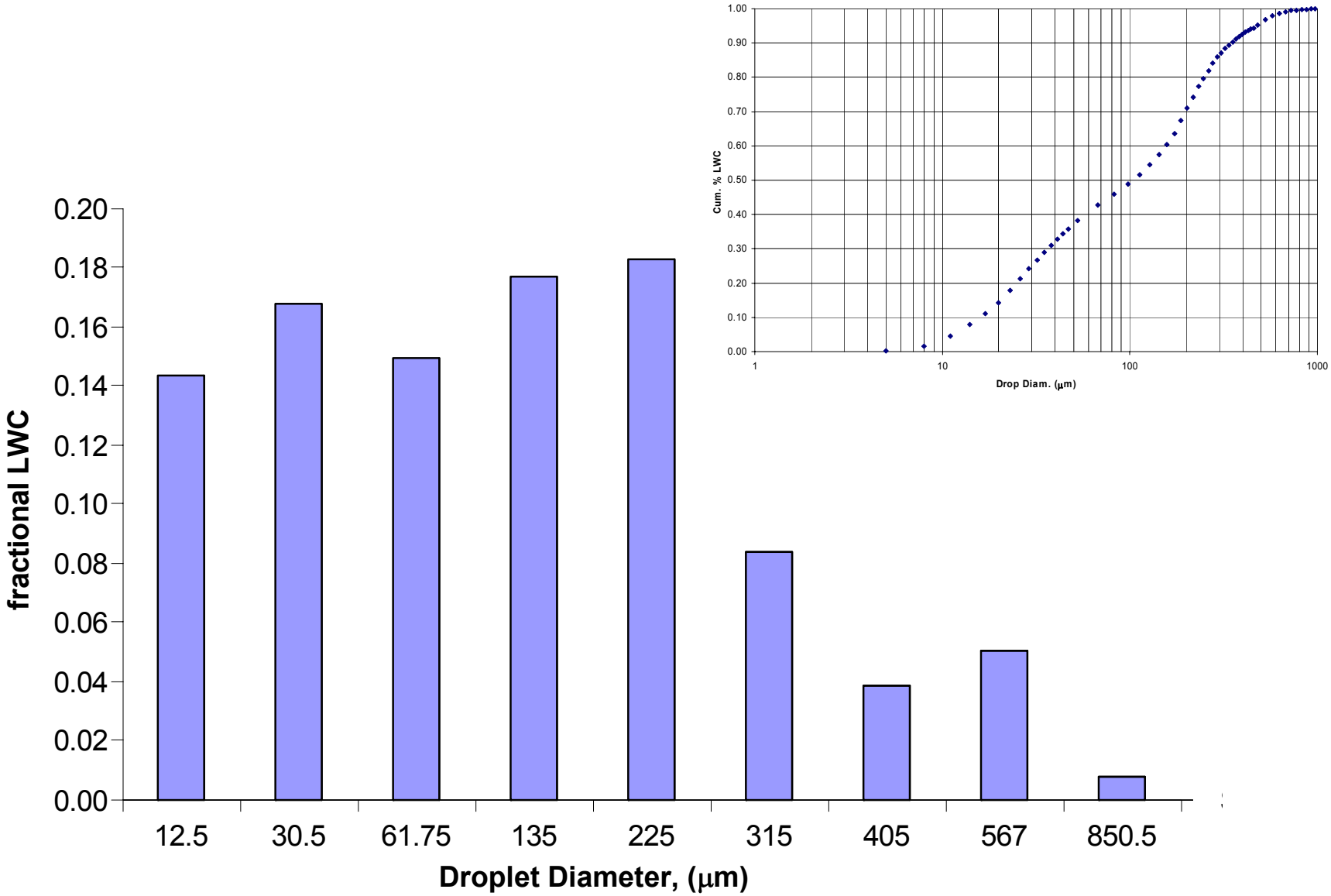
- All work for the experiment is done and has been satisfactory evaluated- March 2006

Numerical Simulation of Ice Shapes from a Bimodal Large Droplet Icing Cloud

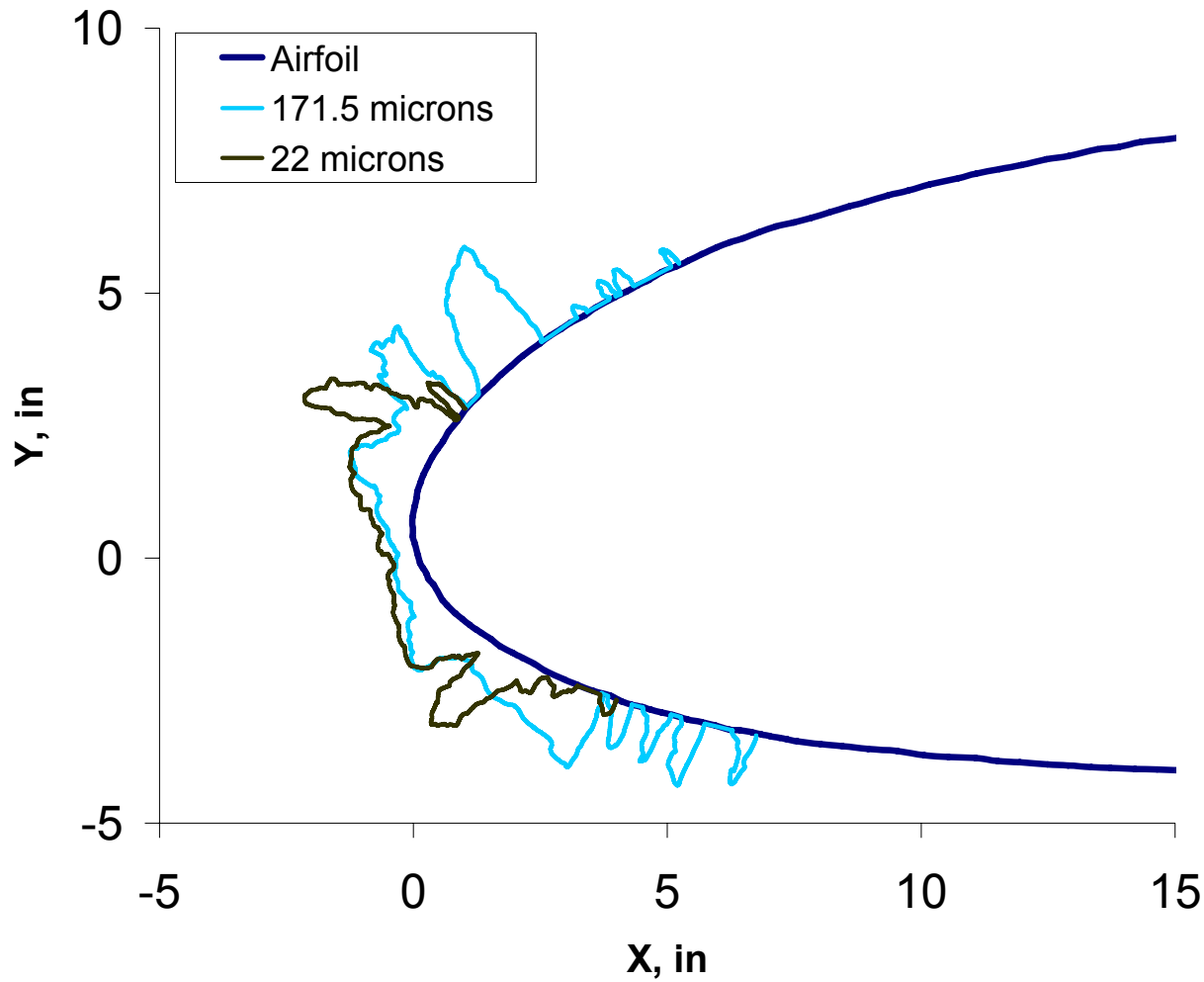
Droplet Distribution for ZLE with MVD > 50 μm



LEWICE droplet distribution for MVD > 50 μm



Component Sprays of Bi-modal Sequencing



171.5 micron MVD:

LWC = 0.878 g/m^3

22 micron MVD:

LWC = 1.3 g/m^3

Common conditions:

V = 150 knots

Ts = 17 ˚F

Time = 20 min.

Component Sprays of Bi-modal Sequencing

171.5 micron MVD

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22 micron MVD

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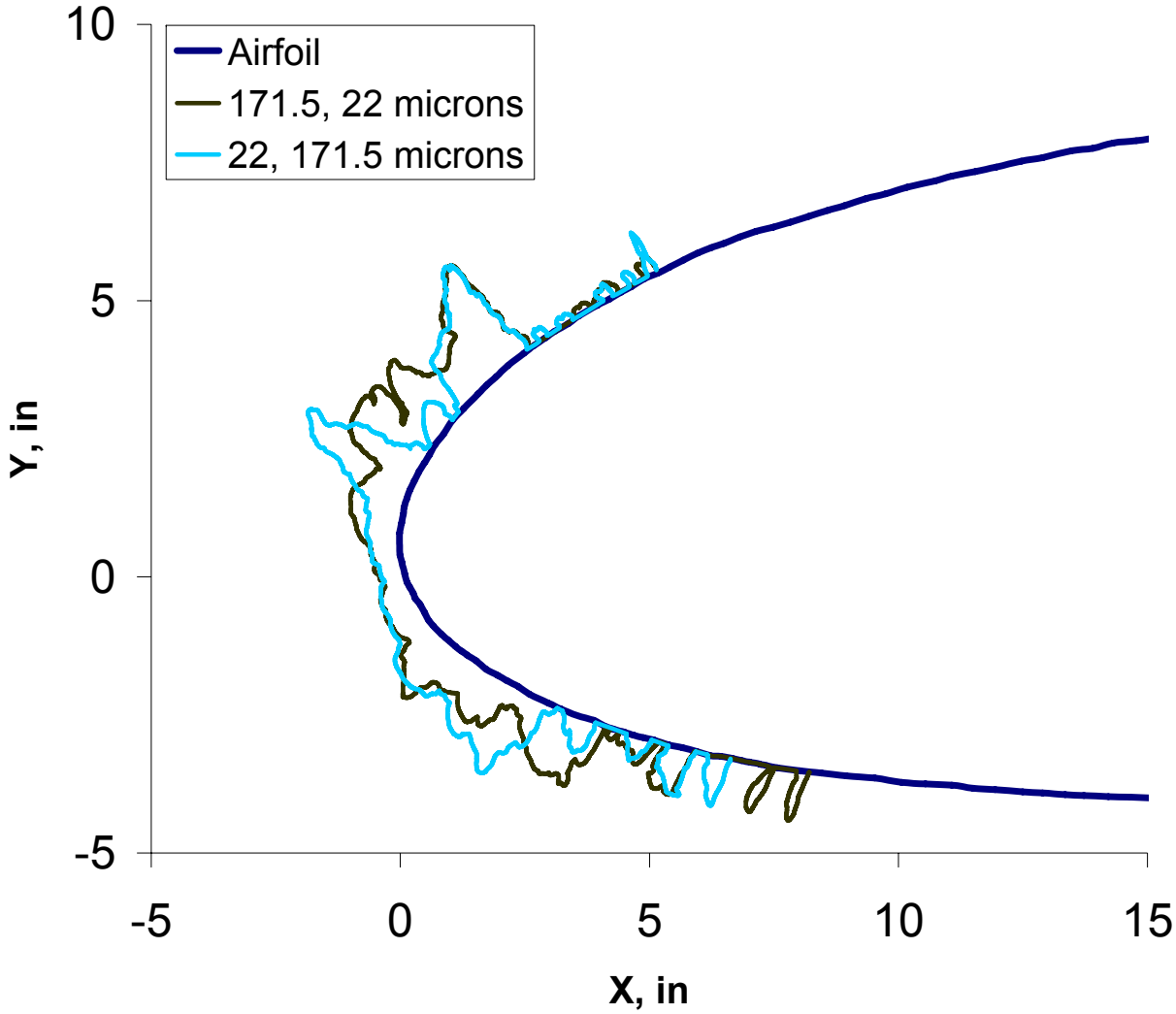
Common conditions: V = 150 knots, Ts = 17 °F, Time = 20 min.

Ice Shapes Produced by Sequencing



171.5 micron MVD:

LWC = 0.878 g/m^3

Δt = 4 min.

22 micron MVD:

LWC = 1.3 g/m^3

Δt = 1 min.

Common conditions:

V = 150 knots

Ts = 17 °F

T_{total} = 20 min.

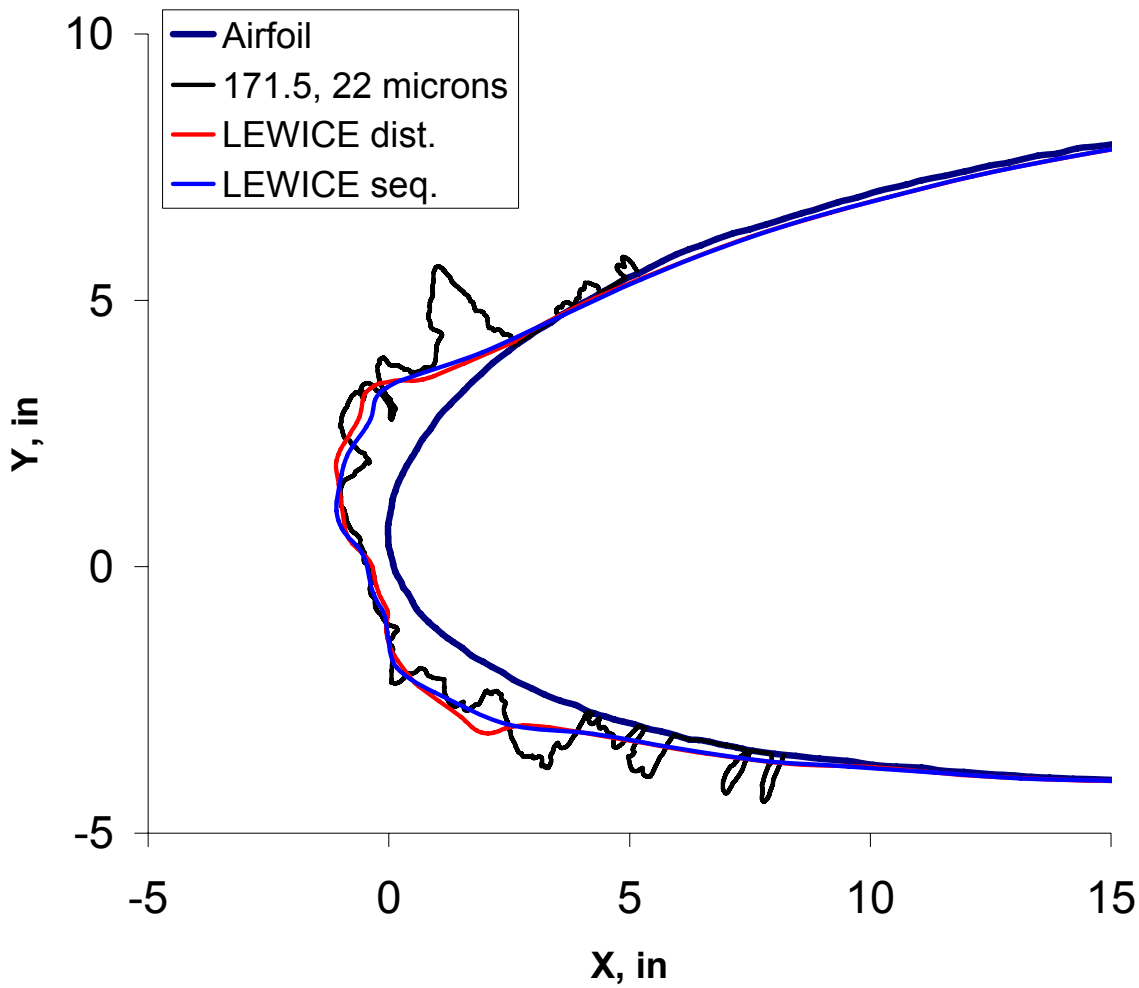
Ice Shapes Produced by Sequencing

171.5 - 22 micron

22 – 171.5 micron

Common conditions: V = 150 knots, Ts = 17 °F, Time = 20 min.

LEWICE Results for Large-Small Sequence



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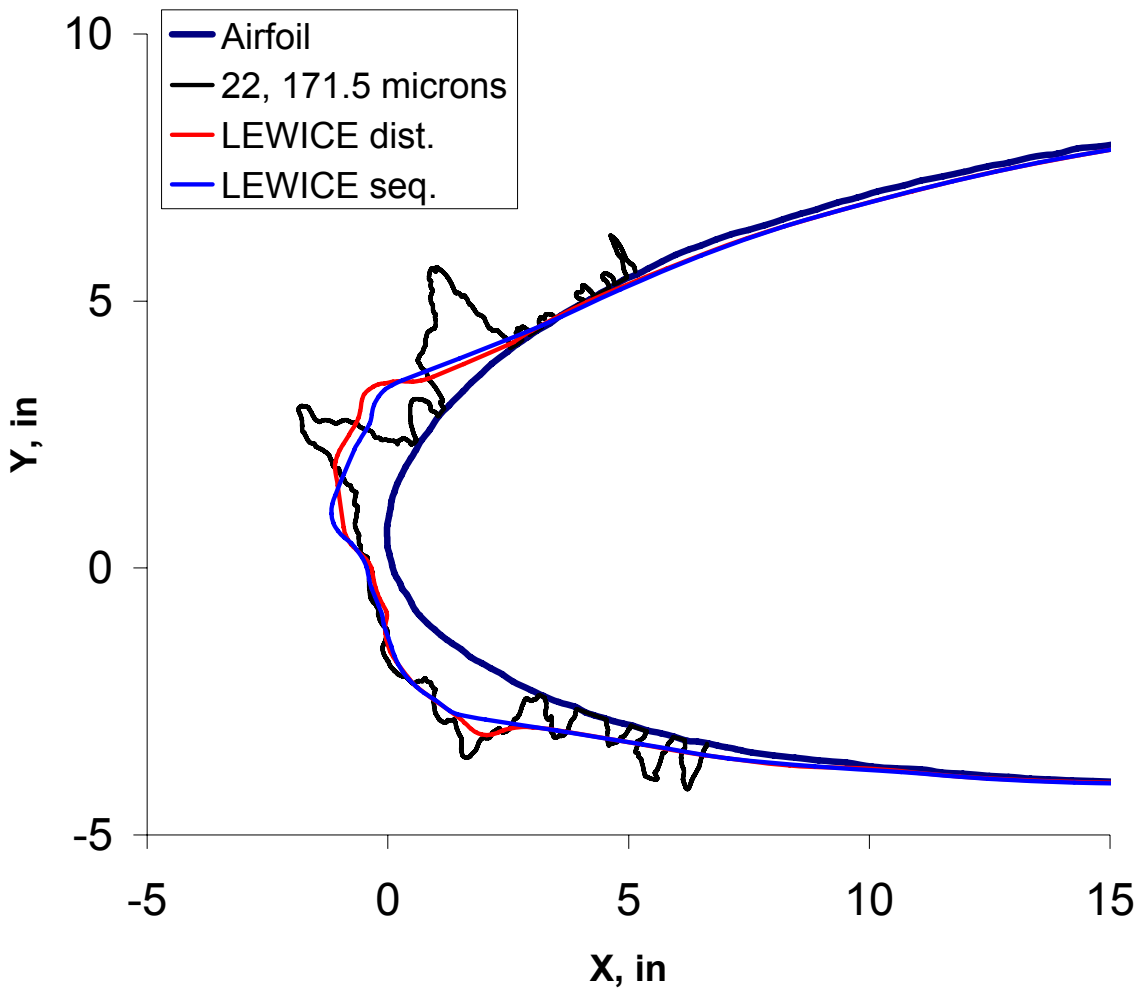
LEWICE Results for Small-Large Sequence



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Conclusions (1)

- Icing physics studies conducted on large droplet break-up, splashing, and re-impingement
- Mass loss experiments performed suggesting effect of splashing at all drop sizes
- Quantitative analysis shows that LEWICE impingement results with splashing are comparable to experimental accuracy
  - Average difference less than 30% for all parameters
- Splashing model improves impingement limit but not necessarily icing limit results in SLD regime
- Splashing model more likely to under predict results
  - Effects much less pronounced in 3.2

Conclusions (2)

- Experimental methods under development to reproduce bi-modal droplet distributions
- LEWICE reproduces bi-modal ice shapes very well
- LEWICE results show little difference between sequenced spray and actual bi-modal ice shape