NASA Aeronautics Research Institute

Centrifugally Powered Pneumatic Deicing for Helicopter Rotor Blades

Dr. Jose Palacios – Assistant Professor
Dr. Douglas Wolfe – Department Head Advanced Coatings ARL
The Pennsylvania State University

Dr. Joseph Szefi – President
Invercon LLC

NASA Aeronautics Research Mission Directorate (ARMD)

FY12 LEARN Phase I Technical Seminar

November 14, 2013

POC: Eric Kreeger, Icing Branch/RTI, NASA Glenn

Agenda

- Background and Motivation
- Objectives
- Prototype Design/Fabrication
- Aerodynamic Testing
- Rotor Ice Testing Results
- Erosion Testing
- Conclusions

NASA Aeronautics Research Institute

Motivation

PENNSTATE 1855

Helicopter icing is introduced by both its mission requirements and operation environments:

- Urgent transportation
- Search and rescue
- Low altitude
- Low temperature
- High humidity, icing cloud possible

Source: BBC NEWS, Mar 2nd 2006 (http://news.bbc.co.uk/2/hi/in_pictures/4768180.stm)

- **Ultimate goal of helicopter icing research: All weather aircraft**
- **Need for fundamental research to:**
  - **Improve and validate ice accretion tools**
  - **Develop and evaluate ice protection systems and protective surfaces**
  - **Develop facilities and testing procedures**

Motivation – Electrothermal Deicing

NASA Aeronautics Research Institute

- Only system qualified by the FAA and the DoD
- Heavy system (4 Blades 12,000 lbs Model: >160 lbs.)
- Does not allow for continuous application due to high power consumption (4 Blades, 12,000 lbs Vehicle: >20 KW, ~25 W/in^2)
- Allows ice accretion up to 0.3 in (10% Torque Increase)
- Melted ice may flow aft and refreeze further
- Difficult to integrate with polymer erosion-resistant materials

ARMY HISS Icing Certification Testing
Ice Protection System (S-92™)

A low-power, non-thermal IPS is desired to have an impact on all-weather capabilities:

- **Compatibility with smaller vehicles**
- **Compatibility with polymer leading edges**

Background

NASA Aeronautics Research Institute

- Pneumatic de-icing boots ➔ used on fixed-wing aircraft for decades
- In the 80's, NASA and Goodrich attempted to develop **rotorcraft** de-icing boots
- Boots were successful in de-icing rotor blades, several problems were identified:
  1) Complicated pneumatic slip-ring transfered engine bleed air out to rotating frame
  2) Erosion of polymer boots
  3) Altered airfoil shape led to rotor performance degradation
- These problems were technology development barriers

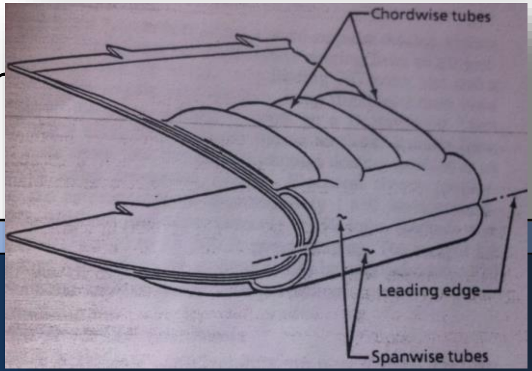


Fig. 1. Photo JUH-1 test helicopter

The Innovation:

- Avoid pneumatic slip rings: CENTRIFUGAL PUMPING
- Avoid pneumatic diaphragm exposure: Ti-Al-N Erosion resistant coating
- Avoid rotor performance degradation: CONTROLLED DEFLECTION ZONES

Centrifugally Powered Pneumatic De-Icing Concept

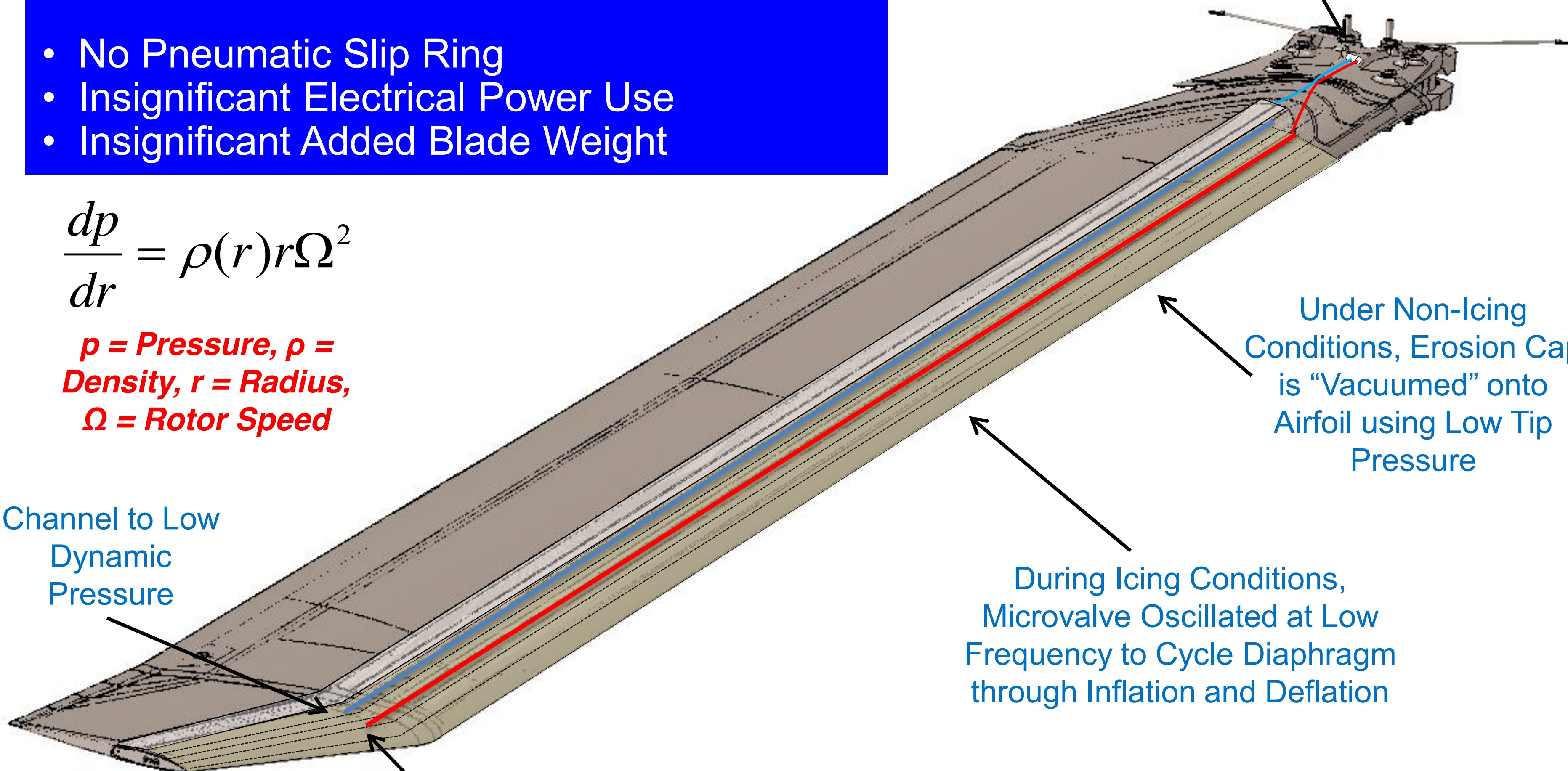
NASA Aeronautics Research Institute

Goal: Surface De-Icing Treatment can be Retrofitted to Existing Blades

- No Pneumatic Slip Ring
- Insignificant Electrical Power Use
- Insignificant Added Blade Weight

$$\frac{dp}{dr} = \rho(r)r\Omega^2$$

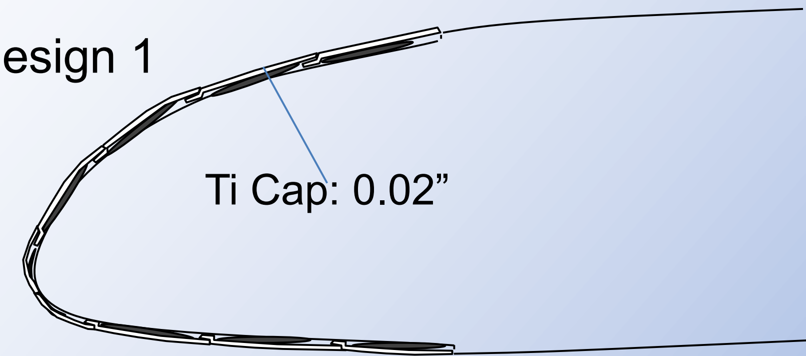
p = Pressure, ρ = Density, r = Radius, Ω = Rotor Speed

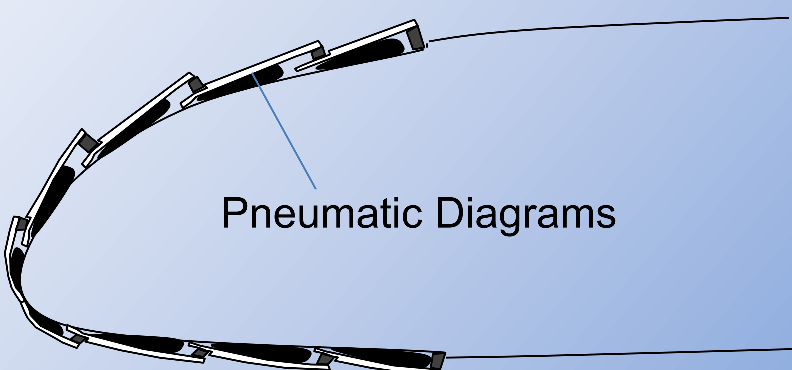


Proof-of-concept: Pneumatic Deicing

- Initial designs considered allowed for local deformation of individual 0.02” thick Ti strips
- Goal: minimal impact on existing blade design (surface treatment)
- Power Consumption: < 1 W of power with no insignificant additional blade weight

Design 1





Agenda

- Background and Motivation
- **Objectives**
- Prototype Design/Fabrication
- Aerodynamic Testing
- Rotor Ice Testing Results
- Erosion Testing
- Conclusions

Objectives

1) To conduct rotor icing experimental testing of a centrifugally powered pneumatic de-icing prototype for helicopter rotor blades

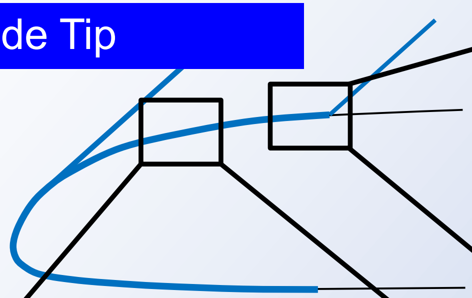
2) To confirm the system effectiveness:

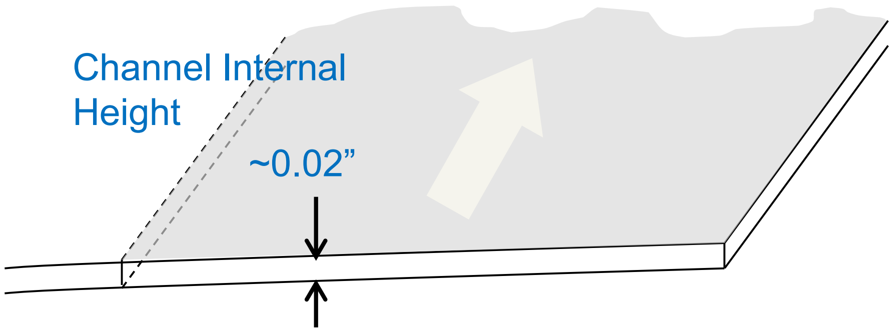
- Low-power consumption
- Robustness under centrifugal loads (CF)
- Reduced aerodynamic penalty
- Erosion resistance

Pneumatic De-Icing Design: Prototype I

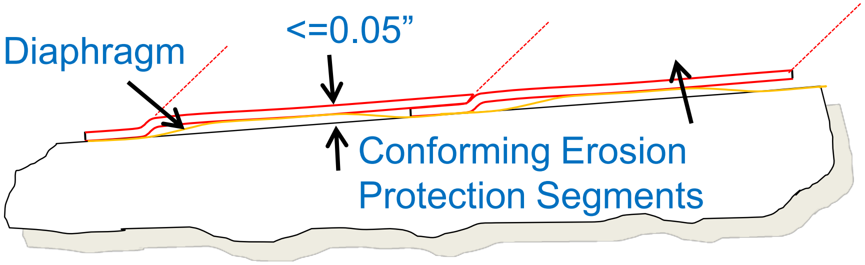
NASA Aeronautics Research Institute

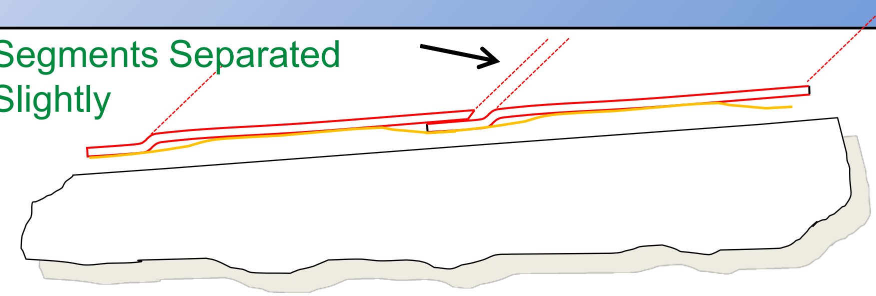
Blade Tip





Thin, hollow channel at end of erosion cap spanning to blade root to access low dynamic pressure





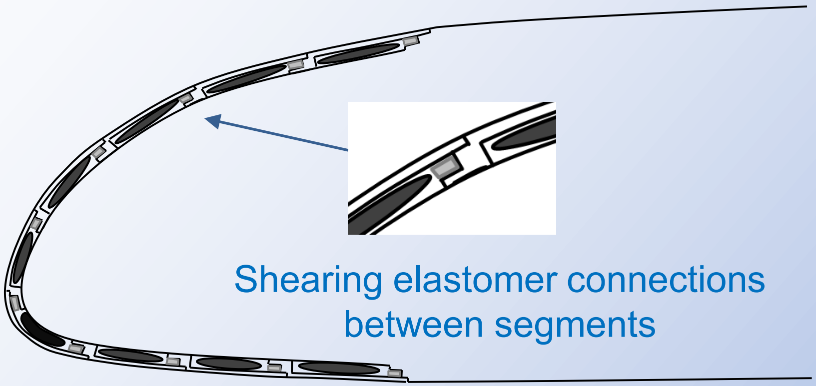
- Power off condition. Volume under diaphragm connected to low dynamic pressure
- Erosion segments conform to desired airfoil shape
- Leading edge maintains rigidity

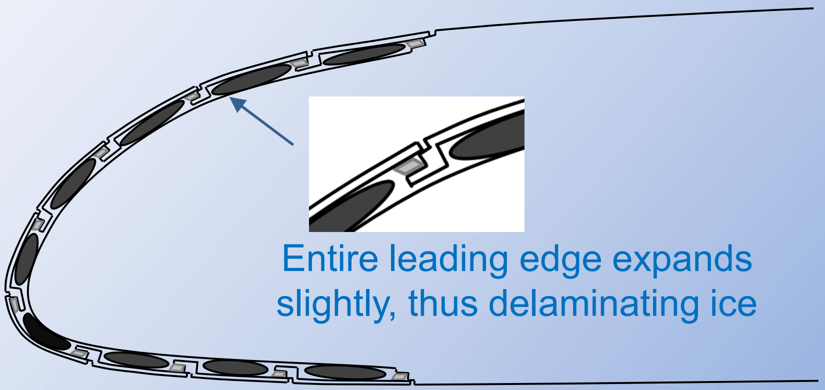
- Microvalve activated at root
- Volume under diaphragm allowed to inflate slightly under CF
- Segments pulled apart slightly, cracking ice
- Vectran bonded to airfoil at cap edges and periodically around entire leading edge

Pneumatic De-Icing Fabrication: Prototype I

PENNSTATE

NASA Aeronautics Research Institute





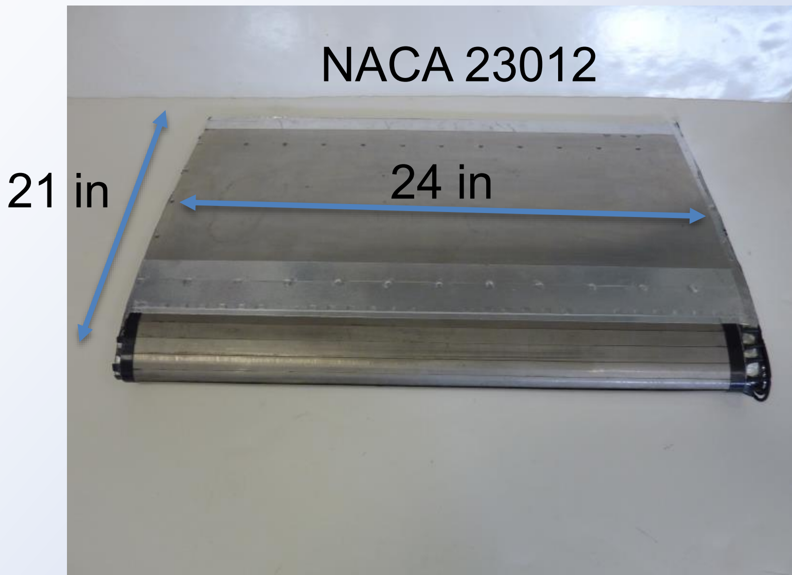
Electrical Discharge Machined Wire Cutting of leading edge segments

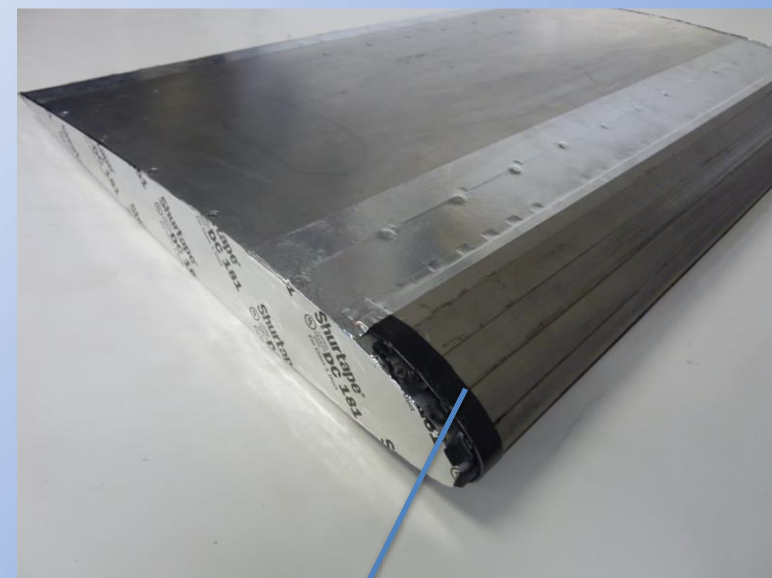
Agenda

- Background and Motivation
- Objectives
- Prototype Design/Fabrication
- **Aerodynamic Testing**
- Rotor Ice Testing Results
- Erosion Testing
- Conclusions

Aerodynamic Testing Prototype I

Model with deployable leading edge fabricated for wind tunnel testing

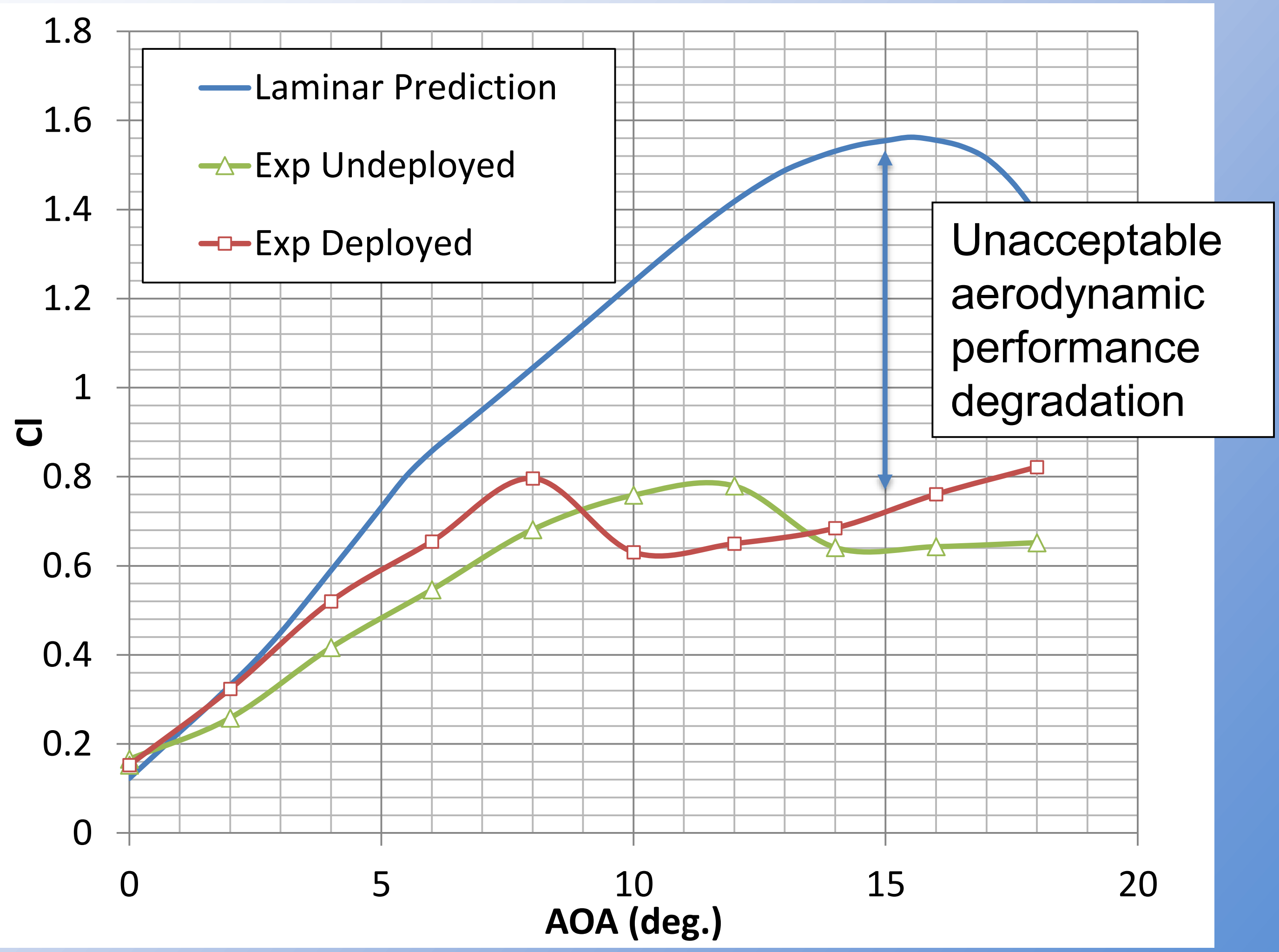




Detail of Segmented Leading Edge

Aerodynamic Testing Prototype I

NASA Aeronautics Research Institute



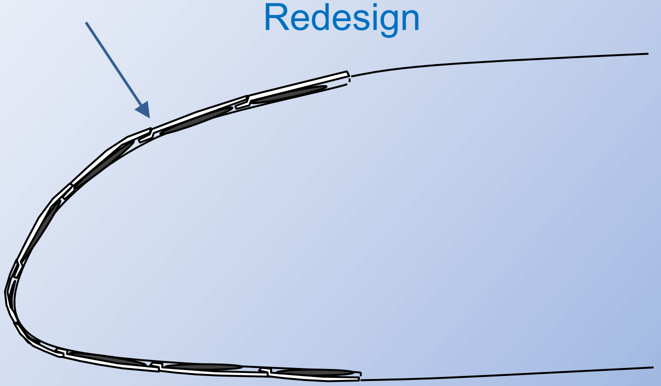
Pneumatic De-Icing Concept: Prototype II

<u>Must mitigate aerodynamic performance degradation concerns</u>

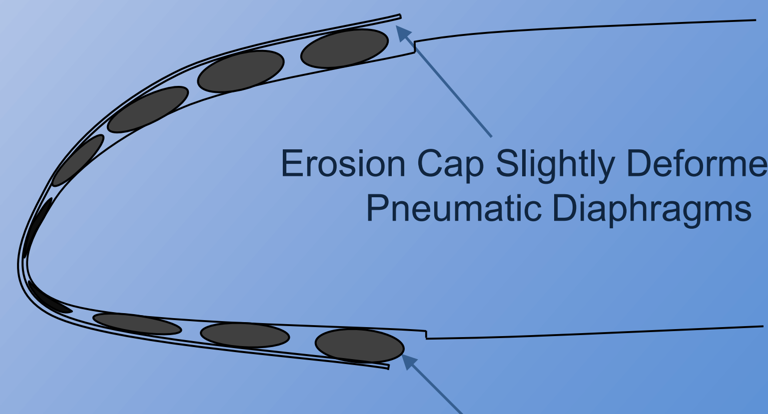
In operation, low internal blade pressure will pull the system (<= 0.2”) onto the leading edge

- Conforming airfoil shape
- No major rotor aerodynamic performance degradation

Goal: Design System Thin Enough to Replace Current Erosion Caps with Little or No Blade Redesign



Exaggerated Displacement

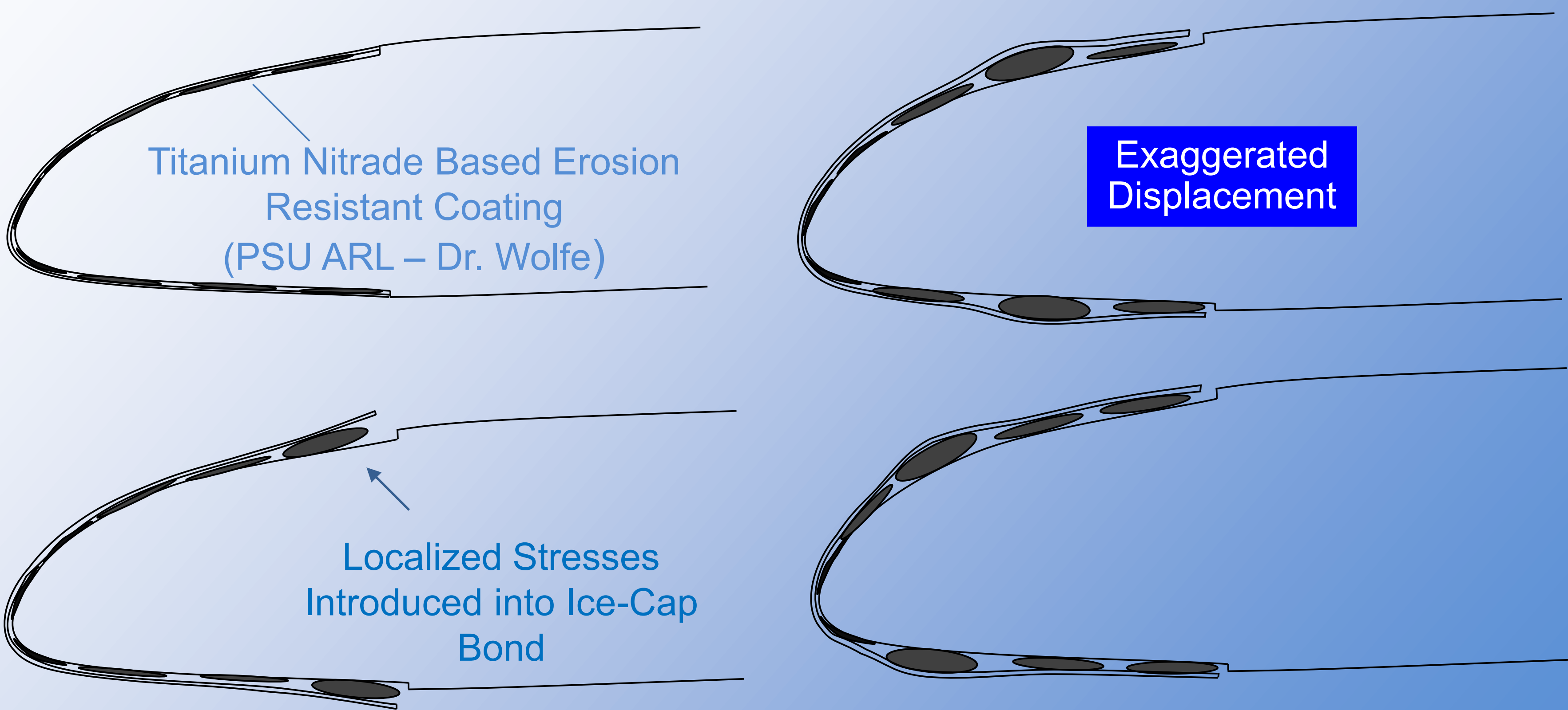


Erosion Cap Slightly Deformed by Pneumatic Diaphragms

Diaphragms inflated using Centrifugally Generated Pressure Differential

Pneumatic De-Icing Concept: Prototype II

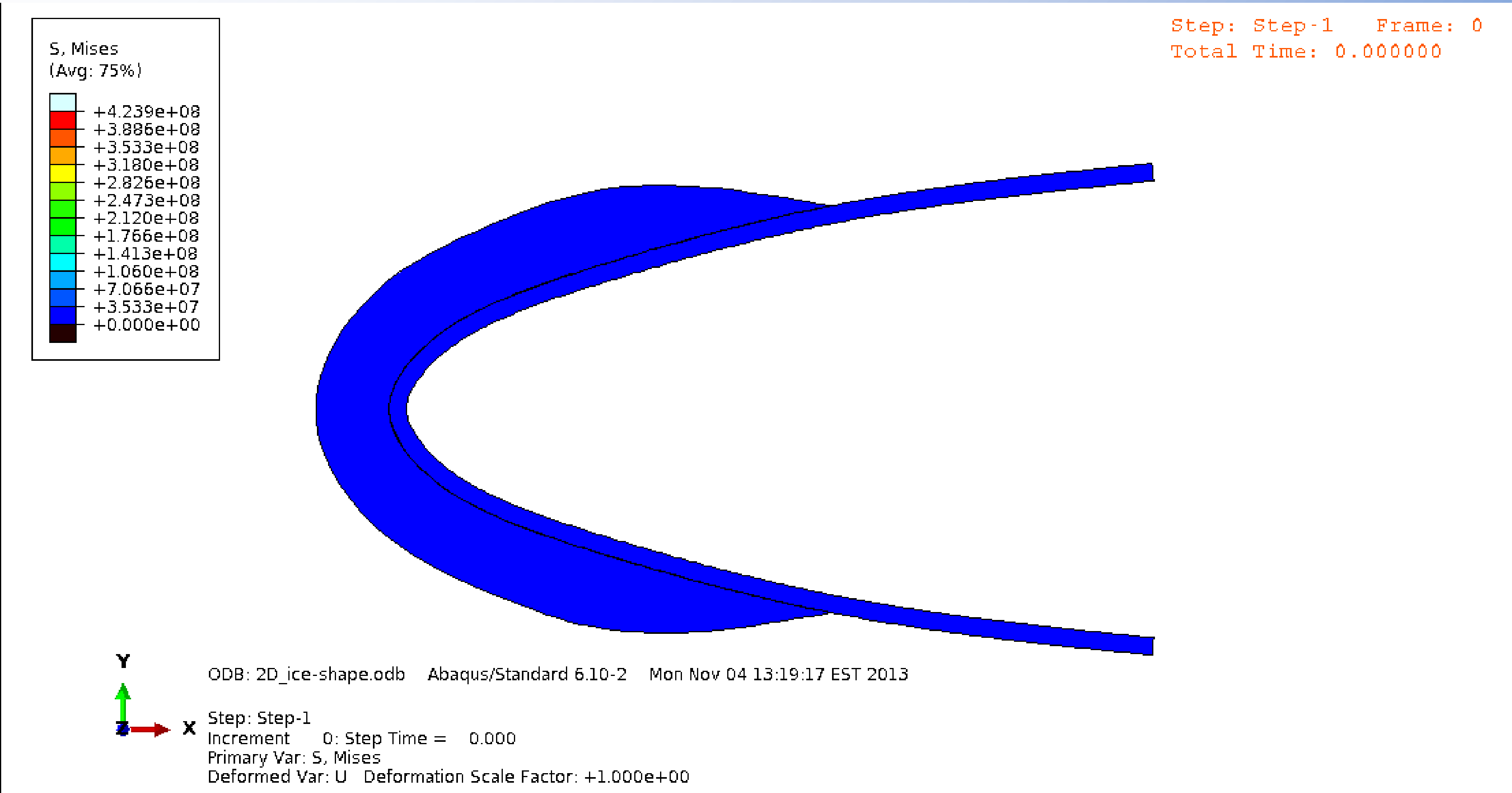
Deflection Modes: concentrate ice interface transverse shear stresses at desired chord locations



FEM Modeling

Cohesive zone method FEM

Barbero, E., "Finite Element Analysis of Composite Materials," 2008, ISBN 9781420054330, xxv, 331

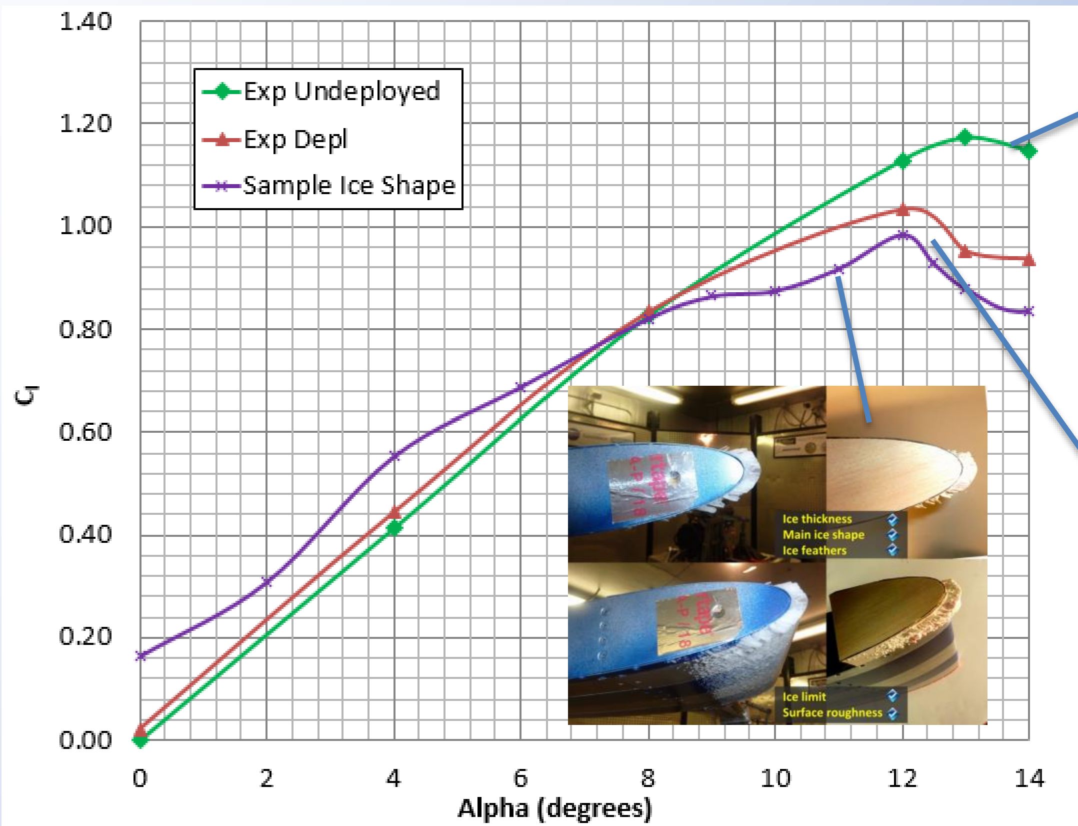


Aerodynamic Testing Prototype II

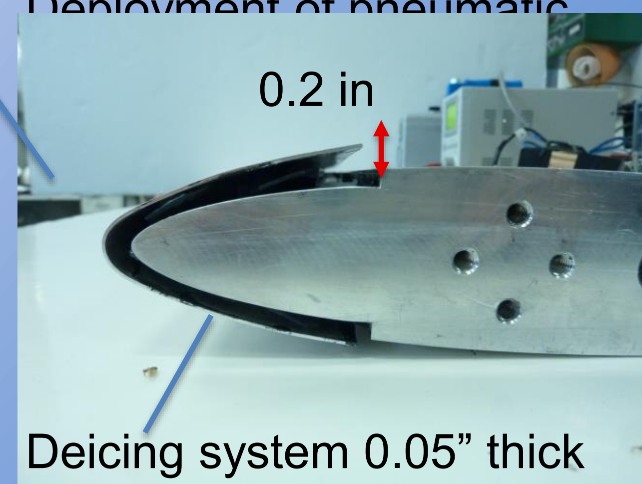
Aerodynamic Testing Prototype II: Results

NASA Aeronautics Research Institute

Cl vs Angle of Attack



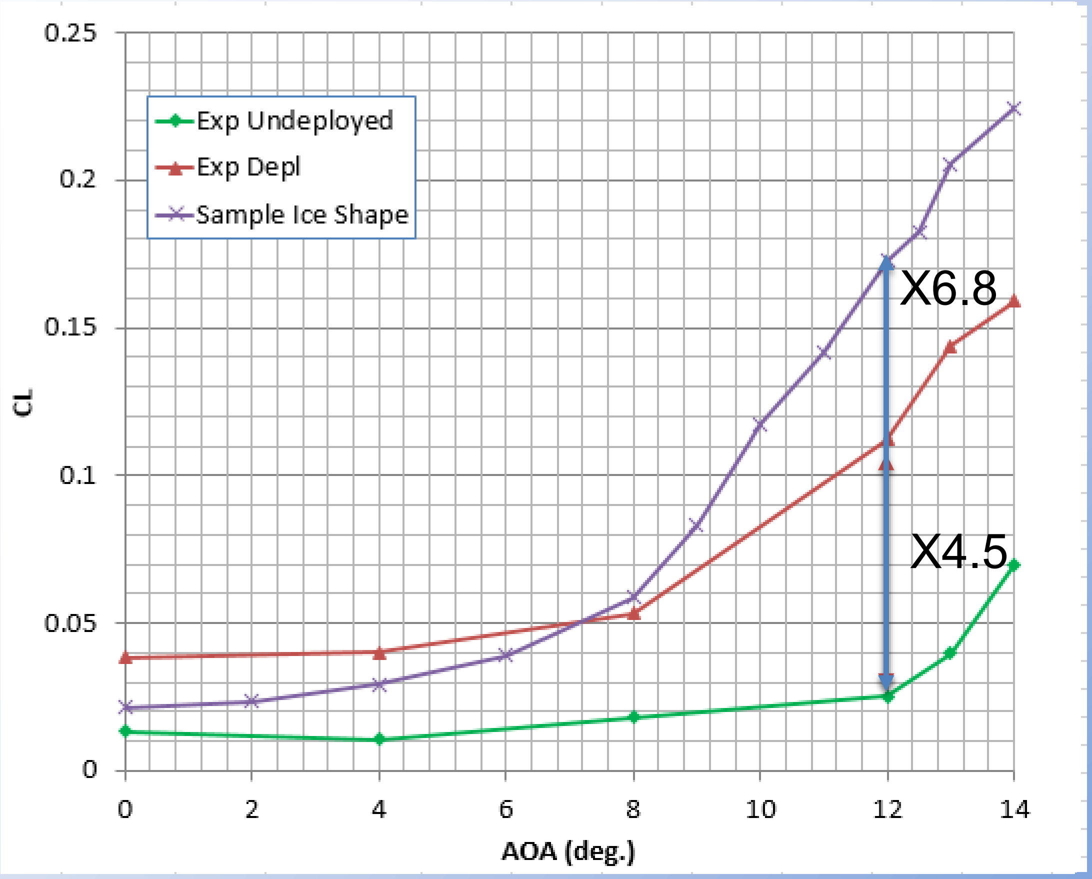
Deployment of pneumatic



Aerodynamic Testing Prototype II: Results

NASA Aeronautics Research Institute

Cd vs Angle of Attack



Deployment of pneumatic deicing degrades the drag performance of the airfoil.

The performance penalty does not exceed the degradation related to ice accretion.

NASA Aeronautics Research Institute

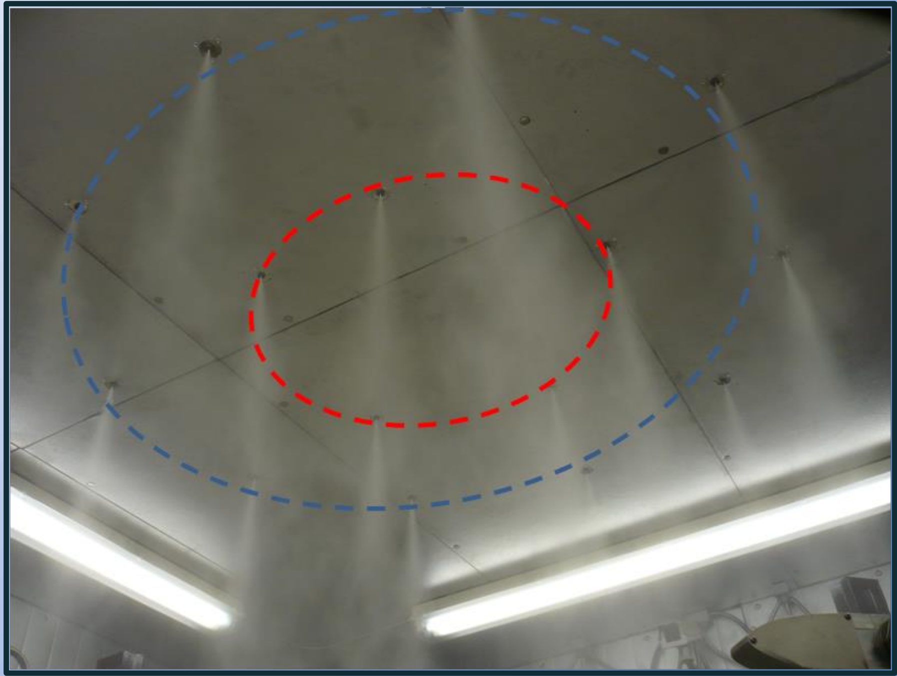
Agenda

- Background and Motivation
- Objectives
- Prototype Design/Fabrication
- Aerodynamic Testing
- **Rotor Ice Testing Results**
- Erosion Testing
- Conclusions

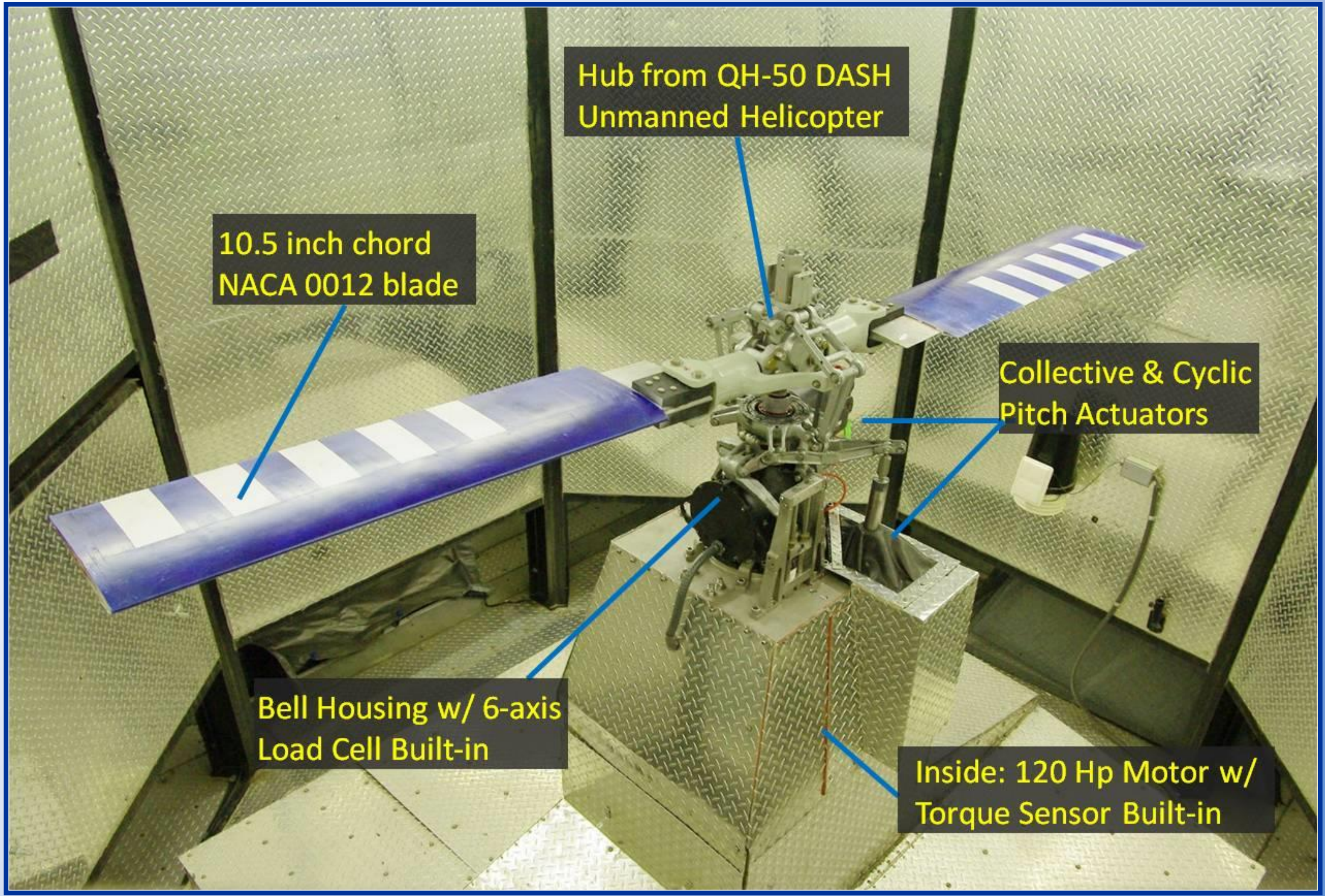
Testing Facility

Parameter	Range
LWC [g/m^3]	0.1 ~ 5 (increments of 0.2)
MVD [μm]	10 ~ 50
Temperature [° C]	-20 ~ 0
Rotor Speed [RPM]	200 ~ 1200
Blade Diameter	3 [m] / 10 [ft]
Blade chord	12.4 ~ 81.3 [cm] / 4.9 ~ 32[in]


Control Room

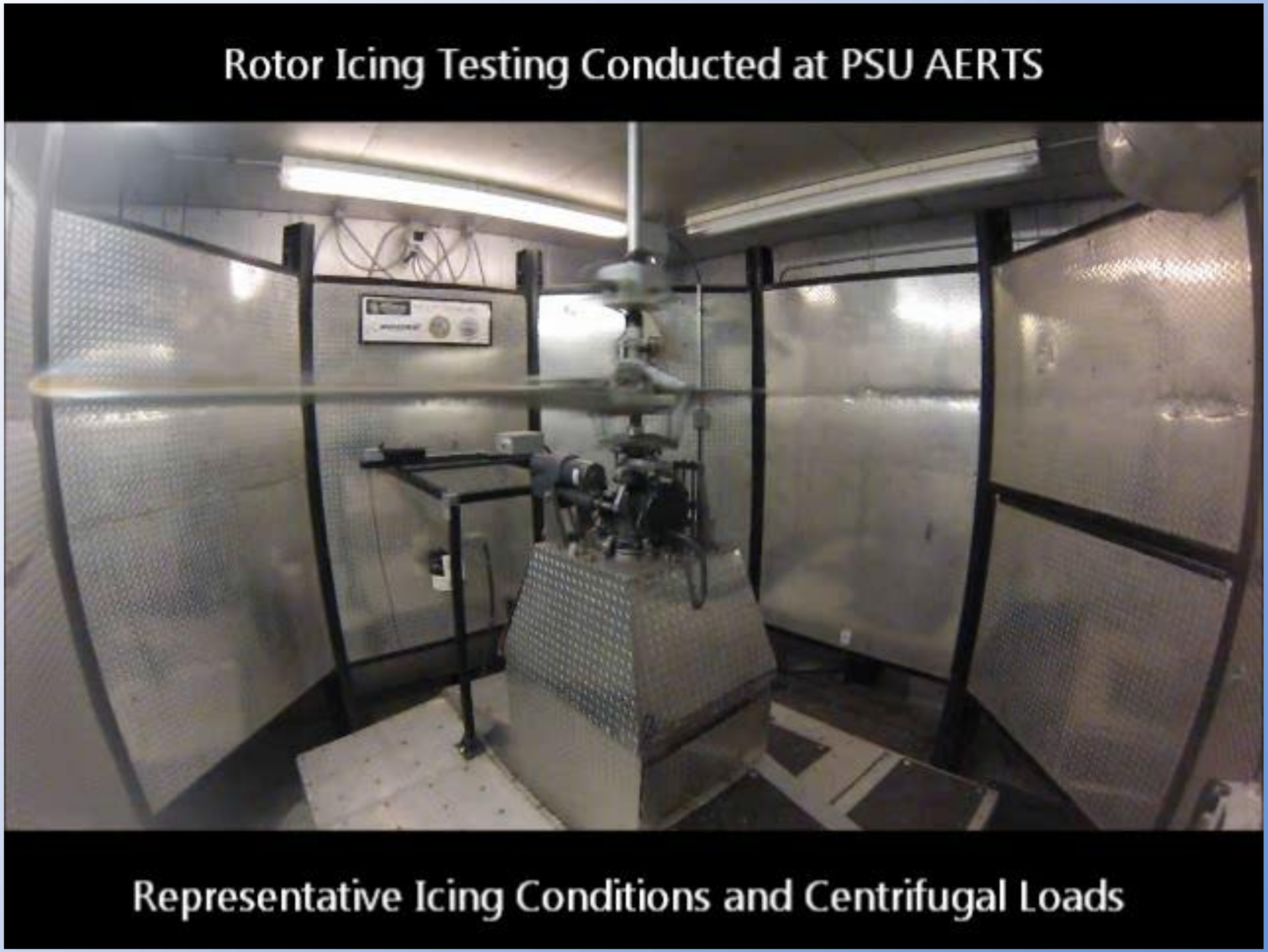

Icing Nozzles control LWC and MVD

- Signal and Power Transmission: 48 signal / 24 power channel slip ring
- Measurement Instrument: Shaft torque sensor / 6-axis load cell
- **Facility proven to create representative icing conditions (and ice shapes)**


Hub from QH-50 DASH
Unmanned Helicopter
10.5 inch chord
NACA 0012 blade
Collective & Cyclic
Pitch Actuators
Bell Housing w/ 6-axis
Load Cell Built-in
Inside: 120 Hp Motor w/
Torque Sensor Built-in

AERTS Facility Video

NASA Aeronautics Research Institute



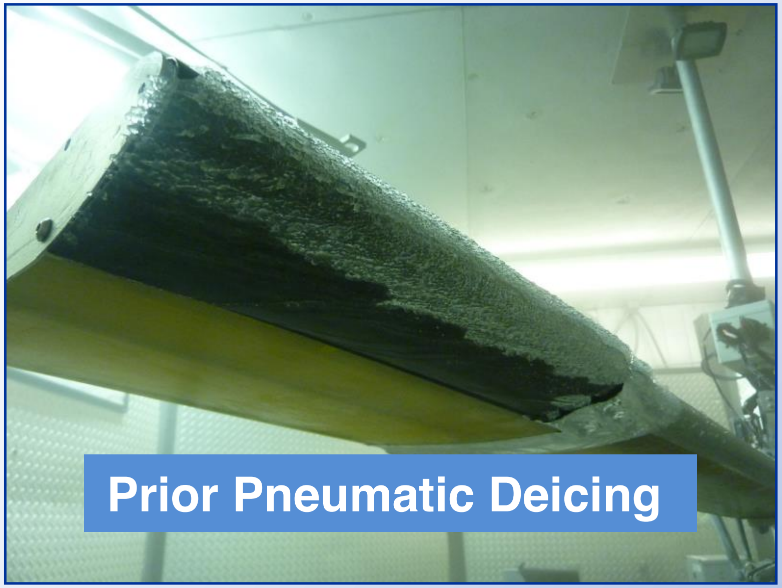
Sample Result

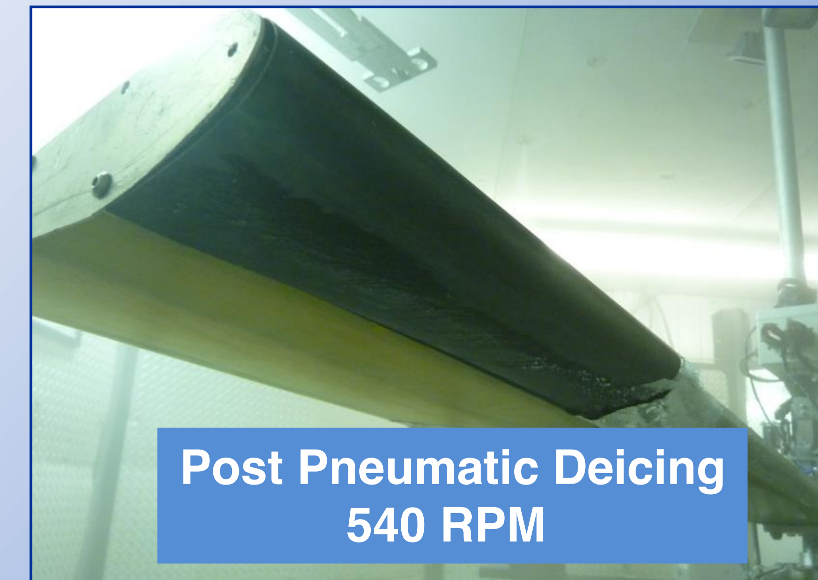
NASA Aeronautics Research Institute

Pneumatic Deicing wihout Centrifugal Loading

Sample Result

NASA Aeronautics Research Institute

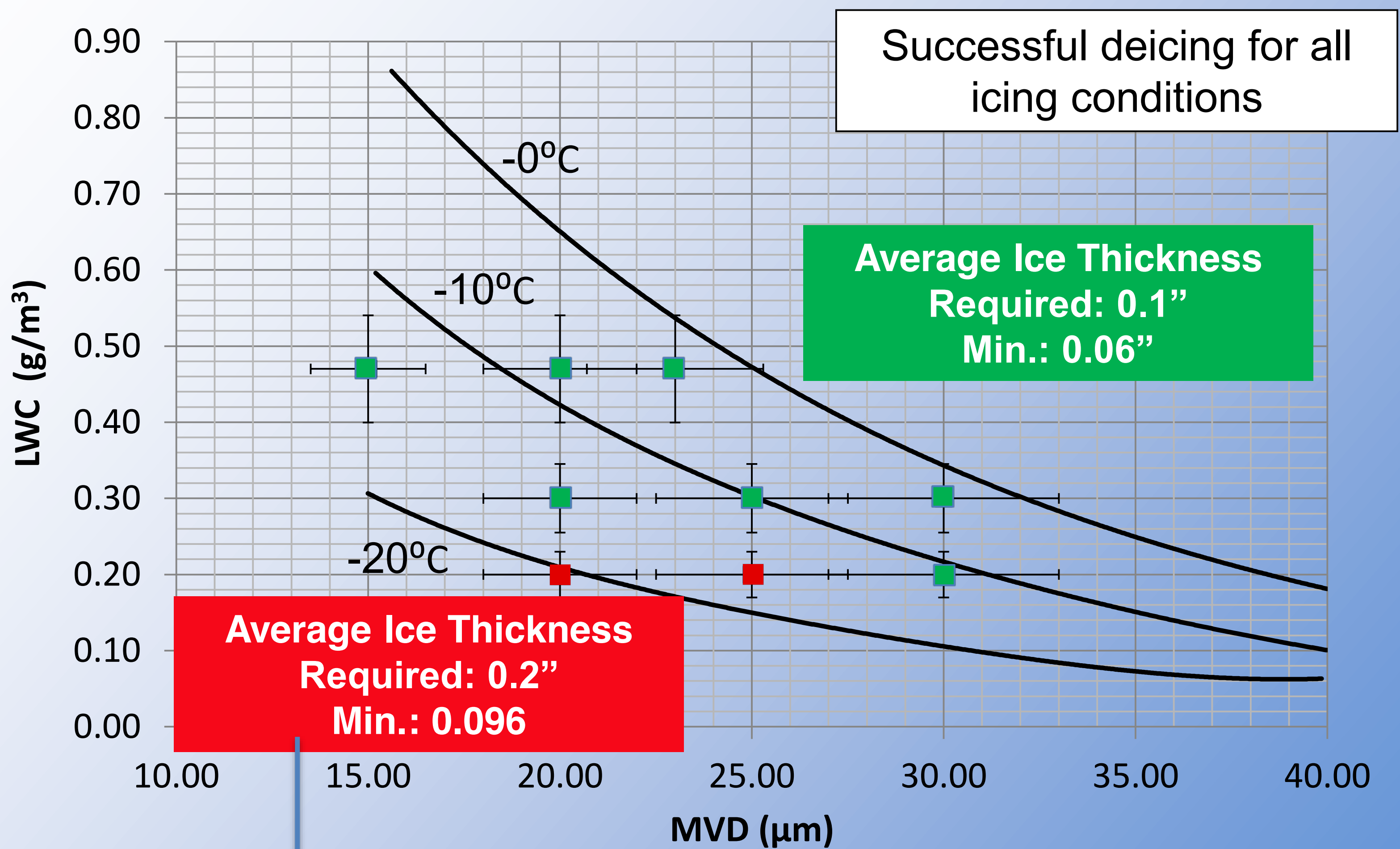




- Ice shedding was achieved at 250 RPM (20% CF) and 540 RPM (90% CF)
- Ice thickness as small as 0.06” were shed at temp. above -15 deg. C
- Air pressure used +/- 3.7 psi (representative rotor blade generation)
- Electrical power consumption: 2.9 Watts

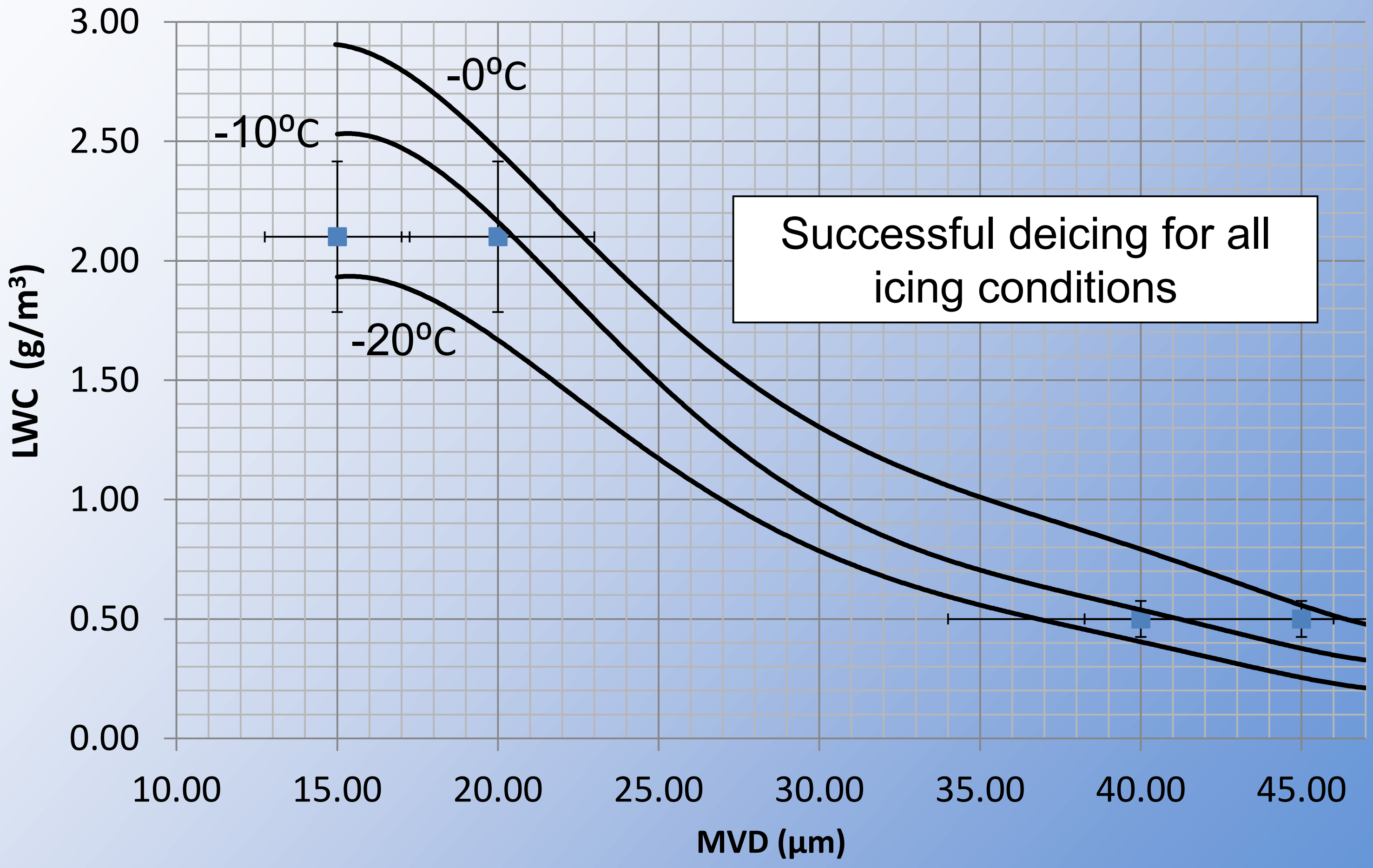
Continuous Icing Cloud Test Results

NASA Aeronautics Research Institute



Diaphragm material stiffens beyond pressure capabilities at Temp. < -15º

Intermittent Icing Cloud Test Results



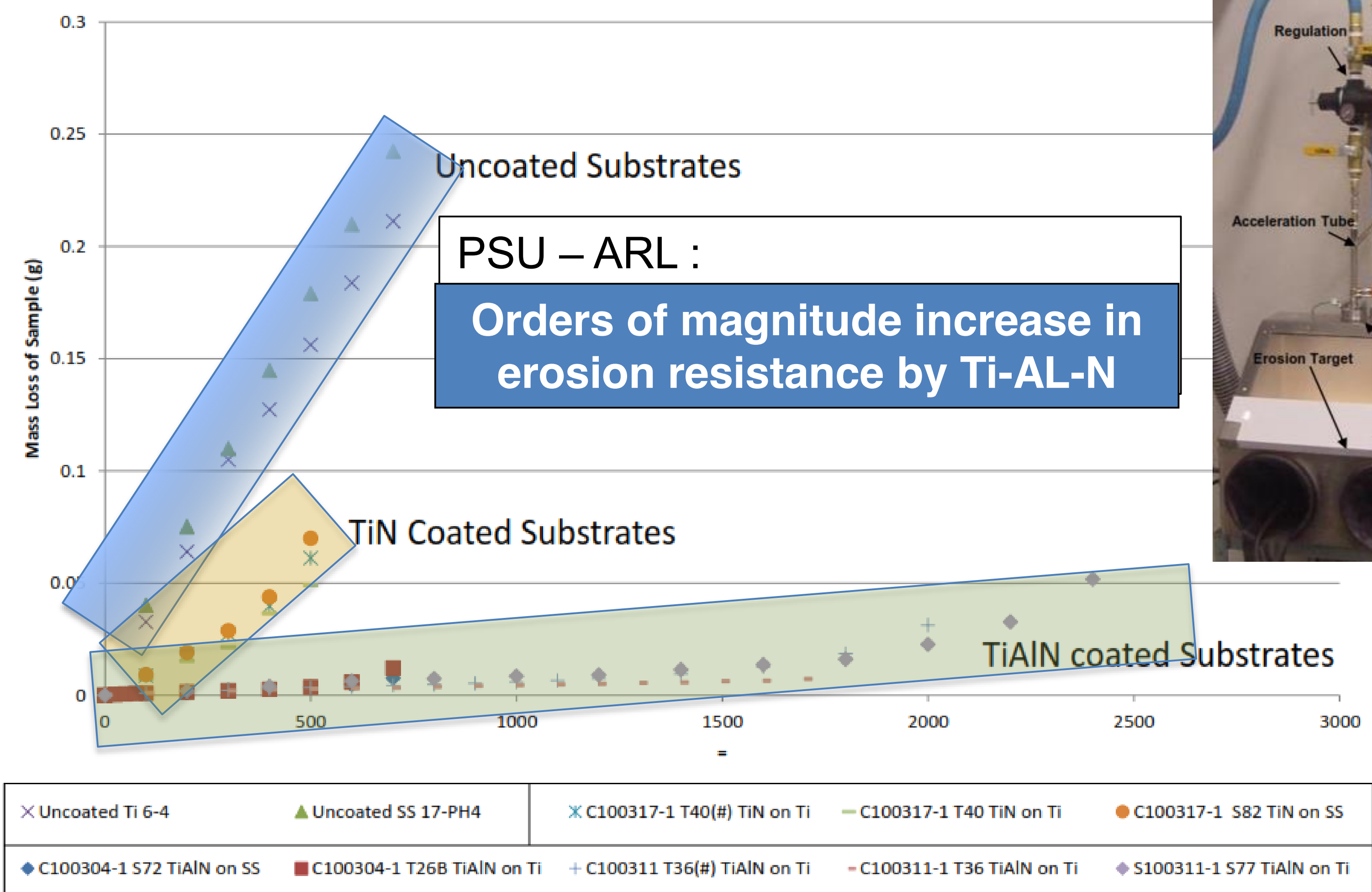
Agenda

- Background and Motivation
- Objectives
- Prototype Design/Fabrication
- Aerodynamic Testing
- Rotor Ice Testing Results
- Erosion Testing
- Conclusions

Proof-of-concept: Erosion Resistance Coating

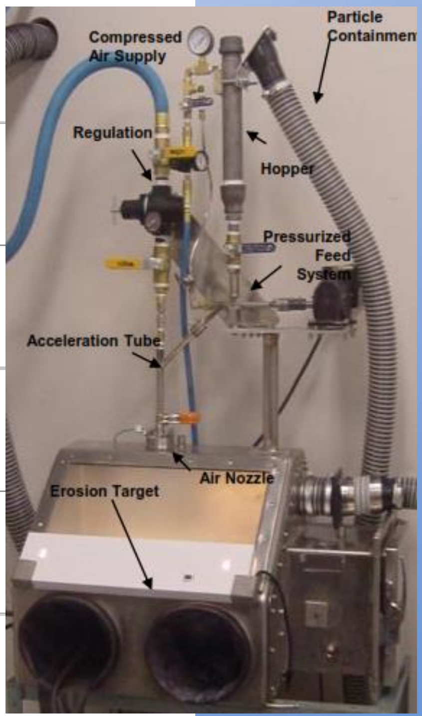
NASA Aeronautics Research Institute

Erosion data, 30 degrees, 156m/s, 240 grit (50um) alumina, 1.125" wear diameter, 9" Stand-off distance, 100g/min feed



PSU – ARL :

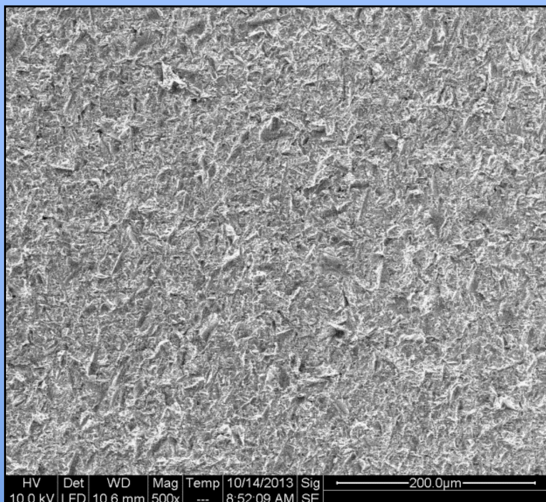
Orders of magnitude increase in erosion resistance by Ti-AL-N

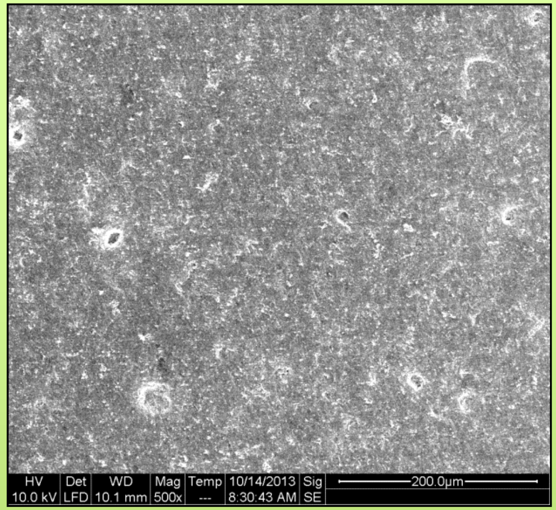


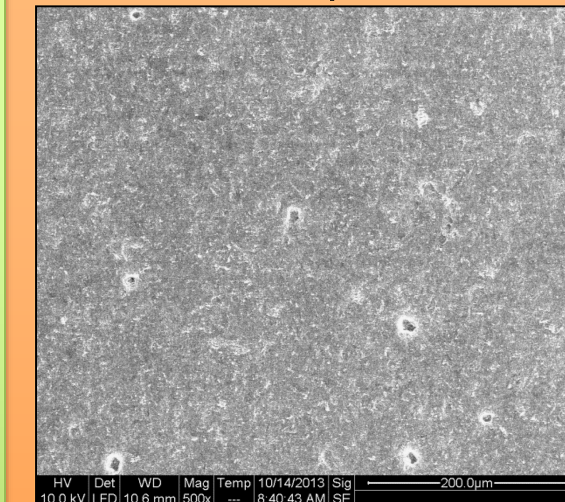
Erosion Testing Ti-AL-N Coating: SEM Surface Morphology 500 g. Exposure

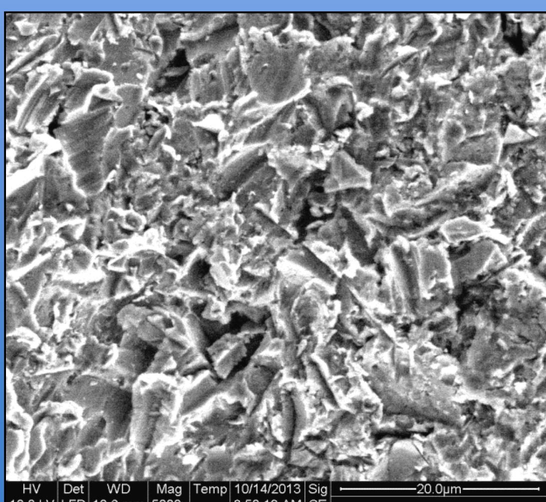
NASA Aeronautics Research Institute

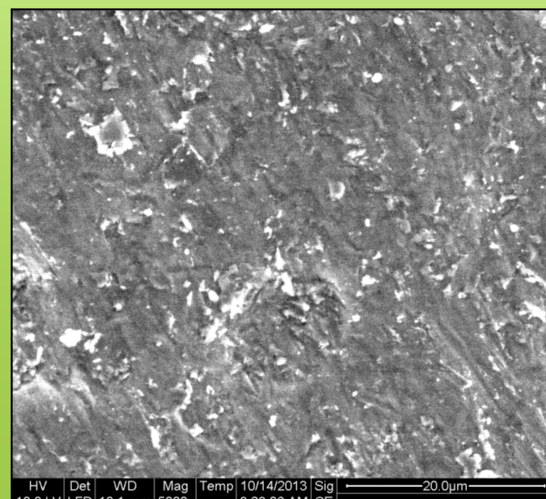
Uncoated Ti	Ti-AL-N: 100µin Thick	Ti-AL-N: 200µin Thick

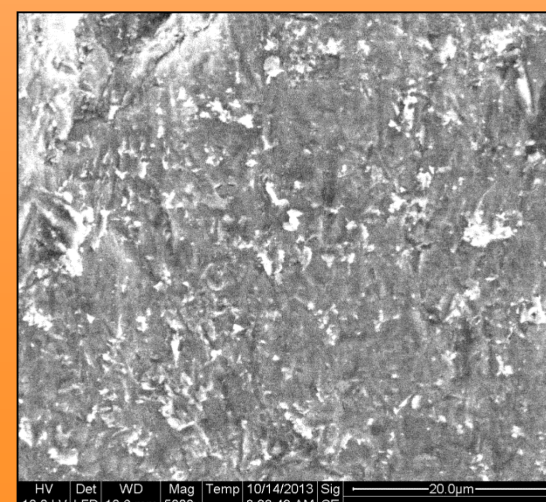












30 degrees, 156m/s, 50 µm alumina, 0.5 wear diameter, 9” stand-off distance, 100g/min

NASA

Conclusions

PENNSTATE 1855

NASA Aeronautics Research Institute

- Smooth leading edge configurations are critical to avoid aerodynamic performance degradation of the blade
- Aerodynamic performance degradation due to system deployment was less than the effects of the ice accretion
- The proposed pneumatic deicing configuration is able to delaminate ice accretion (Appendix C icing envelope) with input pressures as low as +/- 3.7 psi.
- Ice thickness as small as 0.06 in. were successfully removed for temperatures above -15 deg. C.
- The maximum ice thickness needed to promote ice delamination at colder temperatures could reach up to 0.2 in. (comparable to ice accretion allowed by electrothermal deicing).
- The larger ice thickness requirements are attributed to the stiffening of the prototype diaphragm used
- The system performed at 90% and 20% representative CF loads
- Ti-AL-N shows orders of magnitude improvement on sand erosion resistance compared to Ti → allows for a reduction in thickness of the Ti substrate

Goal: Full-scale proof-of-concept testing

– Design system with temperature rated diaphragms
– Access a whirl tower in cold climates
– Full-scale rotor blades to be modified to accommodate pneumatic de-icing
– Design portable cloud generators
– Design an optimized de-icing system (FEM)
– Perform full-scale rotor blade pneumatic deicing
– Rock and small ballistic Impact testing

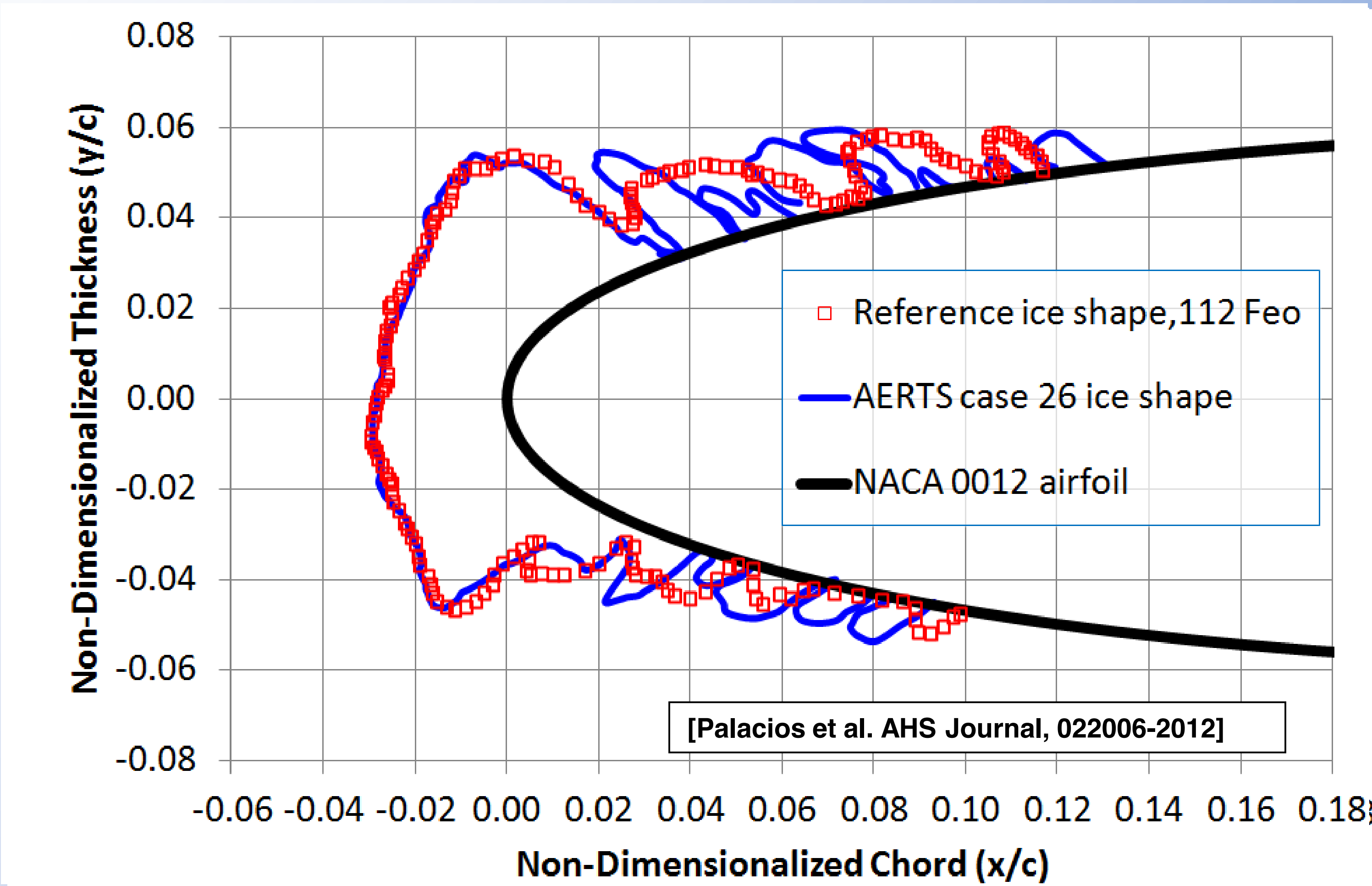
Distribution/Dissemination

- Soltis, J., Palacios, J., Wolfe, D., Eden, T., "Evaluation of Ice Adhesion Strength on Erosion Resistant Materials," AIAA-2013-1509, 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2013, Boston, Massachusetts, April 8 – 11, 2013.
- Abstract submitted to the American Helicopter Society 70th Forum.
- Briefing given to Bell on April 2013
- Briefing given to Sikorsky on June 2013
- Briefing given to Boeing on July 2013
- Rotor Icing and Protection Demonstration given to Boeing on September 2013
- Rotor Icing and Protection Demonstration to be given to NASA and GE on Nove – Dec 2013 (POSTPONED)

Questions?

NASA Aeronautics Research Institute

Ice Shape Correlation: Facility Validation



Case	Chord	MVD	LWC	Temp.	V	Time	AOA	RPM
26, 112	10.5"	27	0.96	-8.2	56.9	4.2'	0	417.21