Overview of Icing Research at NASA Glenn

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Icing Branch

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Outline

- The Icing Problem
- Types of Ice
- Icing Effects on Aircraft Performance
- Icing Research Facilities
- Icing Codes

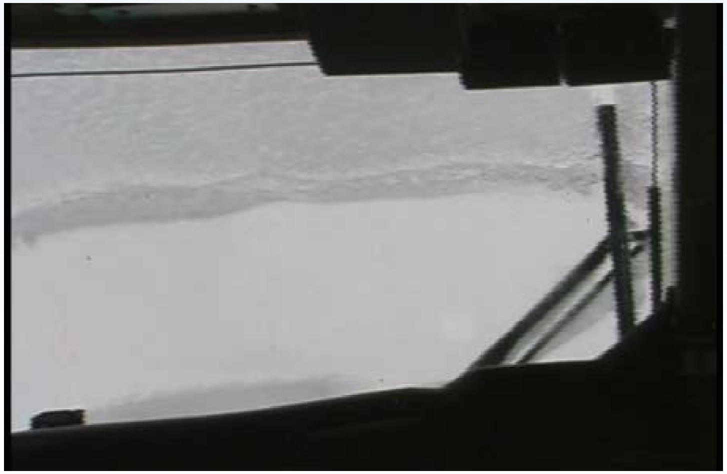
Aircraft Icing

Ice build-up results in significant changes to the aerodynamics of the vehicle

This degrades the performance and controllability of the aircraft

Aircraft Icing

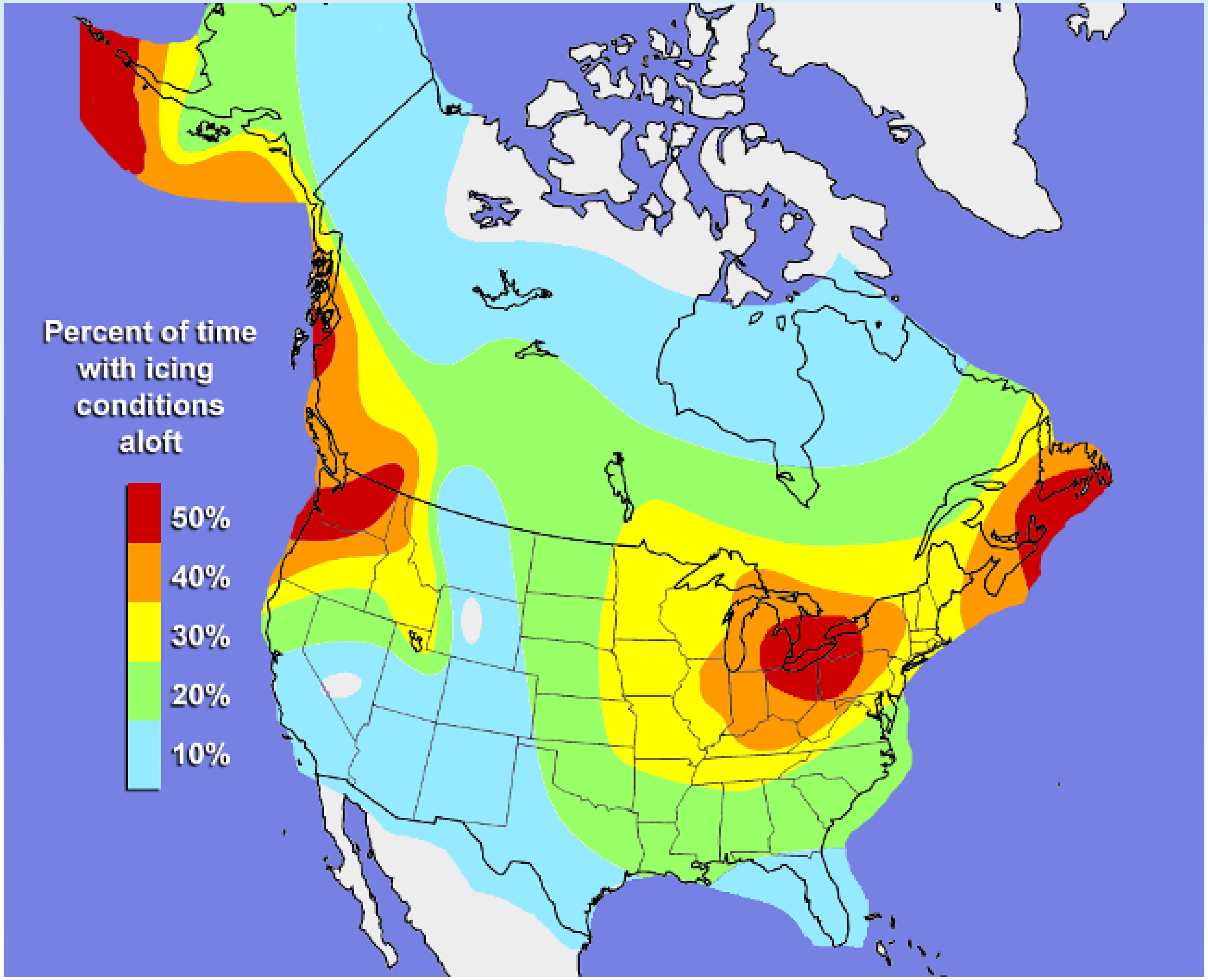
During an in-flight encounter with icing conditions, ice can build up on all unprotected surfaces.



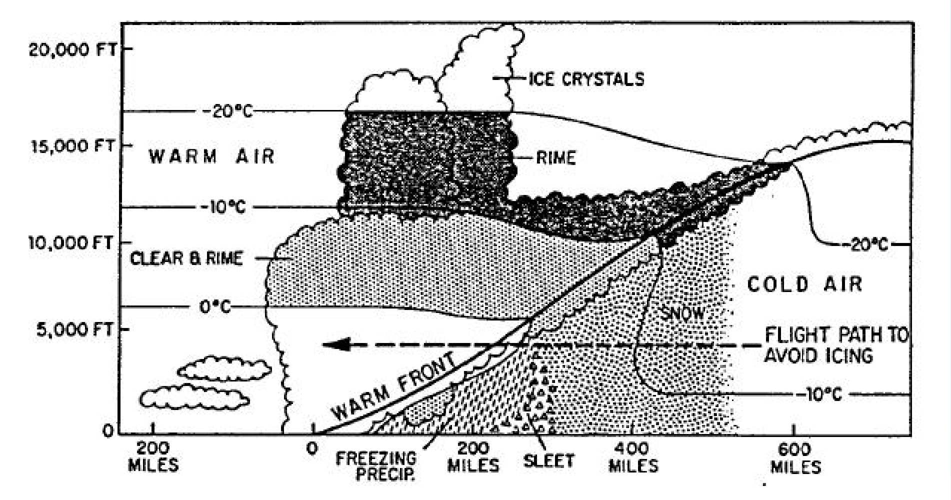
Recent Commercial Aircraft Accidents

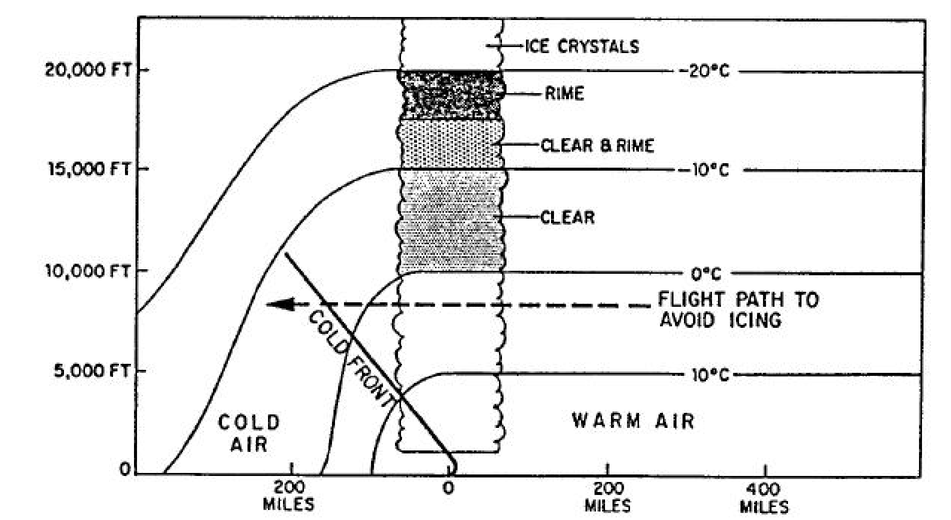
- ATR-72: Roselawn, IN; October 1994
  - 68 fatalities, hull loss
  - NTSB findings: probable cause of accident was aileron hinge moment reversal due to an ice ridge that formed aft of the protected areas
- EMB-120: Monroe, MI; January 1997
  - 29 fatalities, hull loss
  - NTSB findings: probable cause of accident was loss-of-control due to ice contaminated wing stall
- EMB-120: West Palm Beach, FL; March 2001
  - 0 fatalities, no hull loss, significant damage to wing control surfaces
  - NTSB findings: probable cause was loss-of-control due to increased stall speeds while operating in icing conditions (8K feet altitude loss prior to recovery)
- Bombardier DHC-8-400: Clarence Center, NY; February 2009
  - 50 fatalities, hull loss
  - NTSB findings: probable cause was captain’s inappropriate response to icing condition

Where Does Icing Occur?



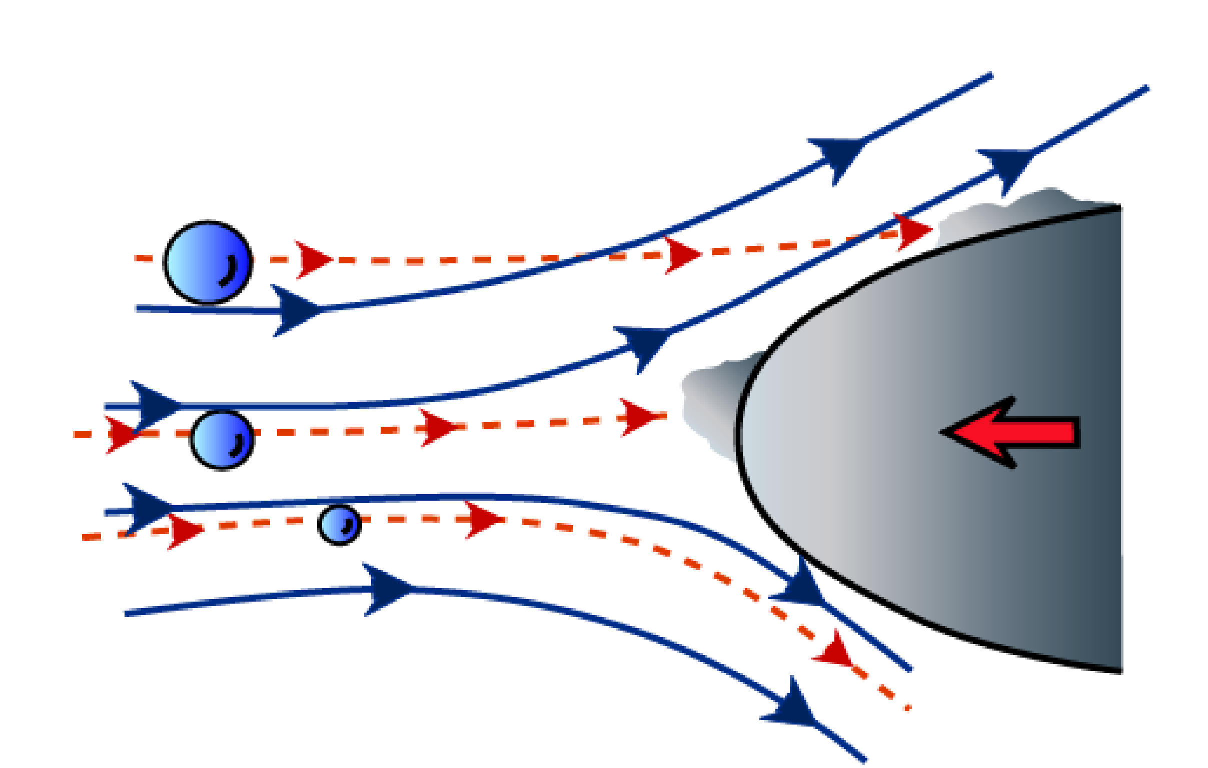
Where Does Icing Occur?





How Ice Forms

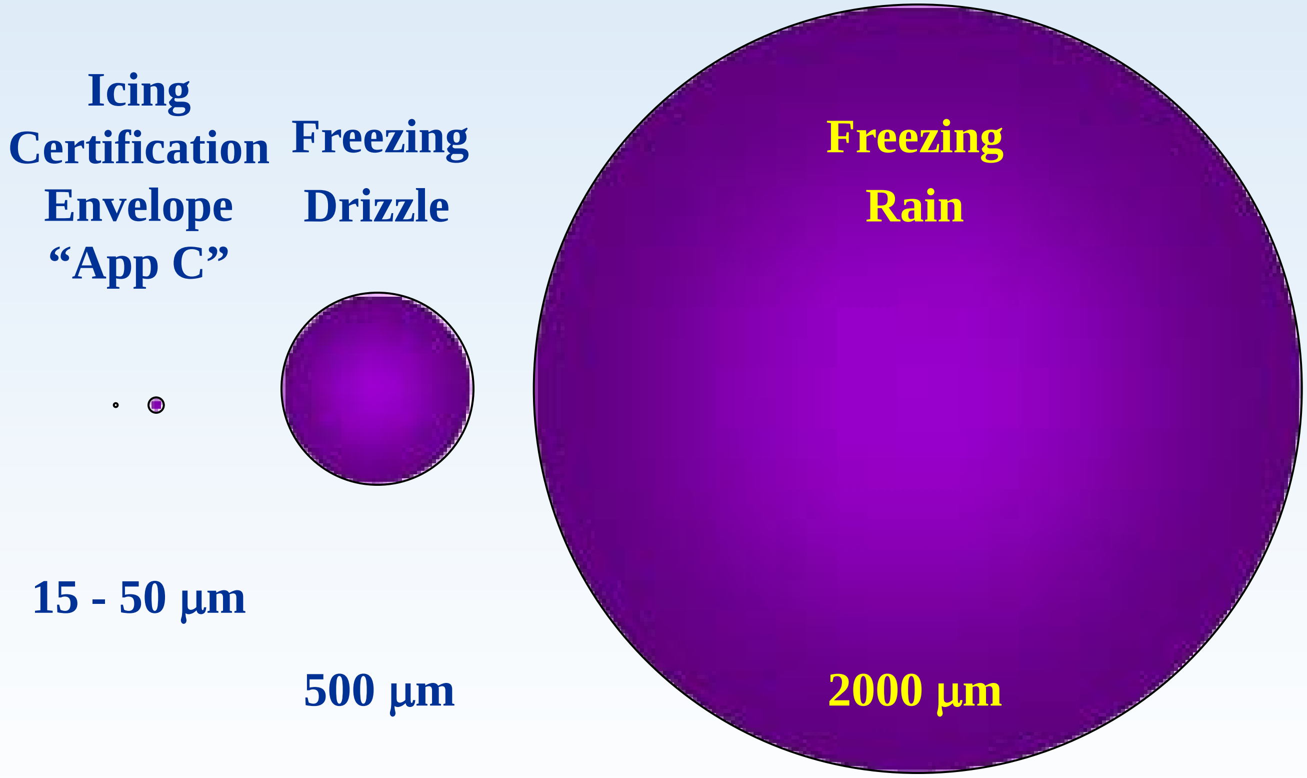
- In visible moisture (cloud & precip)
- Temperature range around -20° to +2°C
- Cloud contains supercooled liquid water, ice crystals



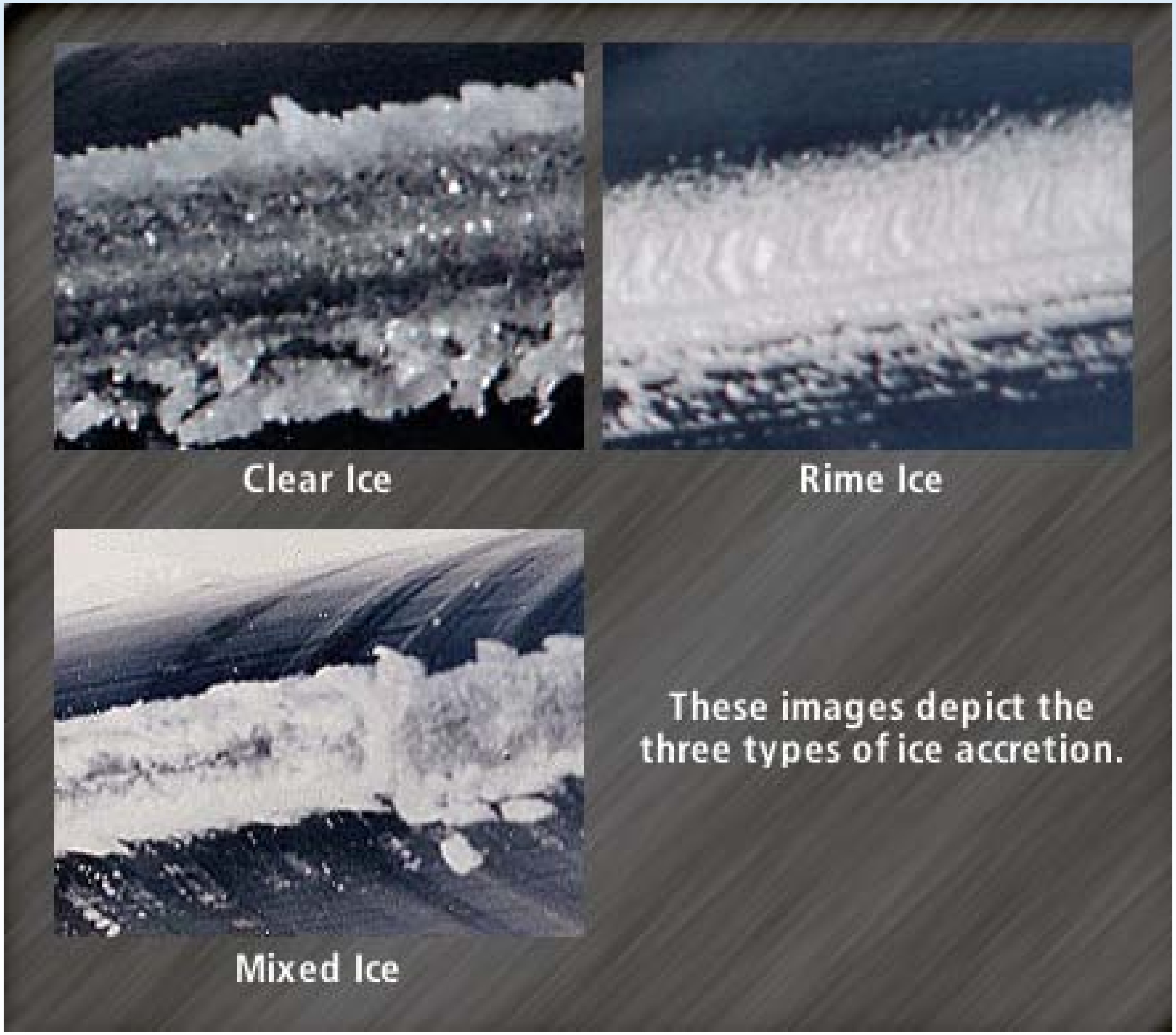
Ice Accretion Parameters:

- Velocity
- Drop Size (MVD)
- Liquid Water Content
- Temperature
- Accretion Time

How Ice Forms

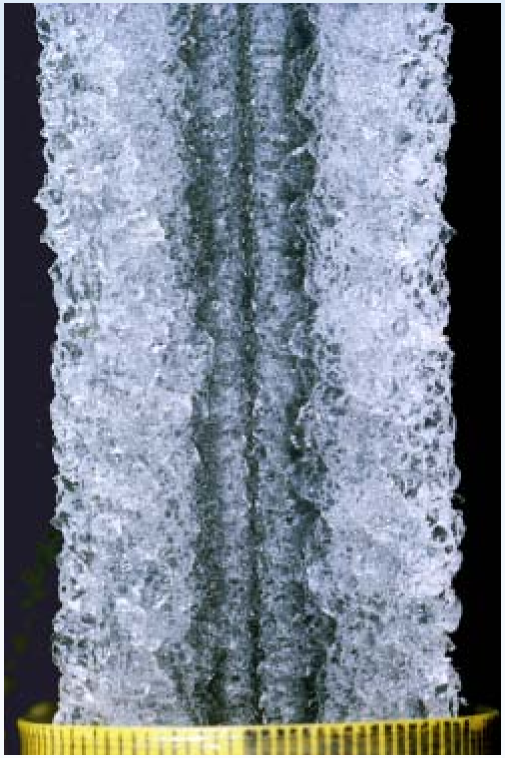


Types of Ice Accretions

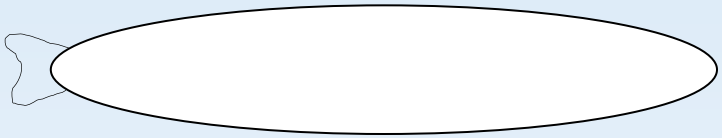


Types of Ice Accretions

Glaze (Clear) Ice



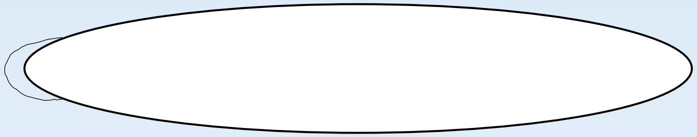
V=225 mph
T_{total}=25 ^{O}F
LWC=0.75 g/m^3
MVD=20 μm
τ=5 minutes

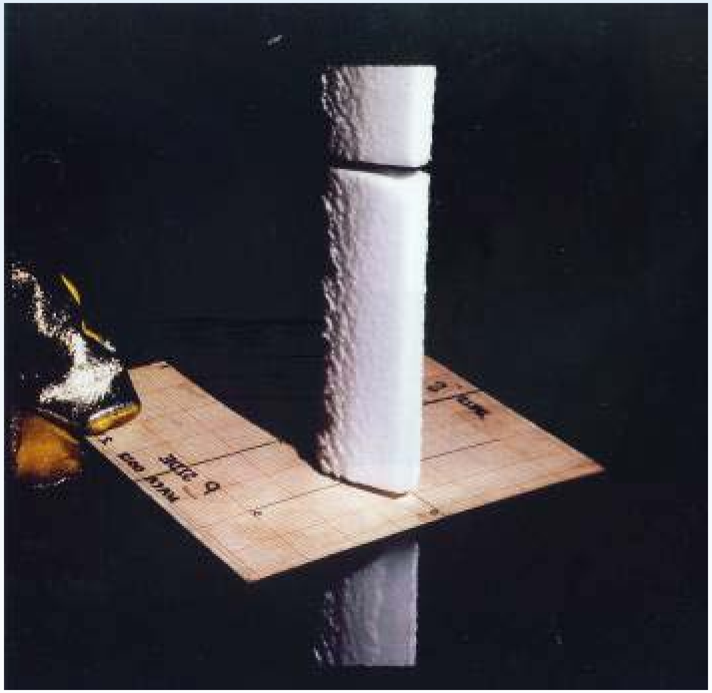


- In general occurs at temperatures near 32^{o}F and high LWCs
- Clear everywhere
- Horns may appear
- Drops do not freeze on impact
- Surface tends to be covered with roughness elements
- Physical mechanism of formation not well understood

Types of Ice Accretions

Rime Ice





From Bidwell

- **In general occurs at temperatures below -10º F**
- **White and opaque**
- **Horns do not appear**
- **Drops freeze on impact**
- **Surface tends to be smoother than for glaze ice**
- **Physical mechanism of formation well understood**

Types of Ice Accretions

Mixed Ice

- Ice accretion exhibits glaze ice around stagnation line and rime ice away from it

- Clear near the stagnation line, white and opaque away from it

- Horns may appear

V=150 mph

T_{total}= 5 ^{O}F

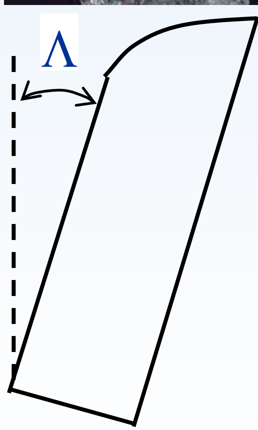
LWC=0.75 g/m^3

MVD=20 μm

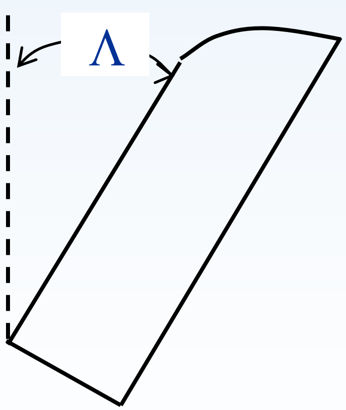
τ=2 minutes

Types of Ice Accretions

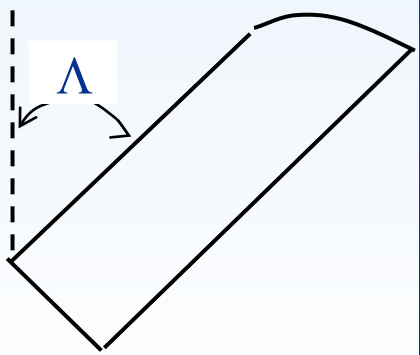
Swept Wing Icing



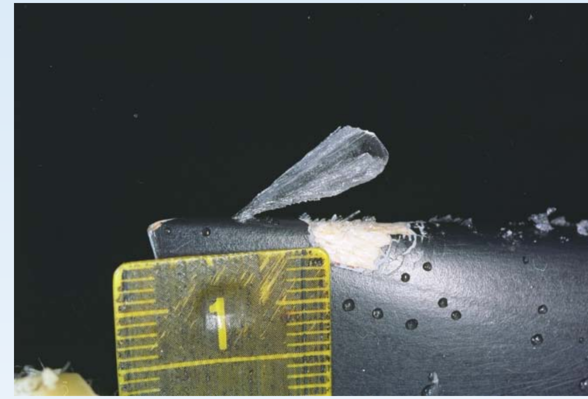
$\Lambda = 15^o$



$\Lambda = 30^o$



$\Lambda = 45^o$

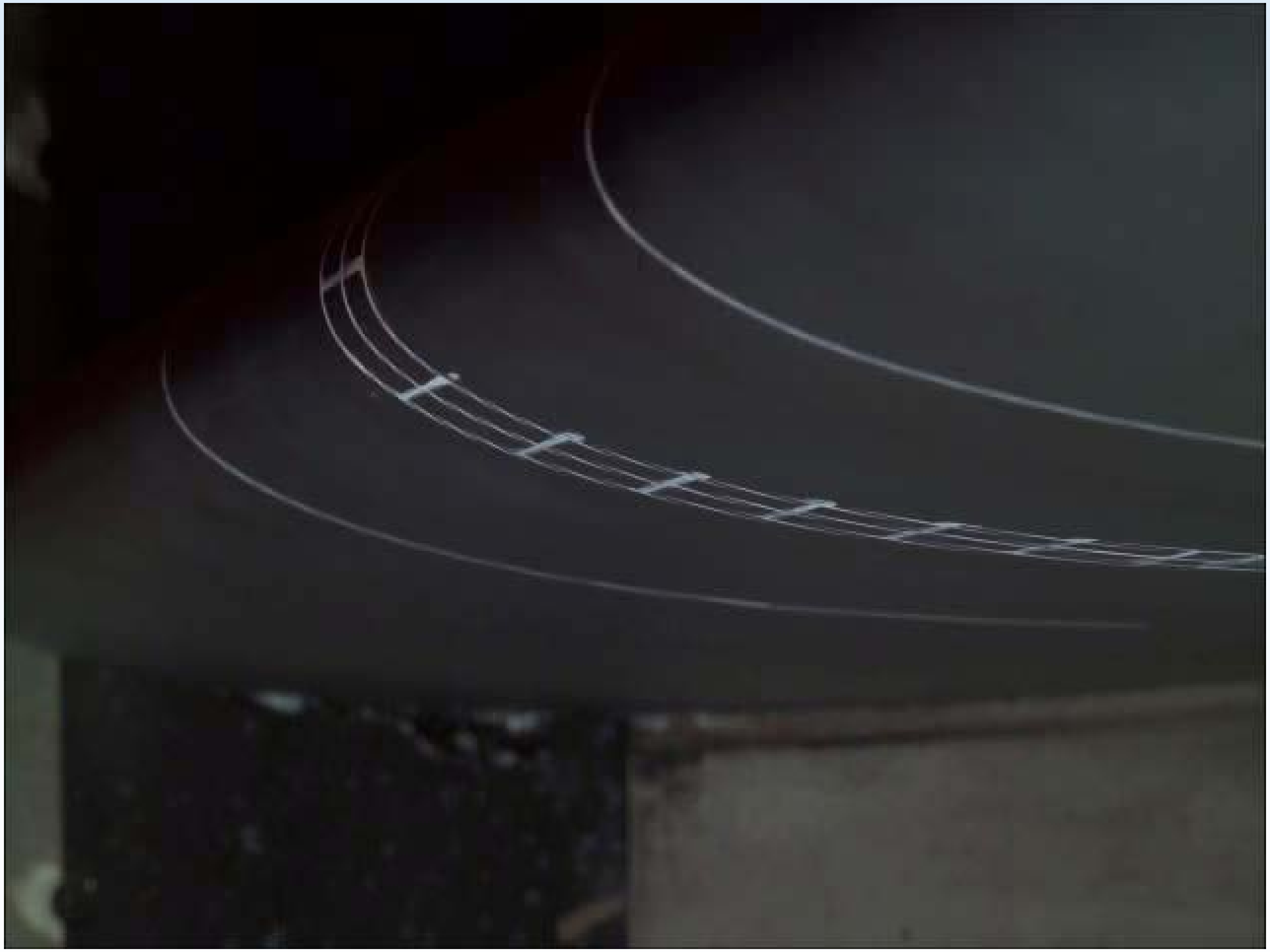


View from the side

View from behind

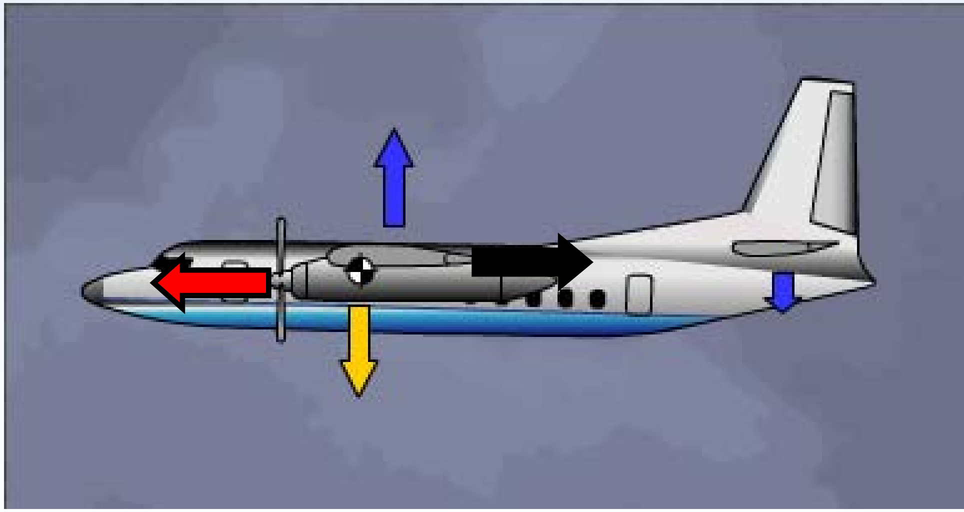
Types of Ice Accretions

Time Lapse



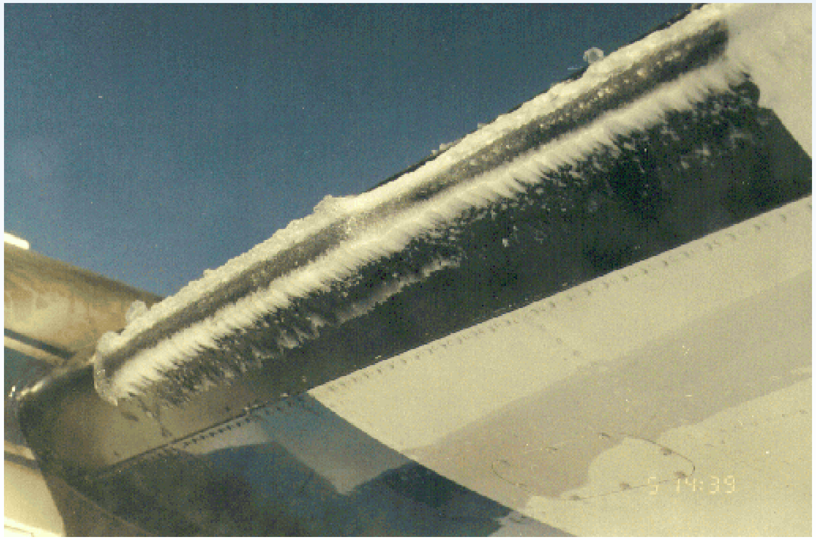
Icing Effects on Airplane Performance

- Reduce maximum Lift
  - Increase stall speed
  - Stall warn system may not compensate for ice
- Increases Drag
  - Reduces Climb rate
  - Reduces max speed
  - May reduce speed to the point of stall.
- Increases Weight
  - Usually not significant, fuel burn will offset
- Thrust
  - Increased thrust required, due to drag increase
  - GA aircraft are, typically, power limited

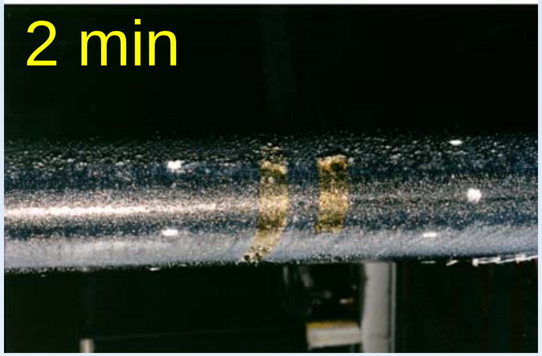


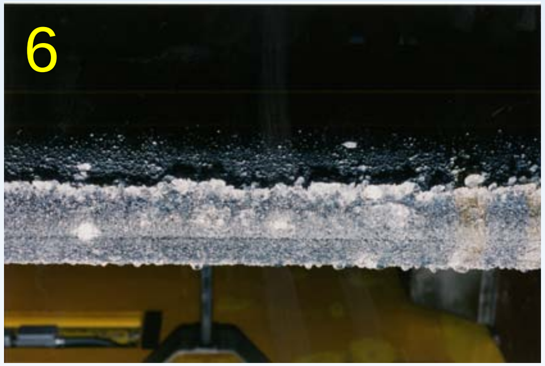
Icing Effects on Airplane Performance

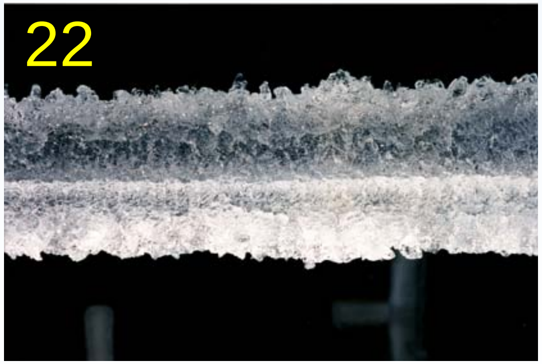
Drag from unprotected surfaces



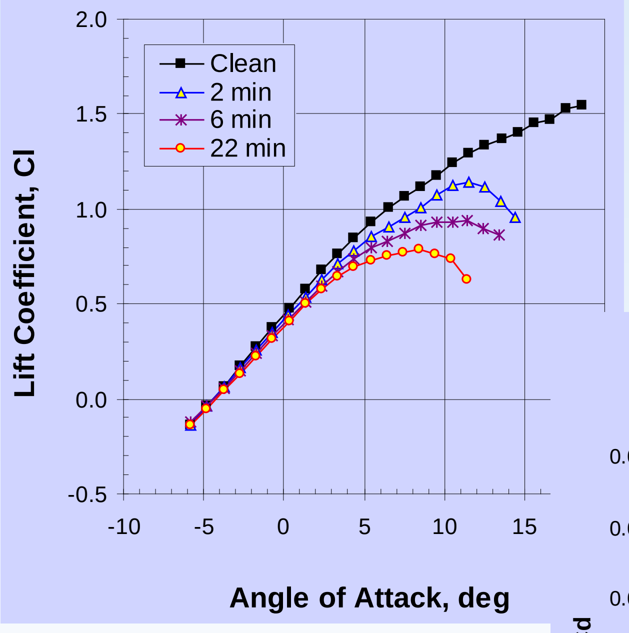
Icing Effects on Airplane Performance

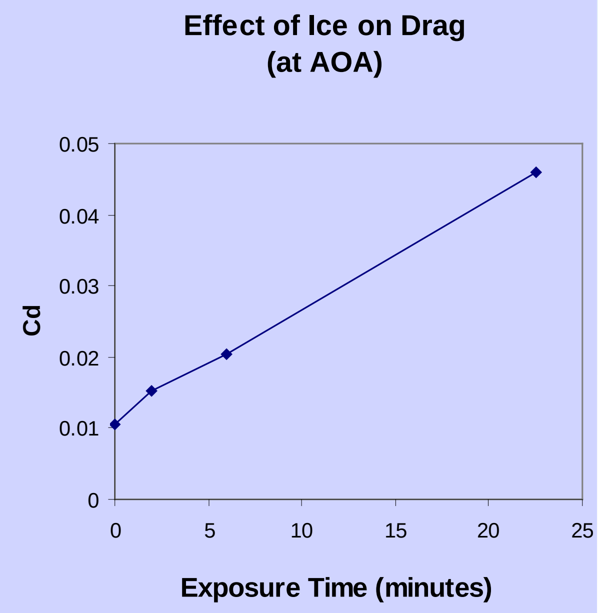






Performance Data on Wing

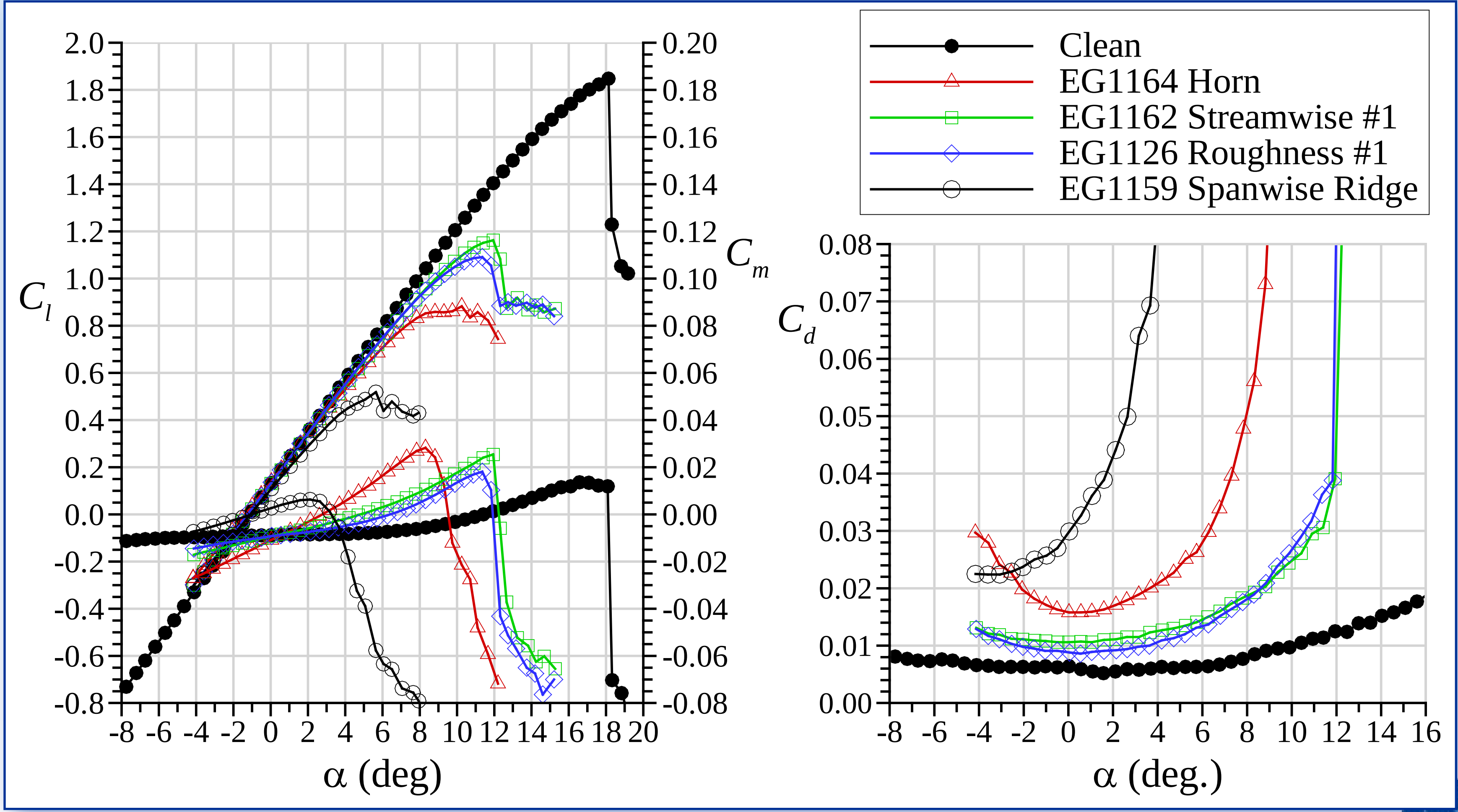




***Airfoil in Icing Research Tunnel**

Icing Effects on Airplane Performance

Comparison of iced-airfoil performance for Re = 15.9x10^6, M = 0.20



Icing Effects on Airplane Performance

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

1994 - ATR-72, Roselawn, IN

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

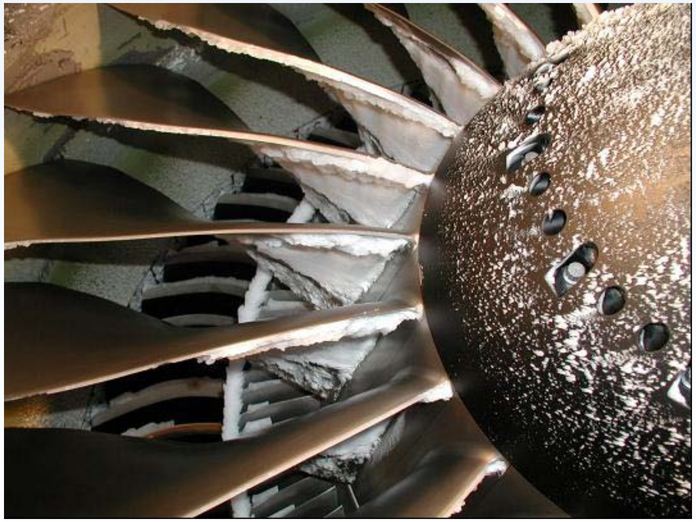
Ice Protection Systems

- Thermal (evaporative and running wet)
  - Heated air
  - Electrothermal
- Mechanical
  - Pneumatic
  - Ultrasonic
- Other
  - Freezing-point depressants

Engine Icing

- Ice crystal ingestion is a high priority area of research
- High ice water content occurs at high altitudes around large convective storms
- Over 200 power loss events since 1988

- Characterize the environment and develop capabilities to simulate and predict engine core ice accretion



Rotorcraft Icing

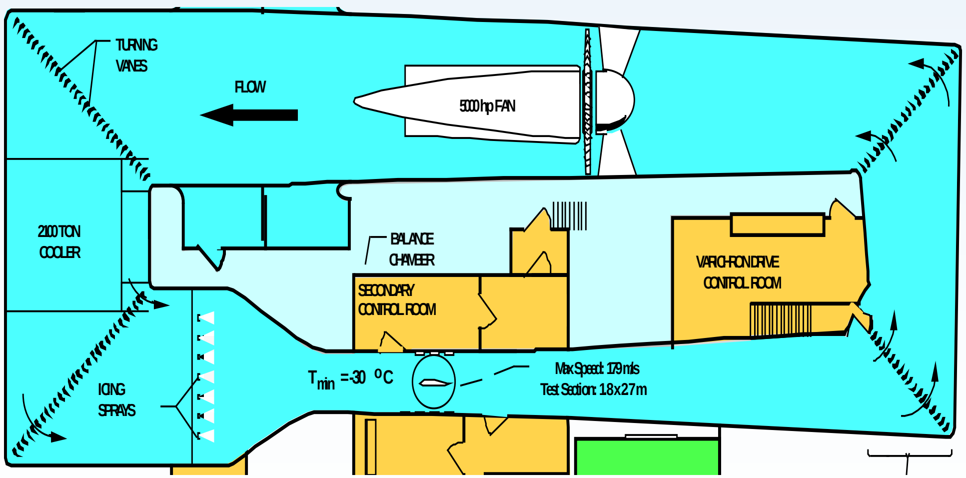
- Research objective is validated coupling of a rotor performance code with an ice accretion code

- Typically cannot fly fast enough (M > 0.6) to prevent icing by kinetic energy heating (except near the blade tips)
- Usually cannot gain enough altitude to fly above weather
- Helicopter operations often require remaining in an area for long periods of time
- Potential for severe vibration or damage due to ice shedding
- Smaller chord lengths

Icing Research Tunnel

<u>Capabilities:</u>

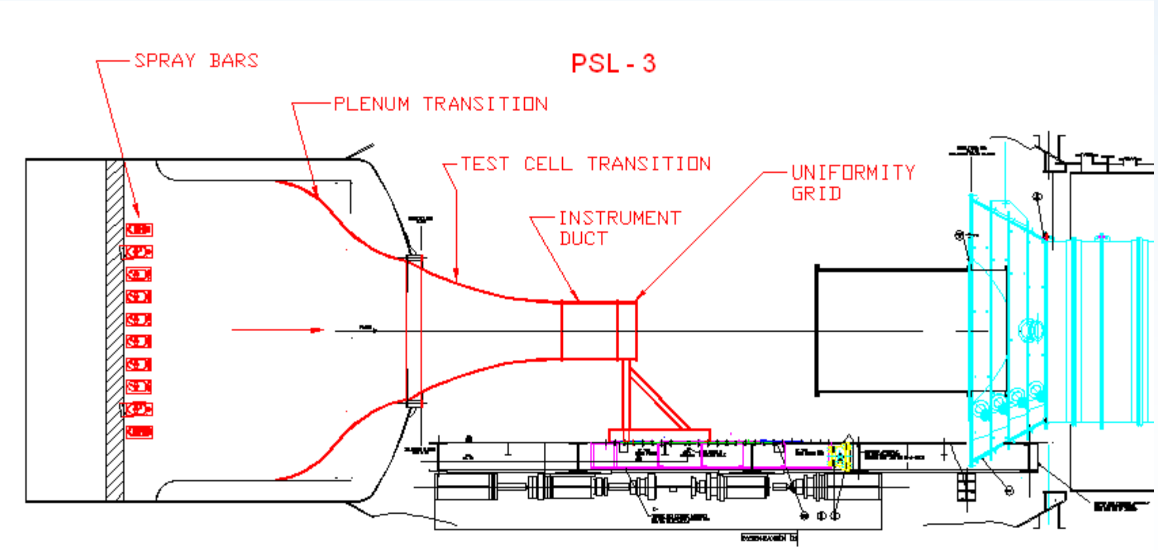
- Develop and test aircraft de-icing and anti-icing systems
- MVD:15-50µ
- LWC: 0.2 to 3.0 g/m^3
- 6' x 9' Test Section
- Temperatures: -25 C to 5 C
- Airspeeds: 50 to 350 kts



Propulsion Systems Lab

<u>Capabilities:</u>

- Altitude testing of mid-size engines
- Ice particle generation (MVD:40-60μ)
- IWC: 0.5 to 9.0 gm/m^3
- Altitude simulation: 4000 to 40000 ft
- Temperatures: -60 F to 15 F
- Altitude simulation: 4000 to 40000 ft
- Airspeeds: M=0.15 to 0.8



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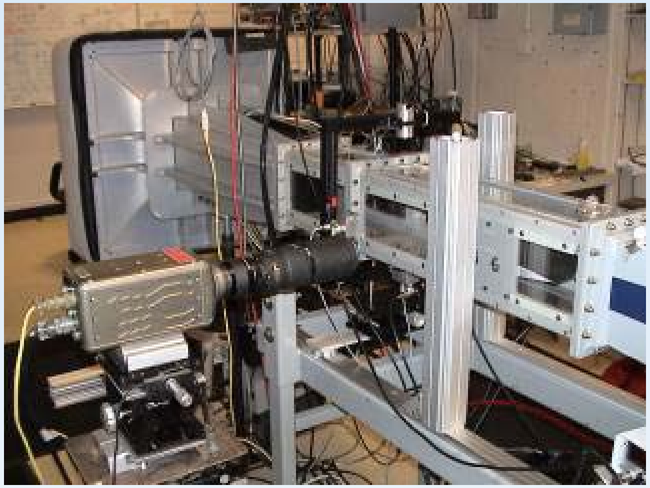
Vertical Icing StudiesTunnel

13’

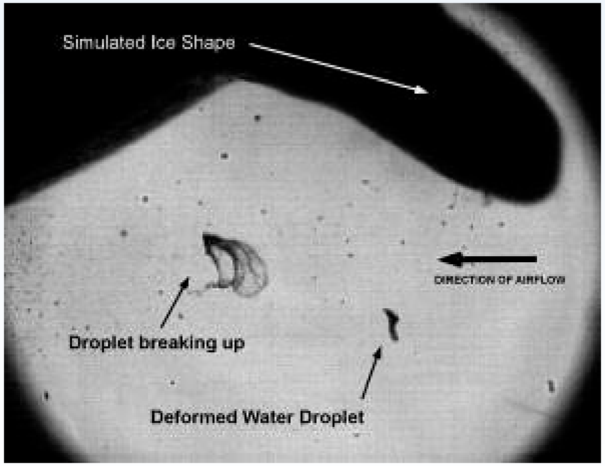
<u>Capabilities</u>

- Planar stagnation point flow
- Test section 64-in x 30-in
- Airspeed at contraction:
  - Max = 25 m/s
  - Design point V_0 = 17 m/s
- Air Temperature: ambient to -15°C
- LWC: 0.1 – 1.5 g/m³ (design spec.)
- MVD: 20 – 2000 µm (design spec.)

Droplet Imaging Flow Tunnel



Capabilities
- 6” x 6” Test Section
- 175 mph (empty tunnel)
- Phantom High Speed Camera
- Sheet Laser and Intensified Camera



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Flight Simulation and Training

Ice Contamination Effects Flight Training Device: for familiarizing pilots with possible effects of ice contamination

Icing Remote Sensing

Remote Sensing Ground Site: for developing and assessing remote icing condition detection algorithms

NASA Narrowbeam Multi-frequency Microwave Radiometer (NNMMR): for terminal area icing detection and warning

Benefits of Using Simulation

- Identify critical conditions for icing test campaigns
- Incorporate icing issues earlier into the design cycle
- Explore a larger portion of the icing envelope than can be examined by tunnel or flight testing
- Provide critical information for certification efforts along with tunnel and flight test information
- Provide a faster, cheaper and equally accurate assessment of icing effects for purposes of design and certification

Icing Data Method	Data Points Obtained	Time Requirements	Cost
Flight Testing	10 - 50	2-3 months	Over $1 million
Icing Tunnel Testing	100 - 150	2-3 weeks	Approx. $500 thousand
LEWICE	Over 1000	1 day	One days salary

LEWICE
Ice Accretion Prediction

LEWICE is a software package the predicts the size, shape, and location of ice growth on aircraft surfaces exposed to a wide range of icing conditions.

- ✓ Flow solution using potential flow or structured viscous solver
- ✓ Particle trajectory calculation, including impingement limit search for collection efficiency and multiple drop size distributions
- ✓ Integral boundary layer routine calculates heat transfer coefficient
- ✓ Quasi-steady analysis of control volume mass and energy balance in time stepping routine
- ✓ Geometry modification using density correlations to convert ice growth mass into volume allows multiple time-step solutions
- ✓ All physical effects modeled, including turbulence, bouyancy, droplet deformation, breakup and splashing
- ✓ Extensive validation against experimental data

LEWICE also models the behavior of thermal ice protection systems while exposed to the same range of icing conditions.

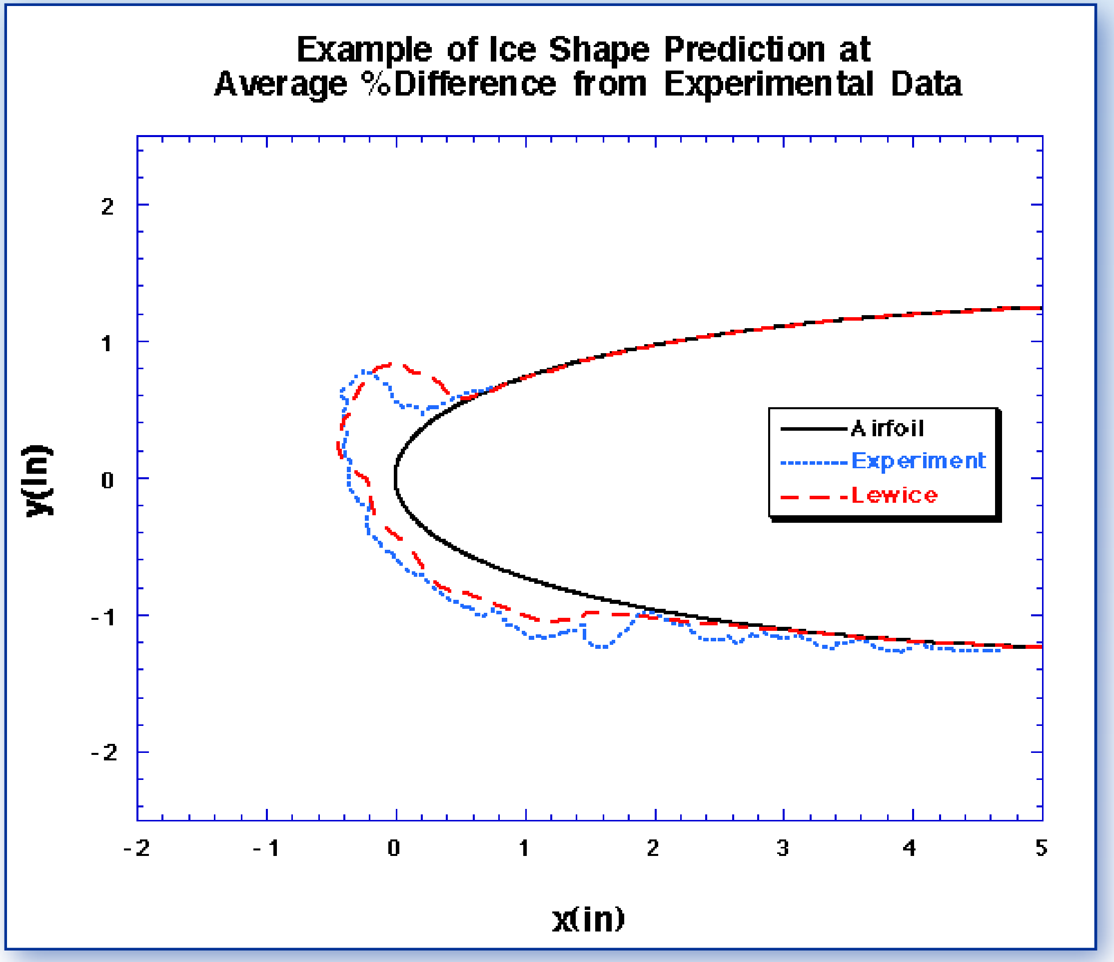
LEWICE: Ice Growth Simulation Software

INPUT:

- Flow Coordinates of a body surface
- Flight conditions (free stream velocity, temperature, angle of attack)
- Icing conditions (water droplet diameter, liquid water content of the cloud, water droplet size distribution)

OUTPUT:

- Ice shape geometry
- Collection efficiency on the surface
- Freezing fraction along ice surfaces
- Heat transfer values along the surface
- Temperatures along the surface



LEWICE User Base

US Aerospace Industry

- Learjet
- Gulfstream
- Raytheon
- Cessna
- Cox & Co.
- Goodrich
- P & W
- Bell
- Beech
- Nordham
- Northrop
- Boeing
- Lockheed
- ALPA
- Sikorsky
- Embraer
- GEAE
- Honeywell
- Boeing Helicopters
- Hamilton Sundstrand
- Engineering Services
- New Piper
- Ice Management Systems
- Many Others…

Universities

- UIUC
- WSU
- MIT
- MSU
- CWRU
- Toledo
- Others…
- NCAR
- Iowa Sate
- Ohio State
- Penn Sate
- GT
- WVU
- Wyoming

US Government

- NASA
- FAA
- CRREL
- NOAA
- NTSB
- AMCOM
- USAF
- NAVAIR

200+ Users of LEWICE

Non-Aerospace

- Bridge cables
- Lake Erie wind turbine project

International Distribution

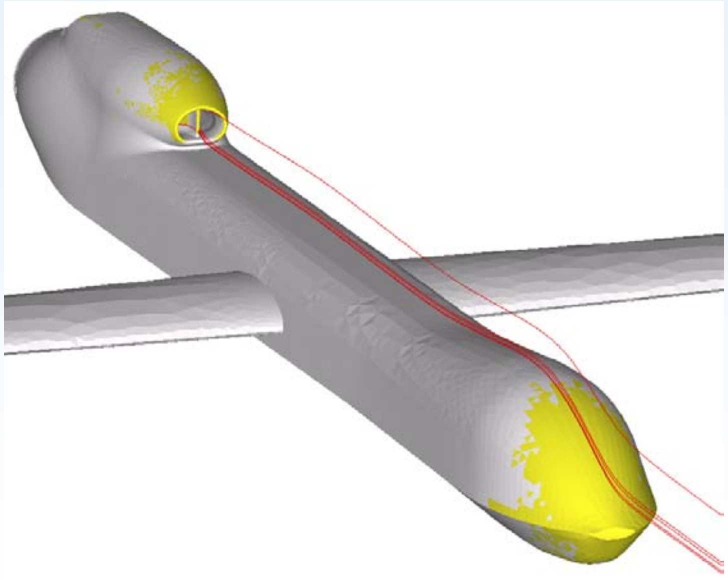
- American Kestrel

LEWICE3D
Three-Dimensional Ice Accretion Software

LEWICE3D is a suite of codes used to determine the amount and location of ice accretion on an aircraft.

- ✓ Based on the Messinger model and Monte Carlo analysis
- ✓ Monte Carlo-based collection efficiency calculation using droplet impact counts
- ✓ Integral boundary layer technique used to generate heat transfer coefficients
- ✓ Ice growth calculated using a modified LEWICE scheme
- ✓ Supports both structured and unstructured grids
- ✓ Calculation off-body concentration factors
- ✓ Determination of shadow zones

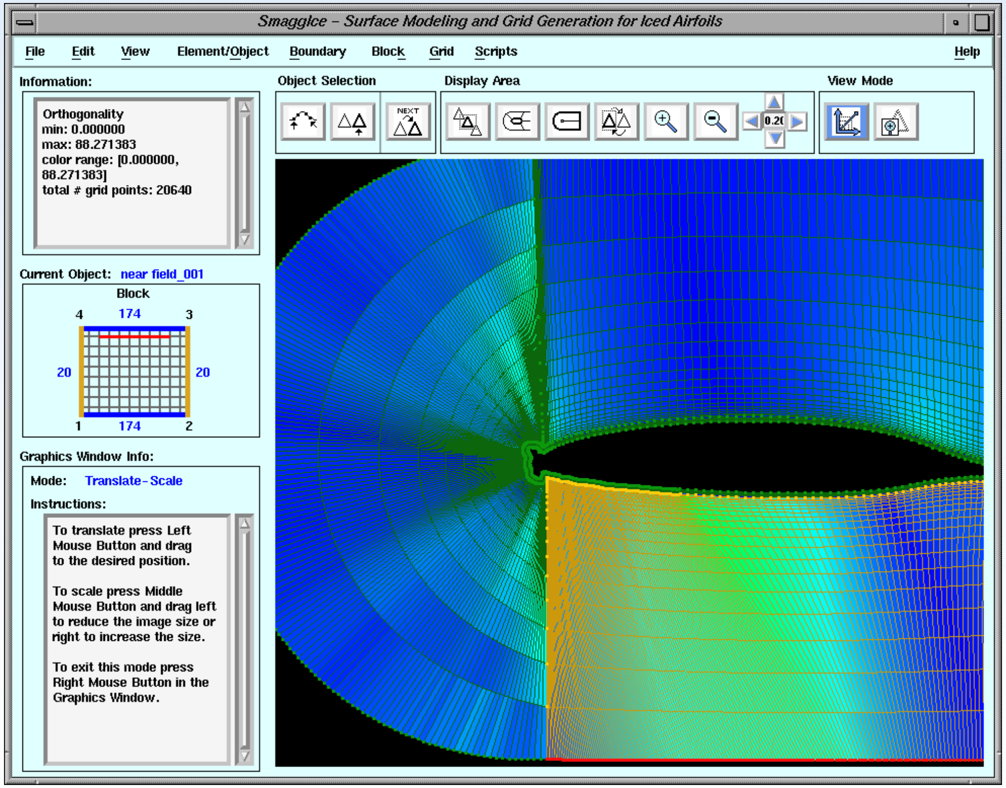
Generation of a full ice accretion for 3D surfaces



SMAGGICE
Surface Modeling and Grid Generation for Iced Airfoils

The SMAGGICE software suite is an interactive toolkit used to prepare 2D cross-sections of iced airfoils for computational fluid dynamic analysis.

- ✓ geometry preparation
- ✓ block creation and grid generation
- ✓ grid quality checks
- ✓ flow solver interface
- ✓ convenience capabilities
- ✓ both single and multi-element airfoils



Summary

- NASA research provides tools, methods and databases for industry, academia, other government agencies
- NASA's icing codes are the gold standard in the U.S. and the world
- NASA's icing tunnel remains highly utilized and continues to expand its envelope of calibrated conditions
- NASA's Propulsion Systems Lab will greatly expand the envelope for engine icing research with its new icing capability
- Few organizations conduct basic icing research in-house
- Pilot and dispatcher education and training, modifications to aircraft, improvements in detection, etc. have all contributed to saving lives
- Flight into known icing conditions will remain important as airspace capacity continues to grow