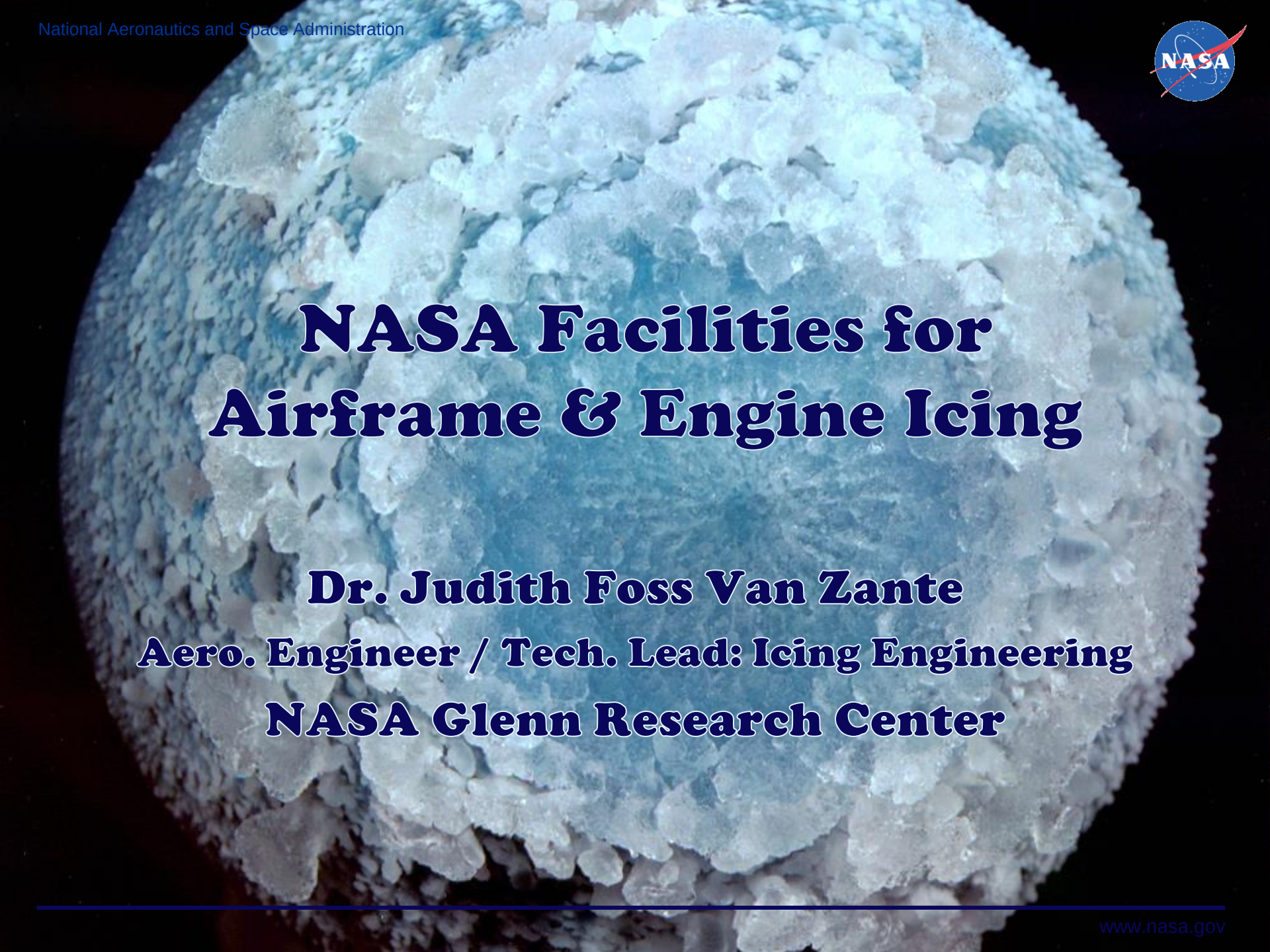


NASA Facilities for Airframe & Engine Icing

Dr. Judith Foss Van Zante
Aero. Engineer / Tech. Lead: Icing Engineering
NASA Glenn Research Center

Outline

- Introduction
- Motivation
- History
- Airframe Icing
  - NASA Glenn's Icing Research Tunnel (IRT)
- Engine Ice Crystal Icing
  - NASA Glenn's Propulsion Systems Lab (PSL)

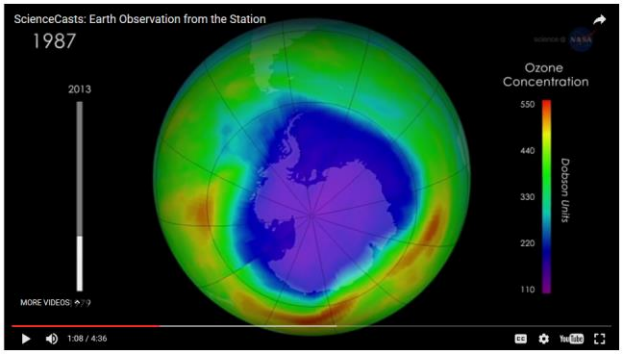
NASA Centers

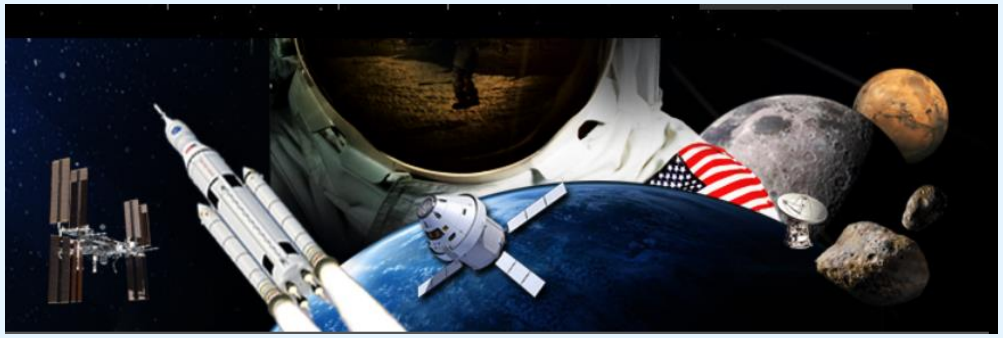


NASA Mission Directorates

- Aeronautics Research
  1. Safe, efficient growth in global operations
  2. Innovation in commercial supersonic aircraft
  3. Ultra-efficient commercial vehicles
  4. Transition to low-carbon propulsion
  5. Real-time system safety assurance
  6. Assured autonomy for aviation transformation
- Human Exploration and Operations
- Science
- Space Technology







Who am I?









1998 – 2005

Icing training aids for pilots at
http://aircrafticing.grc.nasa.gov
or search on
"NASA aircraft icing"

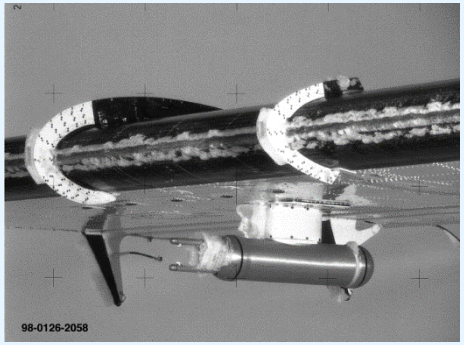
Definitions

Most images from NASA icing research aircraft flights

Airframe Icing:

supercooled *liquid* water impacts external airframe, surfaces, and phase changes to ice.

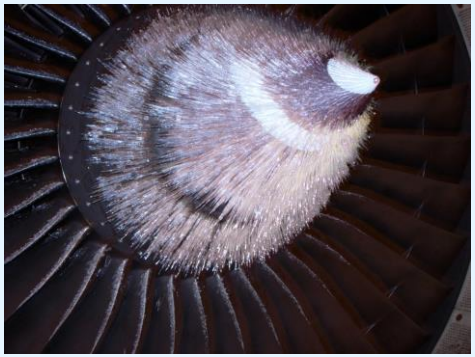




Engine Icing (traditional):

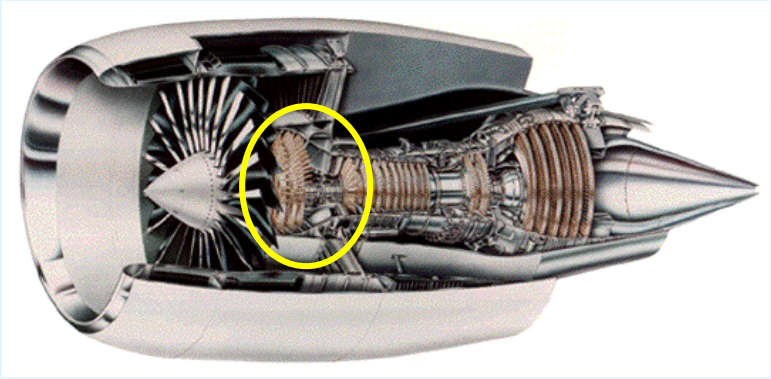
supercooled liquid water impacts spinner, prop, fan, nacelle.





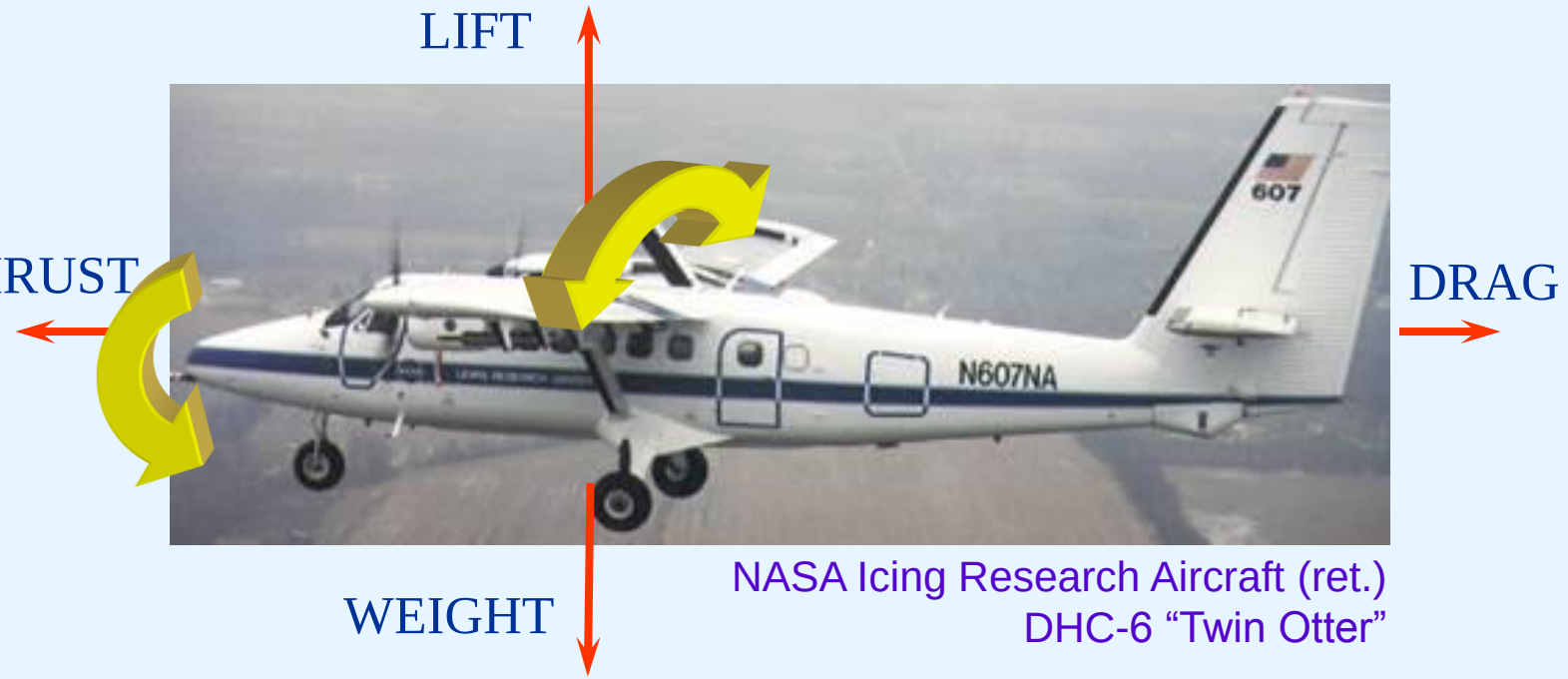
Engine *Ice Crystal* Icing:

ice crystal ingestion into the core of turbine engines, cooling initially hot surfaces inside the booster (LPC), causing power loss events.



Why is Airframe Icing Bad?

Airframe Icing: when Supercooled *Liquid* Water impacts an external aircraft surface and phase changes to ice.



NASA Icing Research Aircraft (ret.)
DHC-6 “Twin Otter”

Icing negatively impacts each of these forces and/or may cause Roll or Pitch Upsets

The Phenomenon of
Jet Engine Icing

Researchers are exploring the theory that flight into certain kinds of storm clouds might cause ice to build up inside the core of an airplane's jet engine. Since 1988 there have been 153 engine power loss events* on a variety of airplane and engine types attributed to engine icing. A power loss event is a surge, stall, rollback or flameout of one or more engines. Events have occurred up to 41,000 feet and in different regions of the world. The majority occurred in descent and cruise. A multi-national research effort is now underway to identify exactly what causes this phenomenon and how to prevent it.

* Events reported through January 2010, FAA.



1 The belief is that jet engine icing can occur during flights into cold, high-altitude storm clouds holding massive quantities of small ice crystals. These conditions are not currently detectable on pilot radar. Ice crystals are drawn into the engine inlet where some are ingested with air that flows through the compressor and engine core; the rest are ejected with the air that bypasses the core.



2 As core flow is compressed, the air temperature rises and internal engine components warm above the ambient temperatures. Some ice crystals impact those components, forming a thin film of liquid water that captures additional ice crystals. This accumulation reduces the engine component temperatures so that ice can form.

3 At some point, ice breaks off from the components, which causes the engine to surge, stall, flame out or experience other malfunctions.



Graphic: NASA

A (very) Brief History of Flight



1902-Sep
Wright Glider
& 1903-Dec
Wright Flyer

1909-Aug
Wright Military
Flyer delivered
to Signal Corps

1918-May
First flight
of Air Mail
Service

During the first two decades of powered flight, pilots avoided the clouds (VFR).

A (very) Brief History of Flight

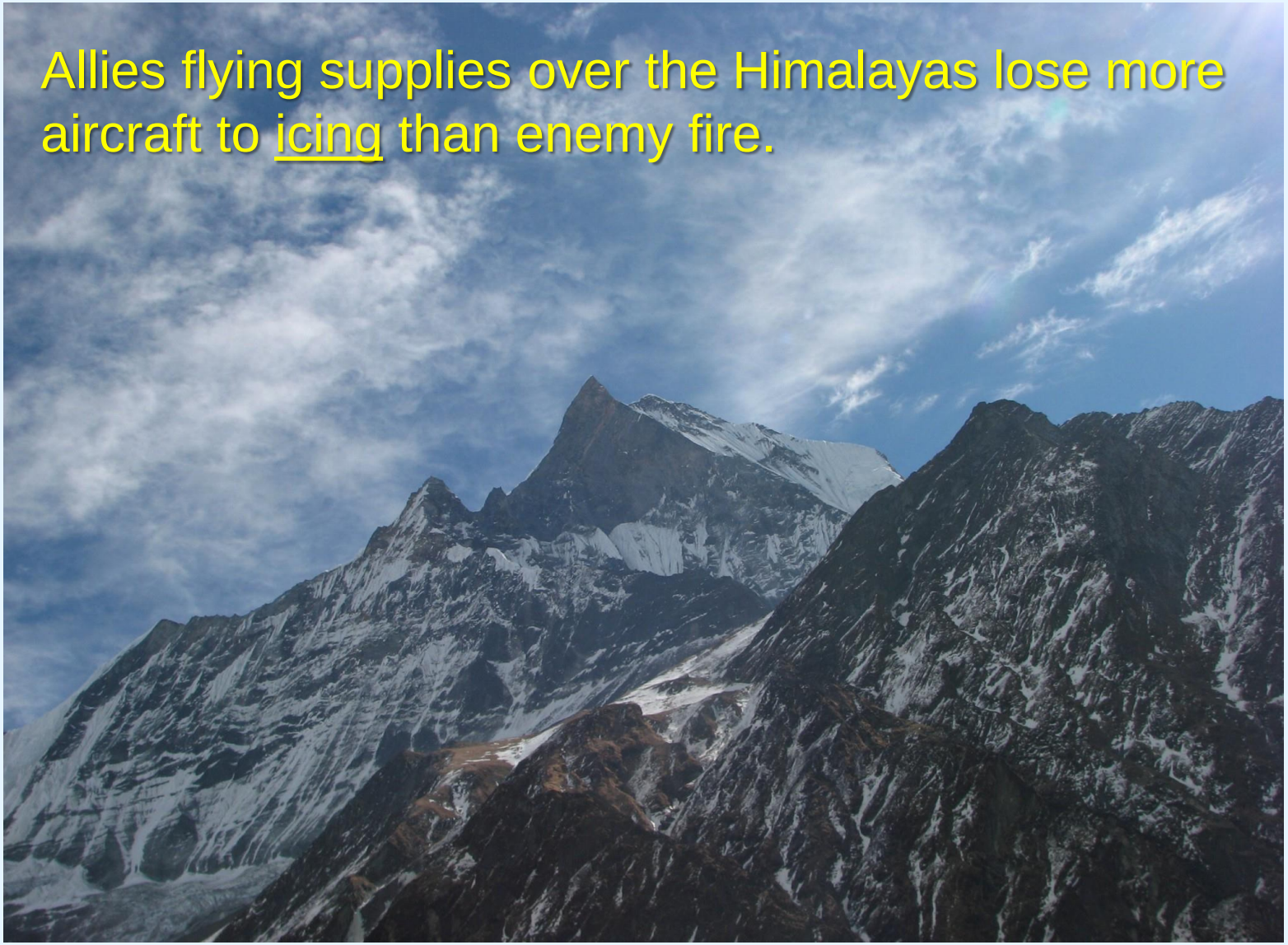
In the late 1920s, onboard flight instruments allowed the various sectors (Air Mail Service, Navy, Air Corp) to start flying in all weather conditions (IFR).

They encountered icing, and reported it as the most significant threat to the safety of flight.

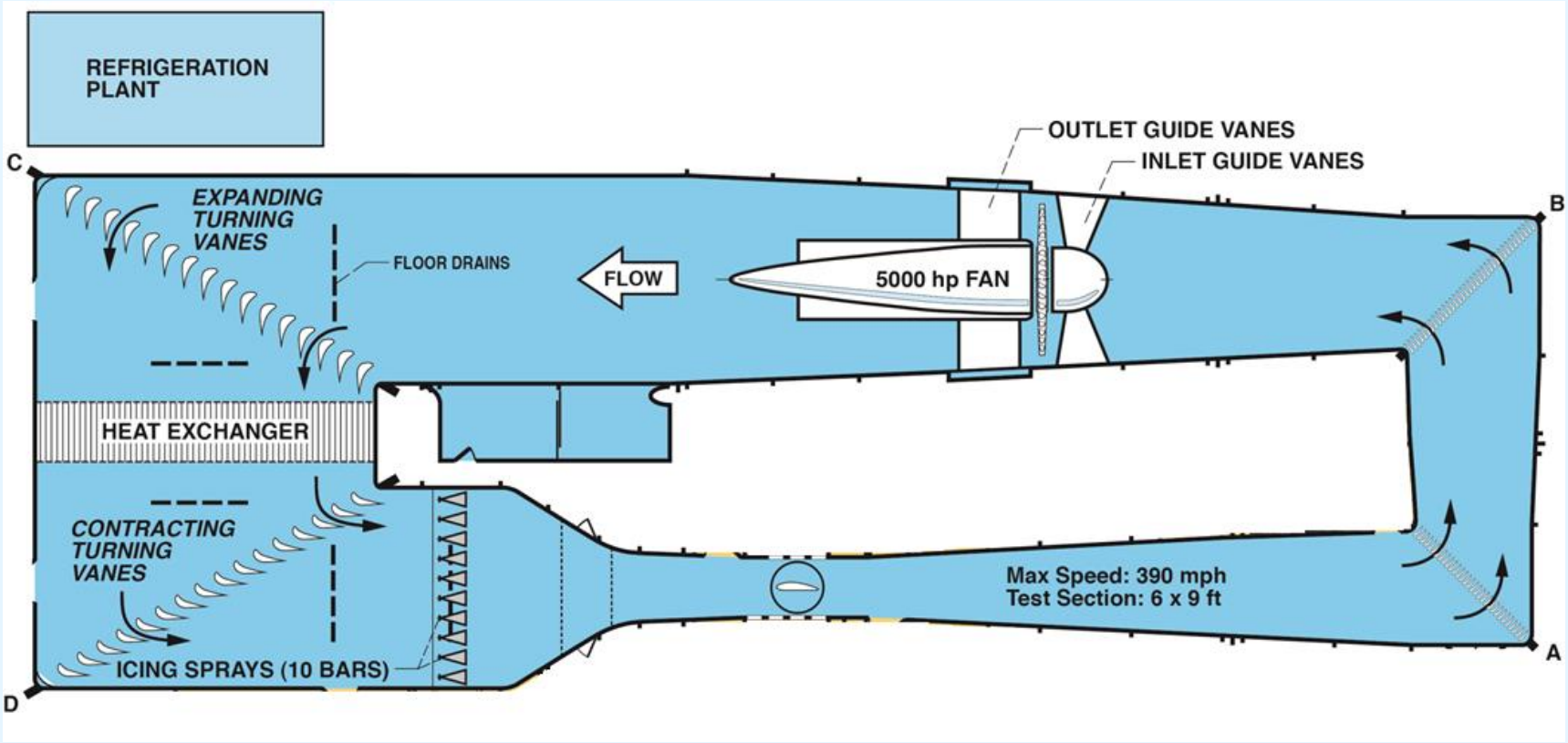
- June 1928 – NACA to study

"Ice Formation on Aircraft"

Motivation for NASA's IRT: WWII



Icing Research Tunnel Schematic



To simulate flight through an icing cloud, the engineers needed to make it Windy, Cold and Wet in the Test Section.

1944 – The IRT is Operational!



Willson Hunter explains to General “Hap” Arnold the need for propeller ice protection as Dr. Lewis looks on.

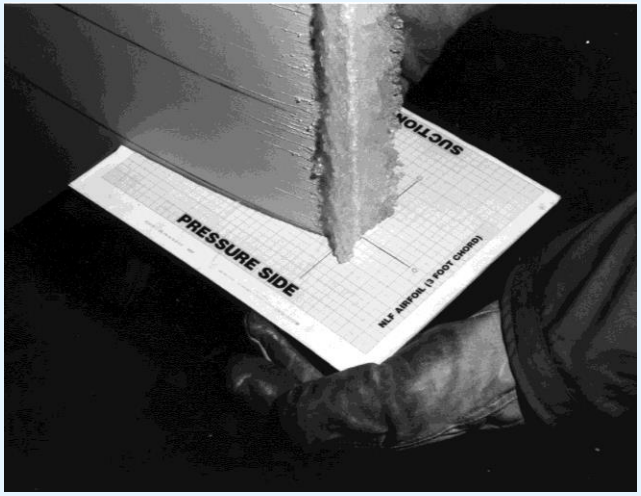
- W. Hunter was head of NACA icing research.
- General Arnold was head of Army Air Force
- Dr. Lewis was head of NACA

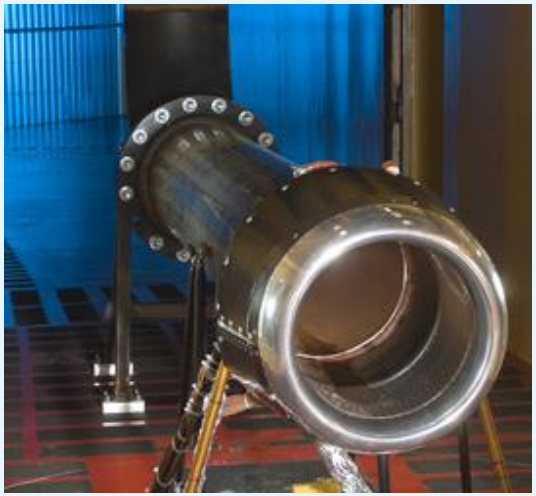
IRT Today

The IRT is a facility of international importance that is used by

- Industry
- Research Agencies
- Military
- Academia







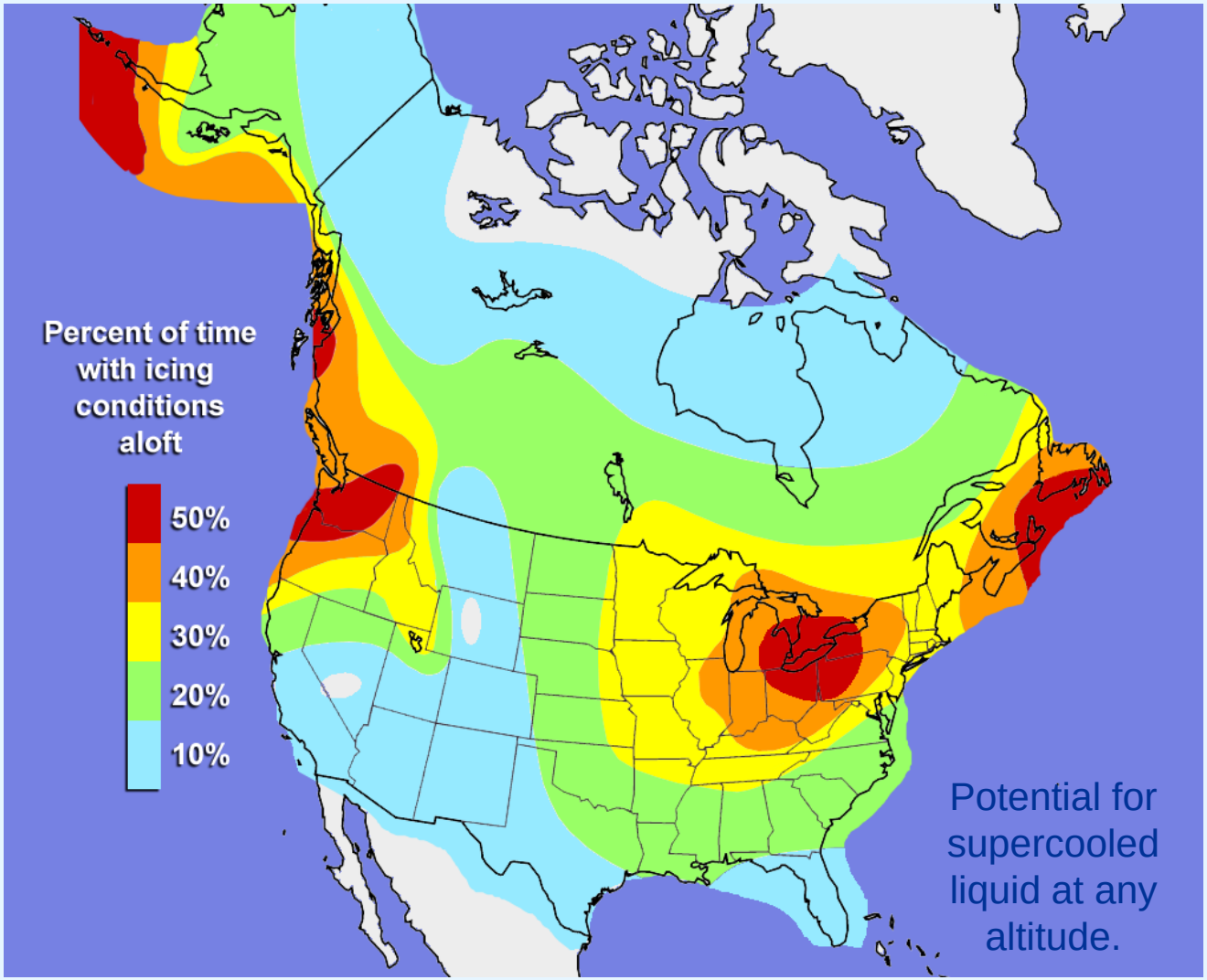


Airframe Icing

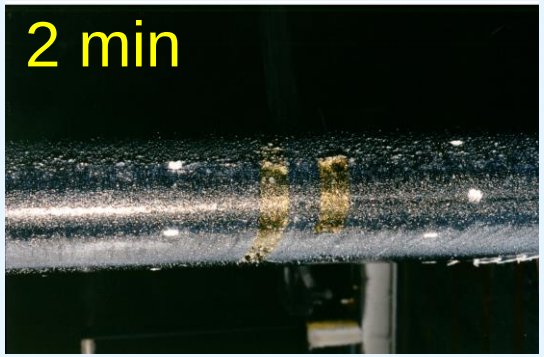


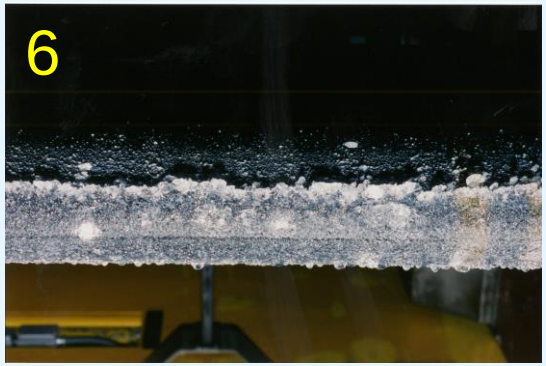
Where is the Ice?

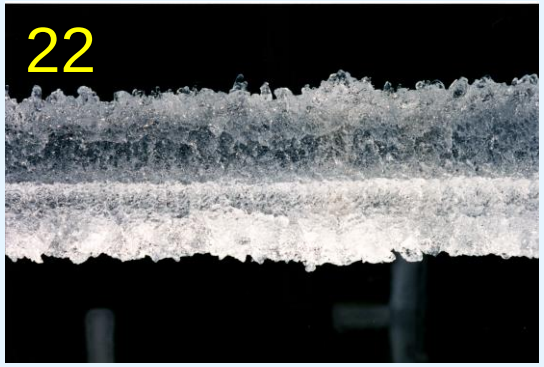
Icing Potential during Winter Months, Nov – Mar. (NCAR)

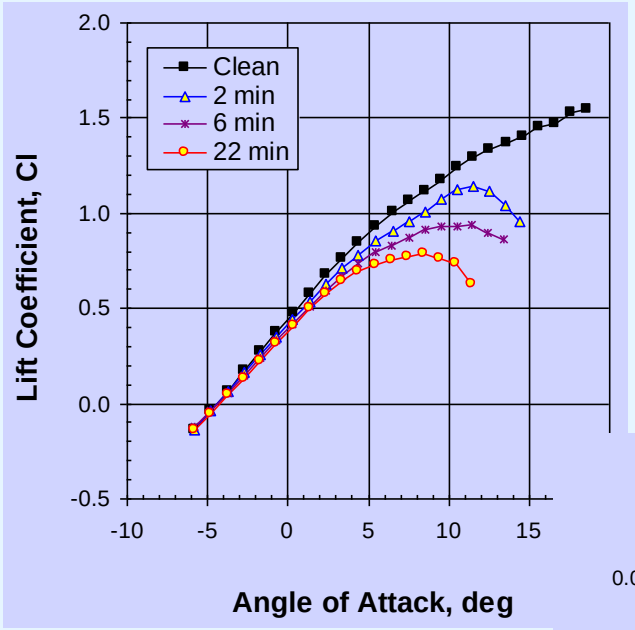


IRT: Performance Data on a Wing

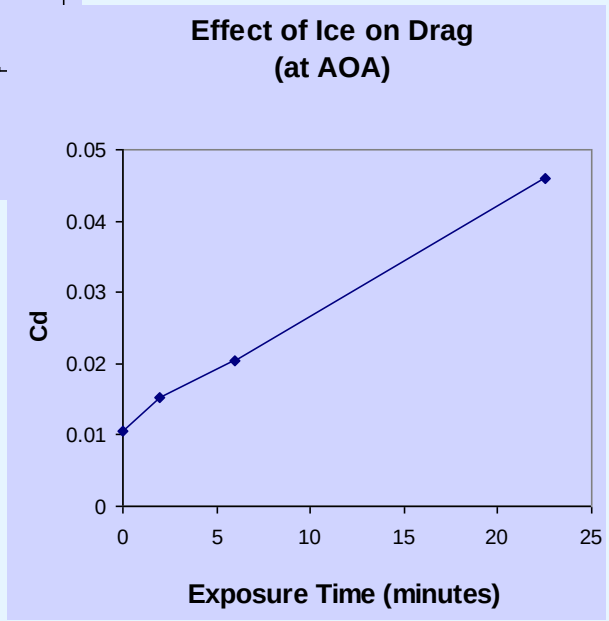








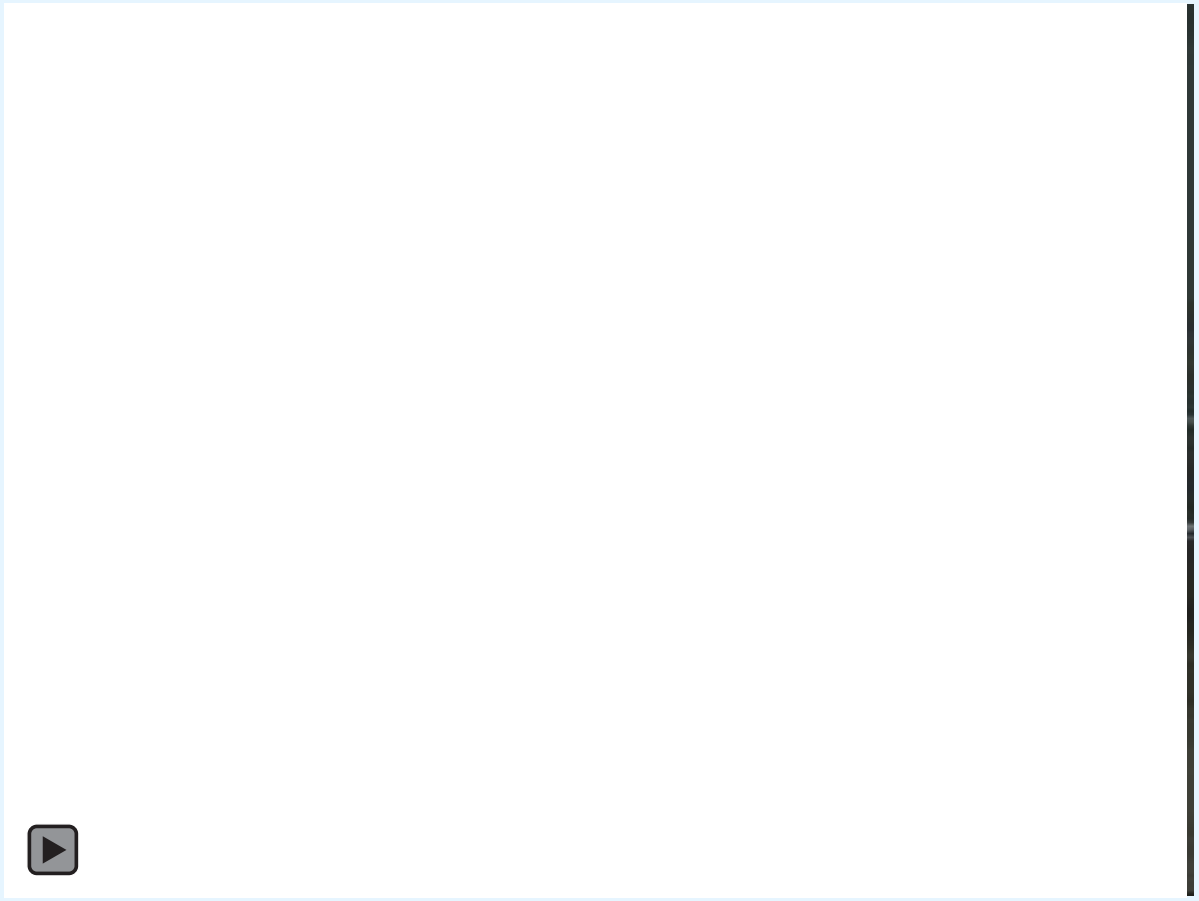
Addy, "Ice Accretions and Icing Effects for Modern Airfoils," NASA/TP-2000-210031, DOT/FAA/AR-99/89, April 2000.



IRT: Ice Accretion Video

Looking along LE of airfoil model in NASA's Icing Research Tunnel.

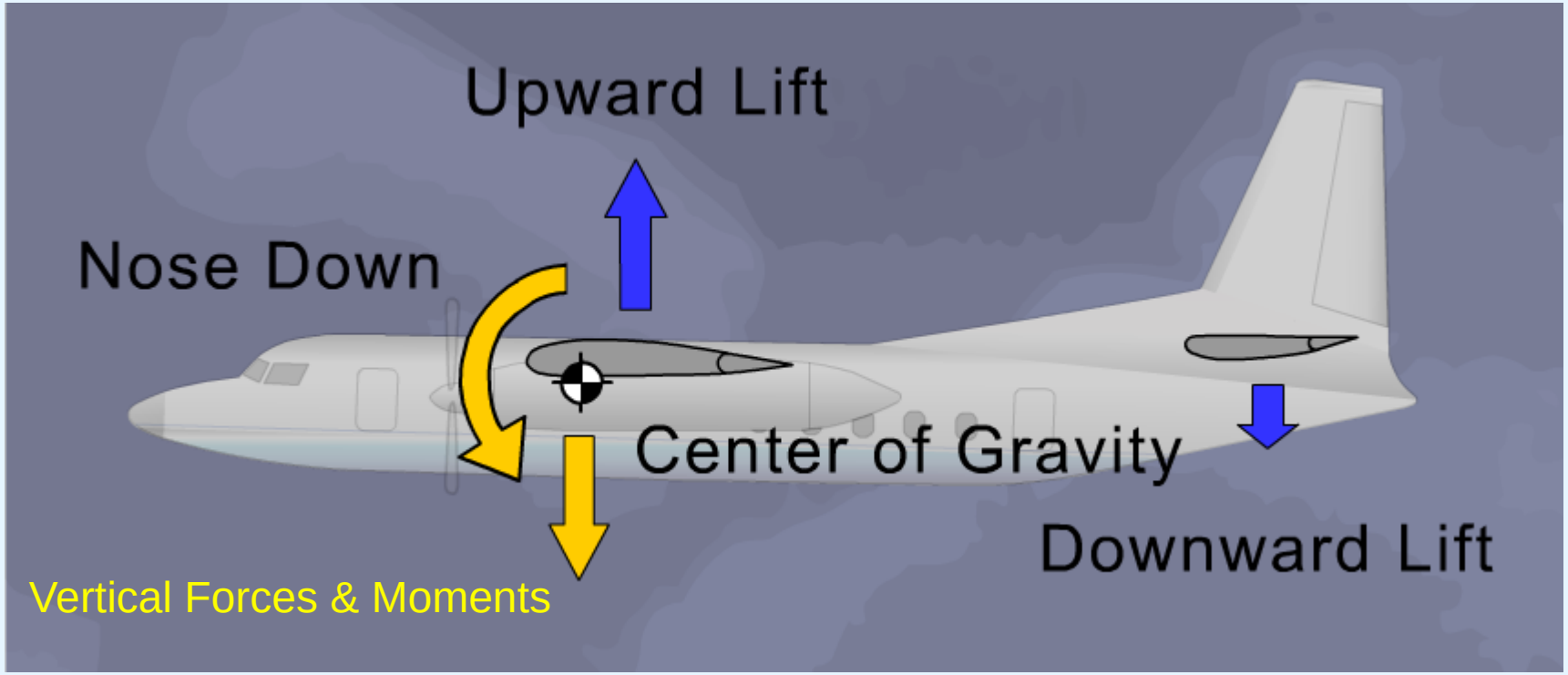
Time lapse video of 15 min accretion in **140 μm MVD (FZDZ)**



J-C Tsao test, C. Lynch videographer

stills

Role of the Tailplane



Tail Provides Downward Lift (upside down wing)

Tail is Opposite of Wing

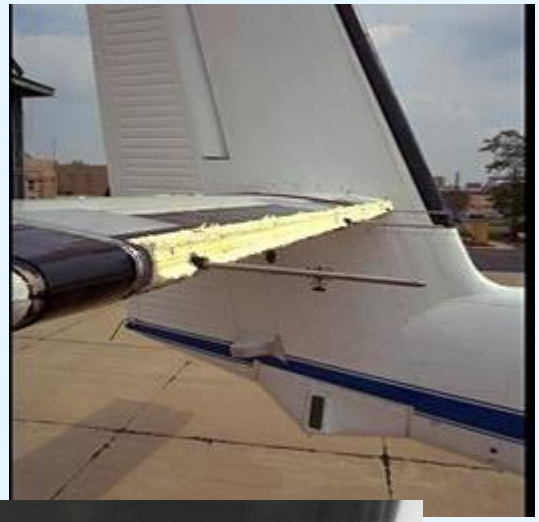
Which aircraft have experienced tail stall? Historically, turboprops w/ large flap deflections and unpowered controls that use aerodynamic balance to trim.

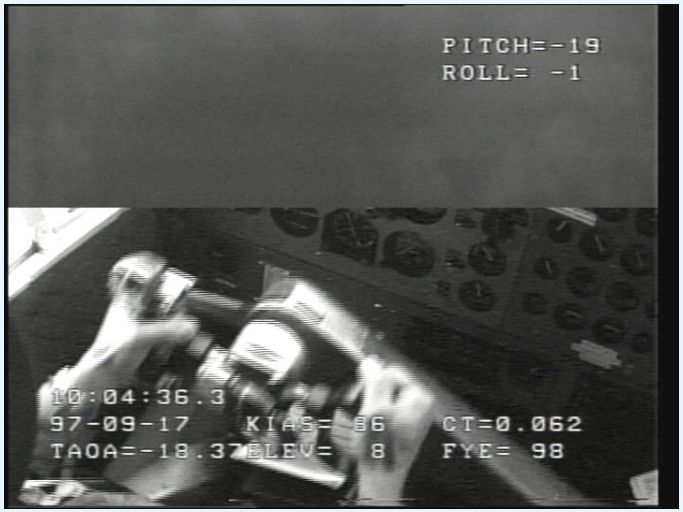
IRA: Ice Contaminated Tailplane Stall

Footage of a Tail Stall Event

NASA Icing Research Aircraft

- 22 min “normal” icing accretion
- V = 1.5 Vs (High Speed)
- Flaps = 40°
- *Increasing Thrust*





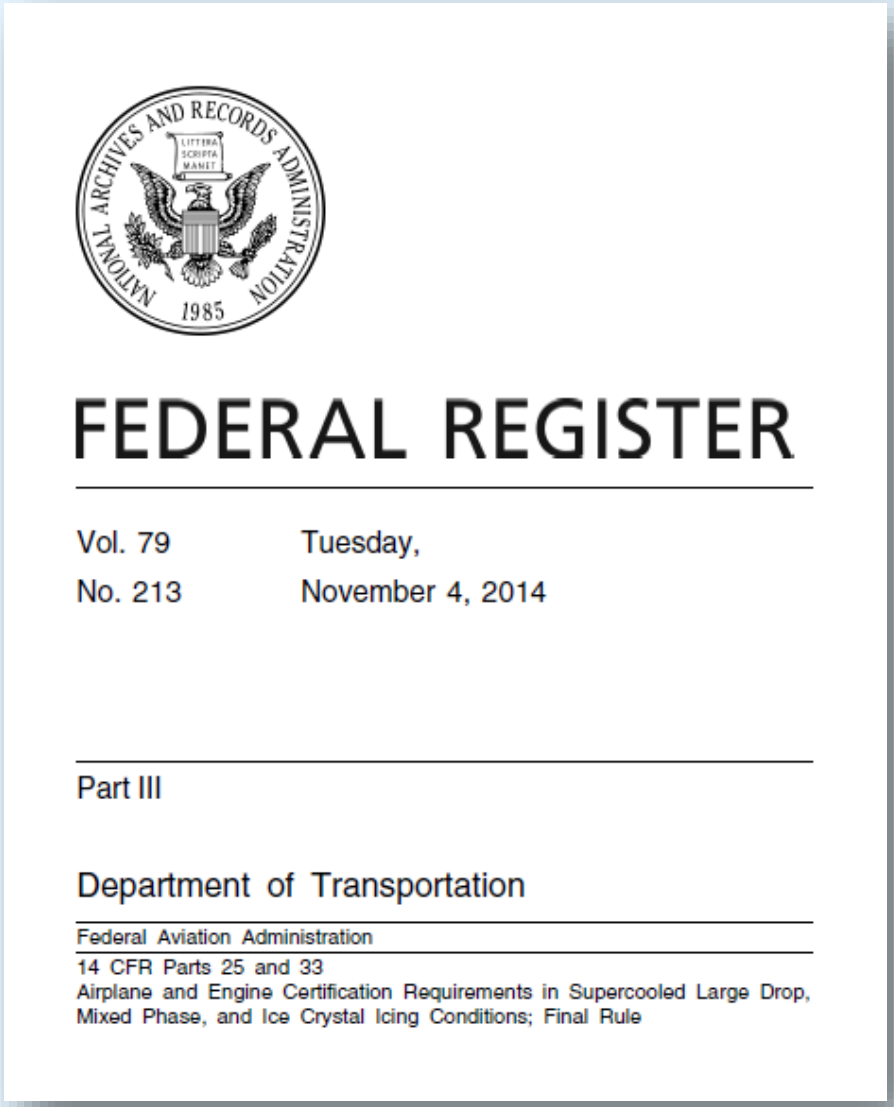


IRA: Tail Stall Event

NASA Icing Research Flight



New Rule for SLD and Ice Crystals



FEDERAL REGISTER

Vol. 79 Tuesday,
No. 213 November 4, 2014

Part III

Department of Transportation

Federal Aviation Administration

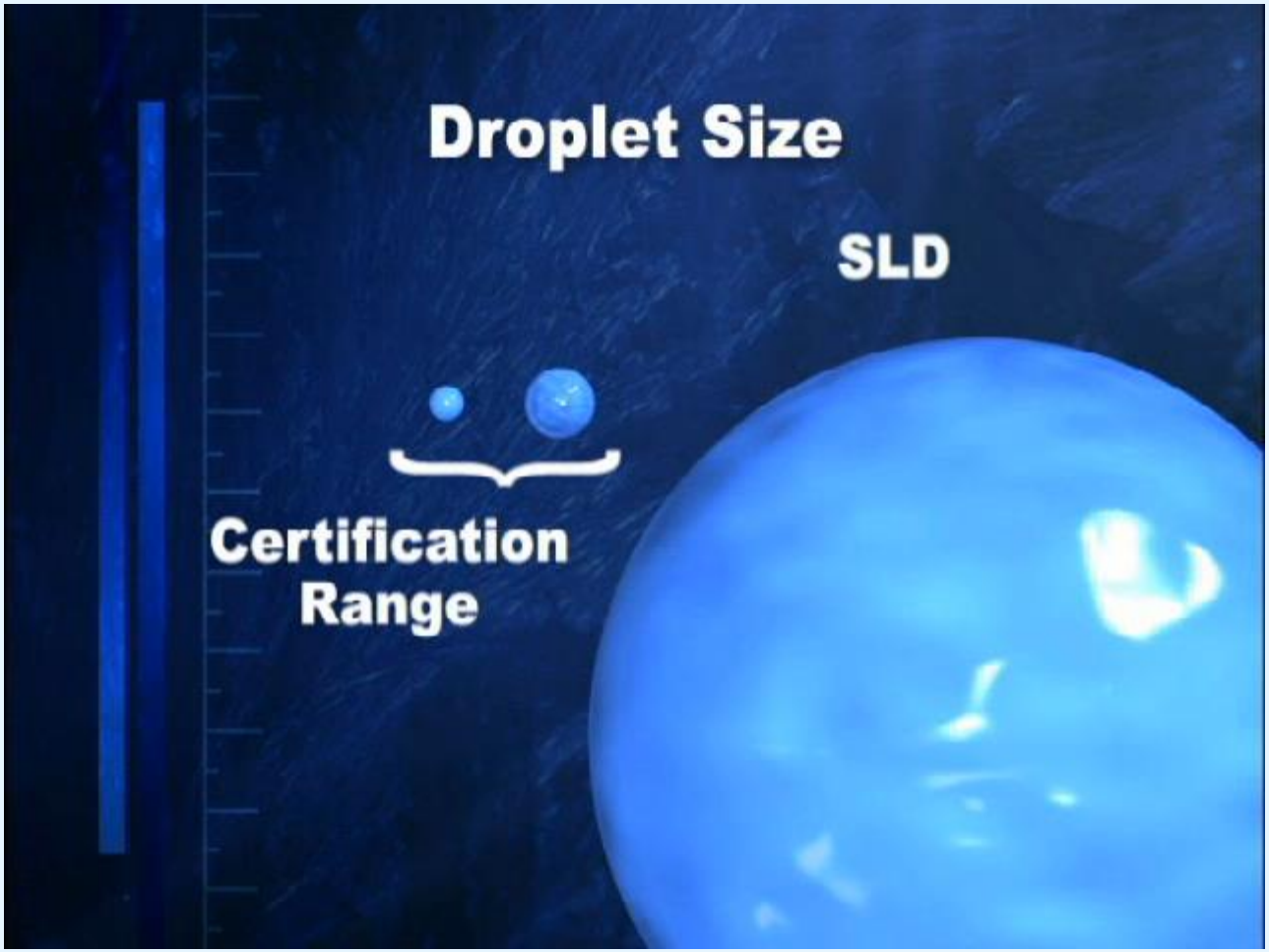
14 CFR Parts 25 and 33
Airplane and Engine Certification Requirements in Supercooled Large Drop, Mixed Phase, and Ice Crystal Icing Conditions; Final Rule

14 CFR Parts 25 and 33
Airplane and Engine
Certification Requirements in
Supercooled **L**arge **D**rop,
Mixed Phase and
Ice **C**rystal **I**cing Conditions;

Became law Jan 5, 2015

Part 25 ≈ Airframes (Large Transport)
Part 33 ≈ Engines (Turbofan)

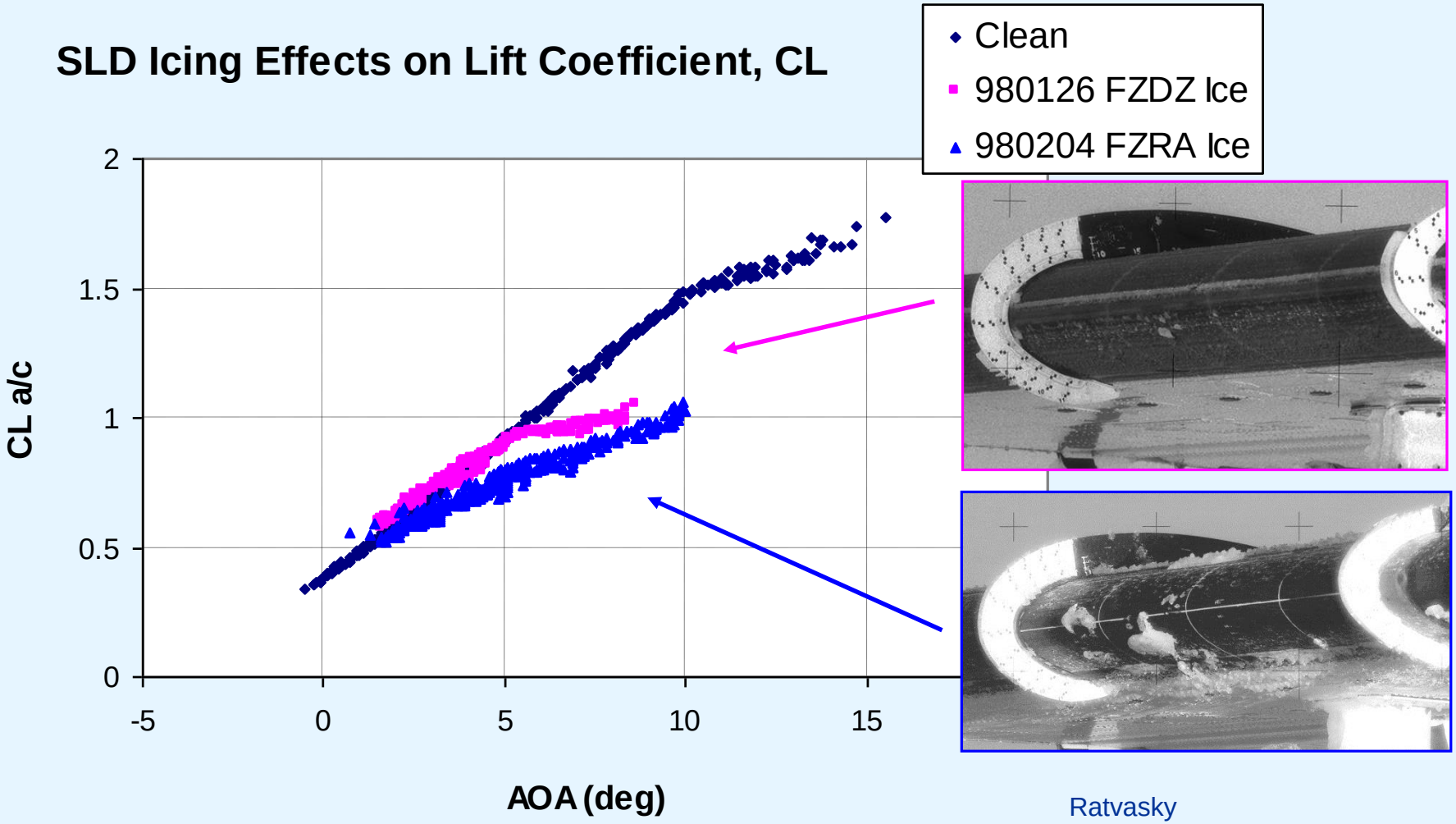
Supercooled Large Drop (SLD) icing



Until Jan 2015, FAA certification required testing in “typical” clouds. Now SLD conditions are required.

SLD can be 10 – 100 times larger than “typical” drops.

IRA: Flight Campaign in SLD



Ratvasky

FAA Certification for Flight in Icing

All revenue service aircraft must be certified by the FAA for flight in known icing (FIKI). These aircraft have ice protection systems.

- Anti-ice = prevent ice accretion (usually Jets)
- De-ice = accrete, then break off ice (usually Turboprop)

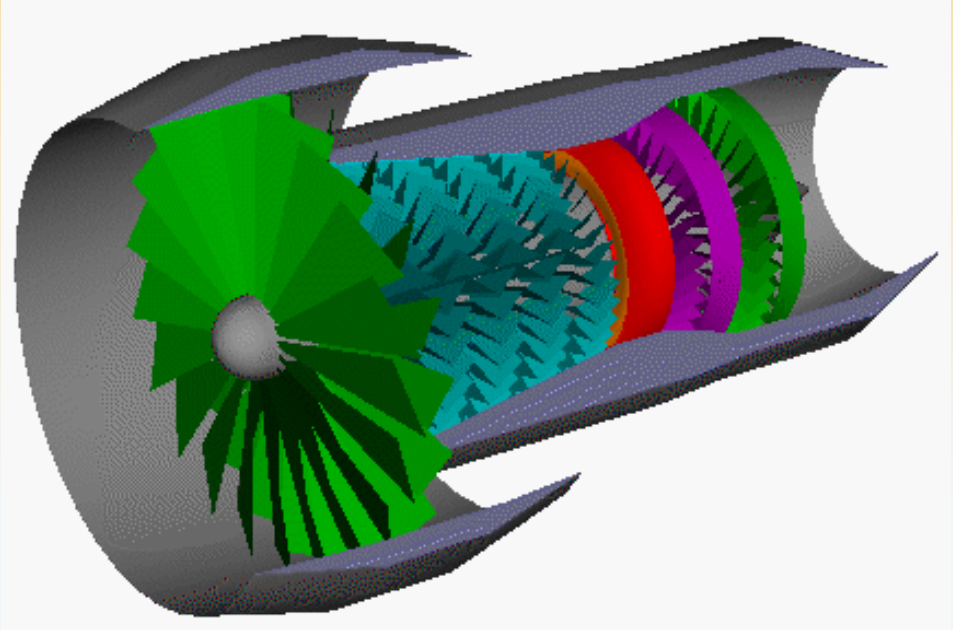




Turbine Engine Ice Crystal Icing

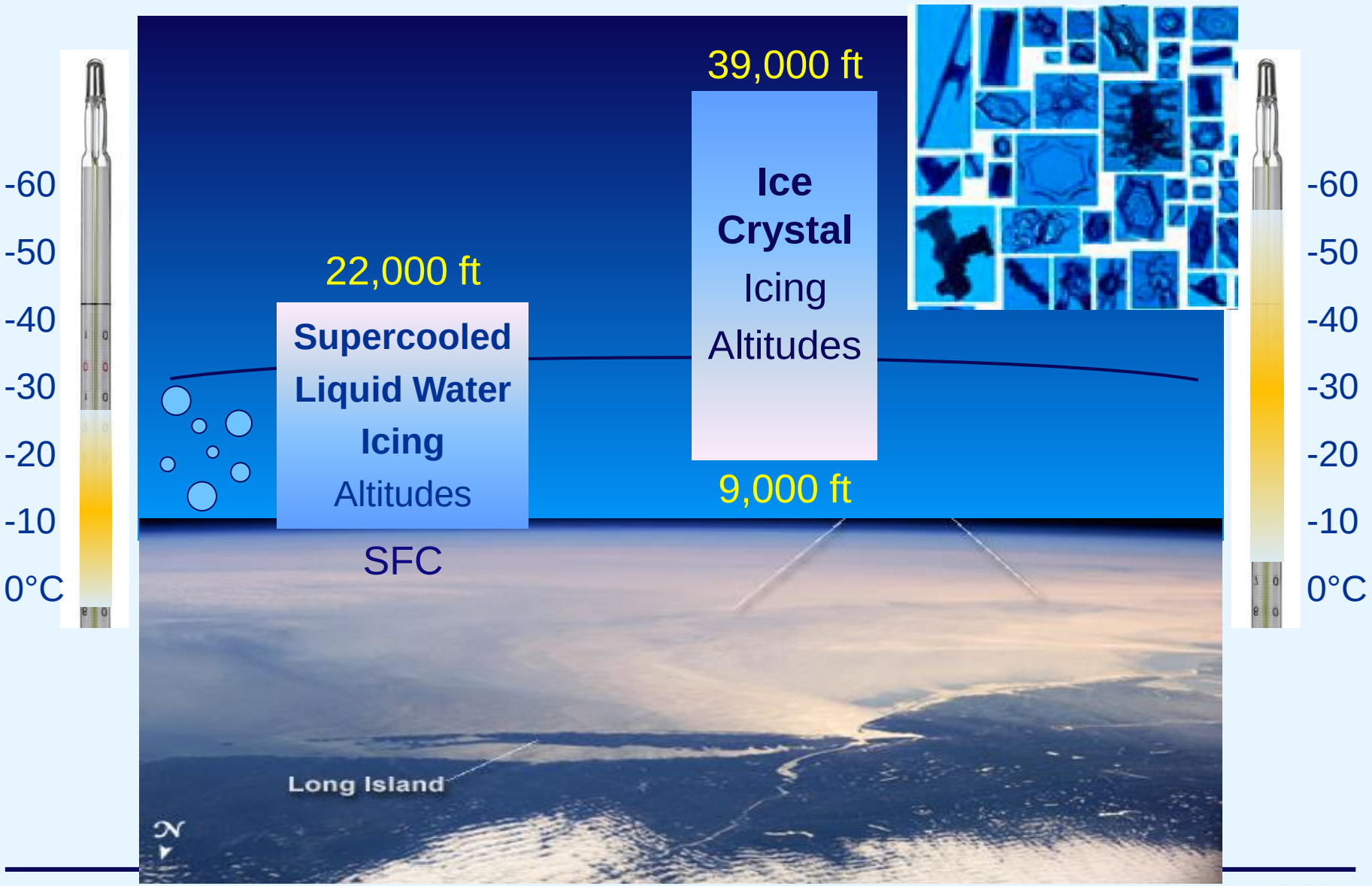
Engine Ice Crystal Icing: when ice crystals, in high quantities (g_ice/m^3), are ingested into a turbine engine.

Sometimes the engine experiences power loss events such as **rollback, stall, surge, flameout or FOD**.

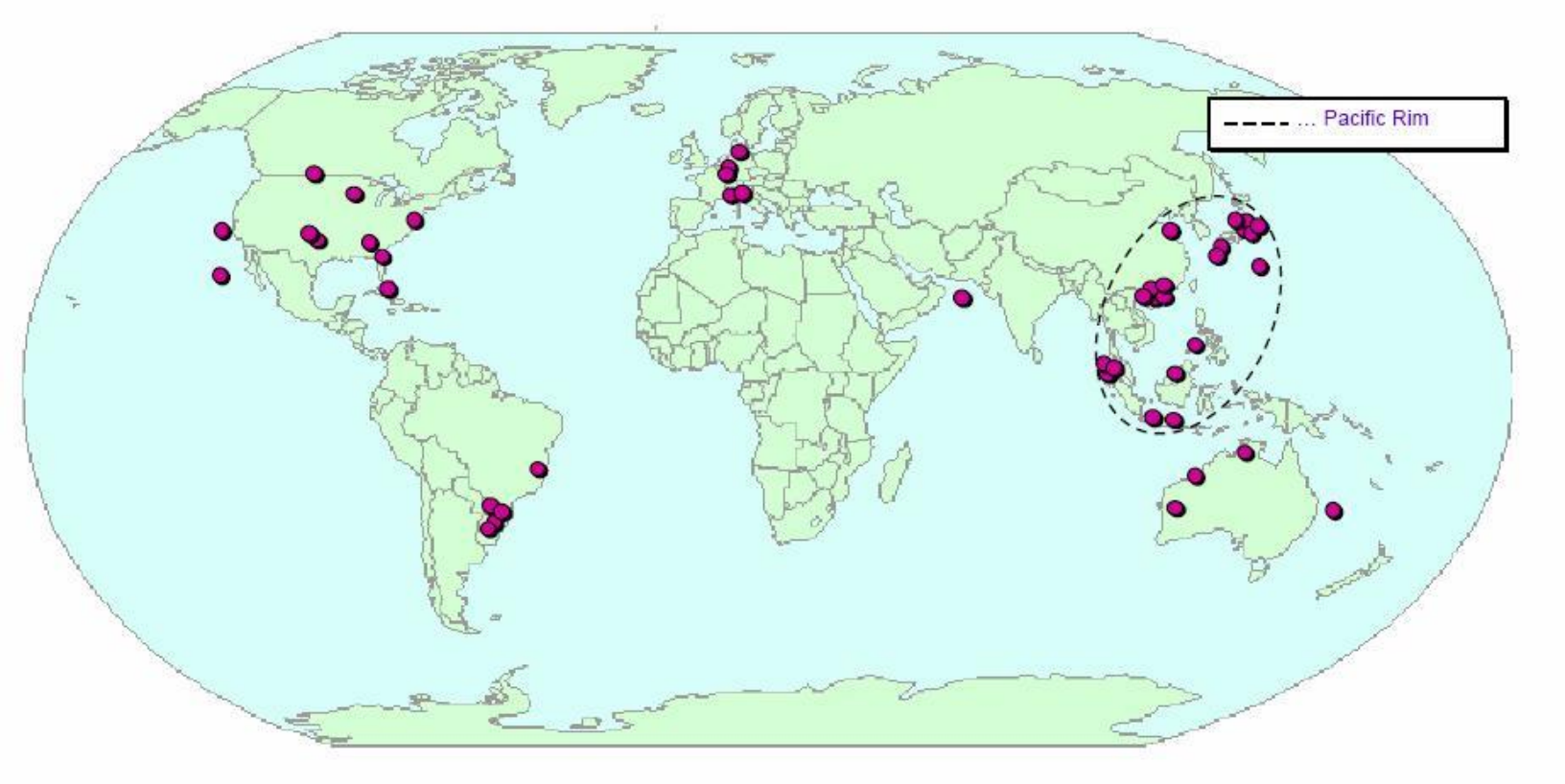


NASA Glenn's: *A Beginner's Guide to Propulsion*

Liquid Water vs Ice Crystal Environment

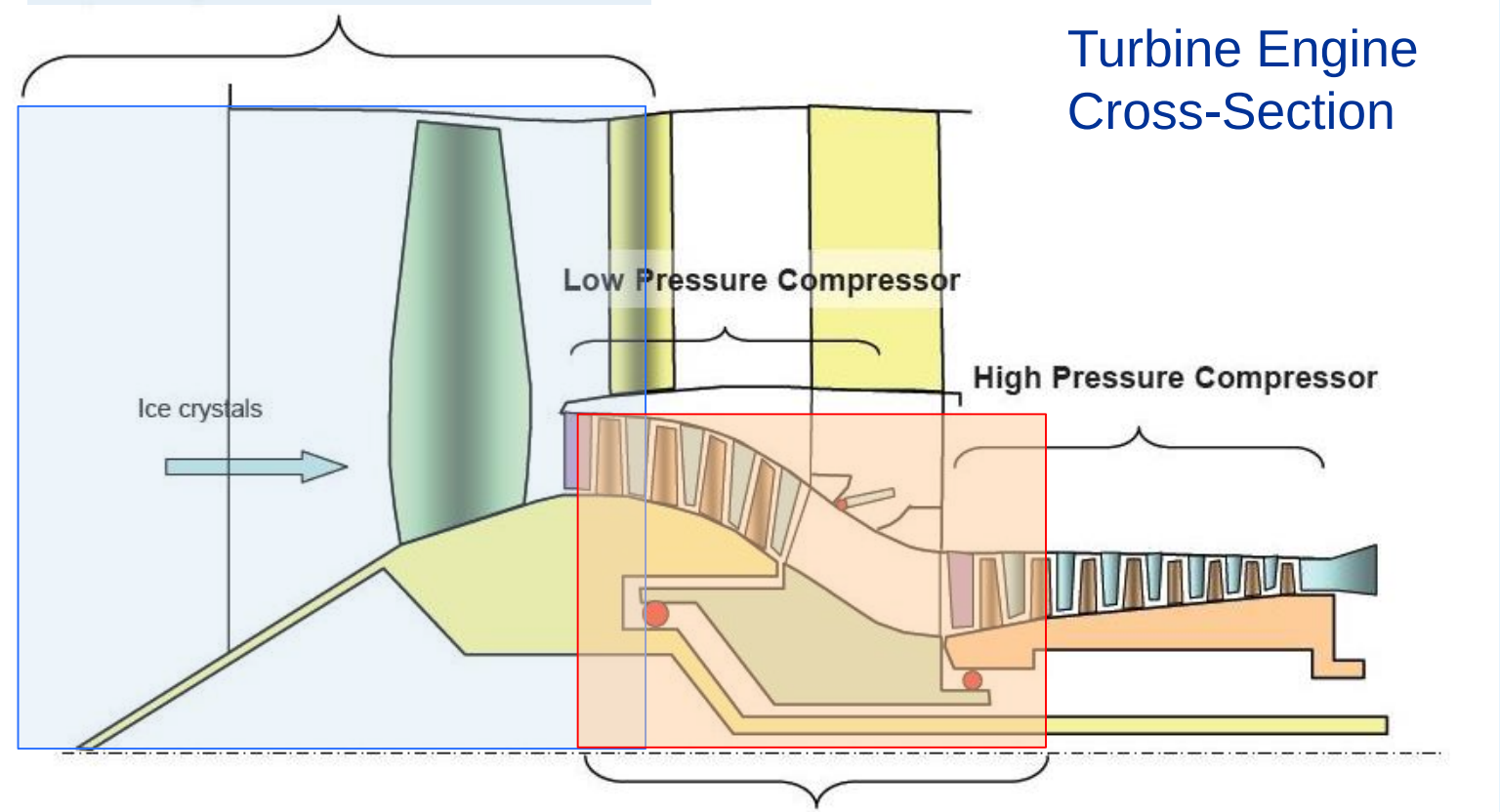


Engine Ice Crystal Icing Power Loss Events



Icing Threat Regions w/in Turbine Engines

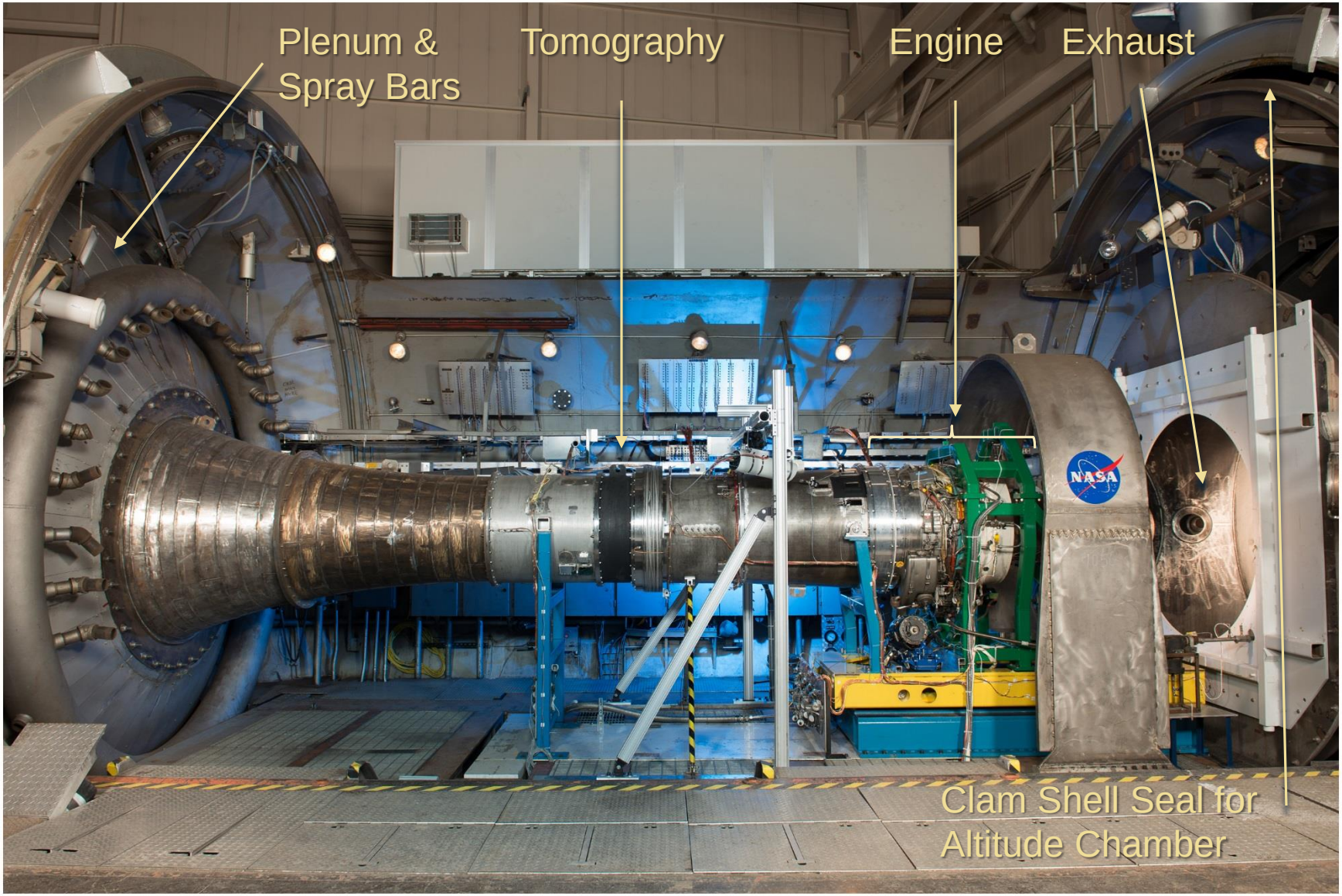
Supercooled Liquid Water Impact Regions



Suspected Ice Crystal Impact Regions

C-2013-409

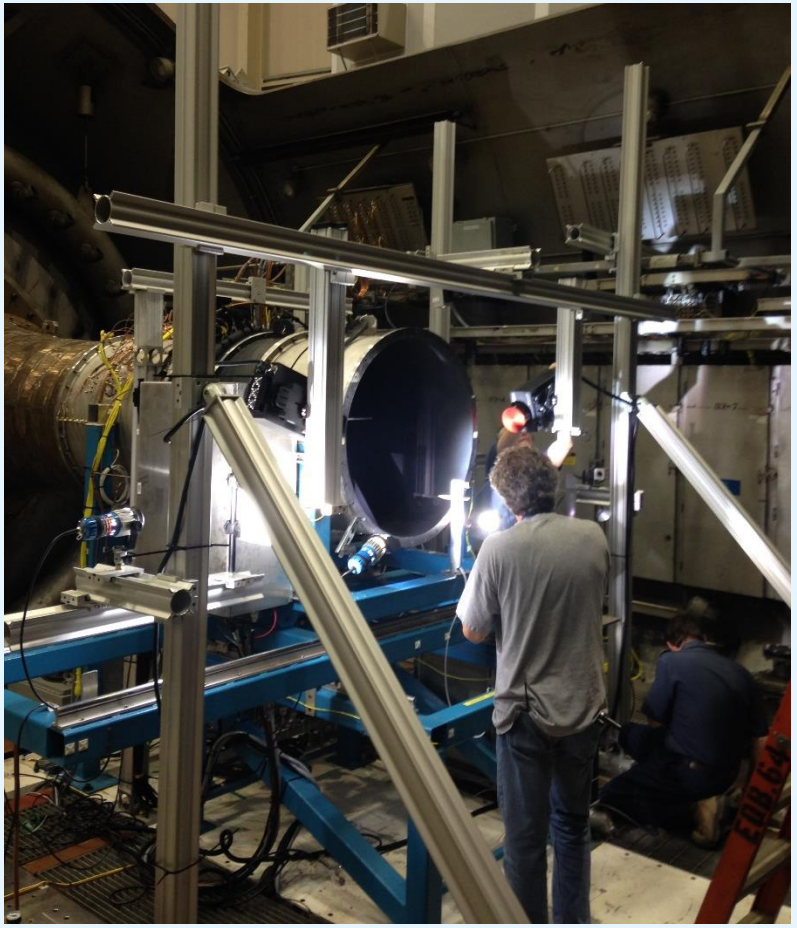
PSL's Inaugural Engine Ice Crystal Test



PSL Icing Enhancement Hardware

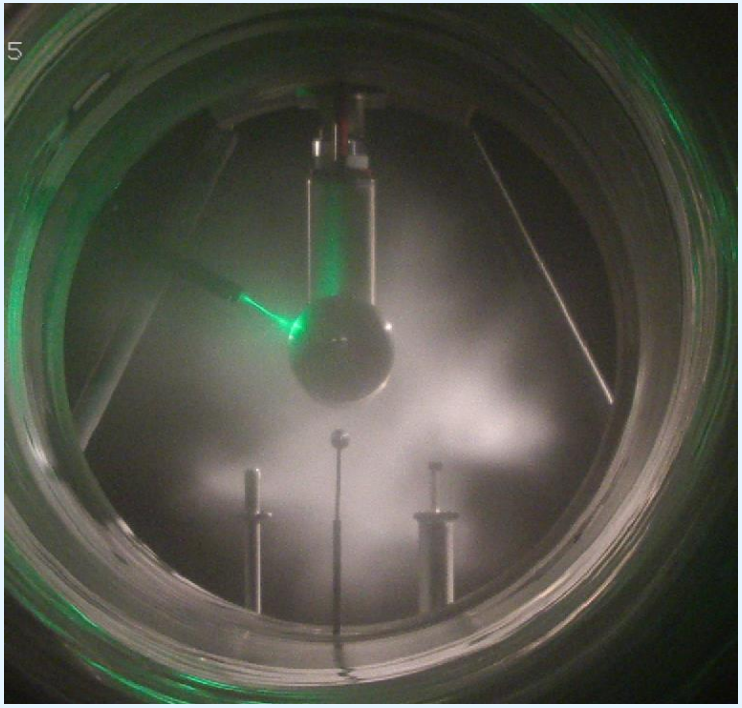


18-ft dia. Plenum
and Spraybars



Station 1 (Cal Plane)
3-ft dia. Duct

Cloud & Instrumentation in PSL



View from the Plenum

Instrumentation to measure:

- Total Water Content, g_{H2O} / m^3_{air}
- Temperature of air
- Temperature of particles (ice and/or water)
- Specific Humidity, $g_{water\ vapor}$/ $kg_{dry\ air}$

For Engine Icing Testing:
PSL is a Unique, One-of-a-Kind Facility in the World

Facilities	Liquid Water	Altitude	Ice Crystals	Notes
PSL Cell-3 NASA GRC	✓	✓	✓	
DGA Saclay, France	✓	✓	–	(tried; restart?)
ASTEF C-2 AEDC Tullahoma, TN	✓	✓		Highly utilized Non research
NRC/IAR Canada	✓		✓	From ice blocks
General Electric 2x Test Site	✓		✓	Ice particles with LN2

PSL: Engine Ice Crystal Icing

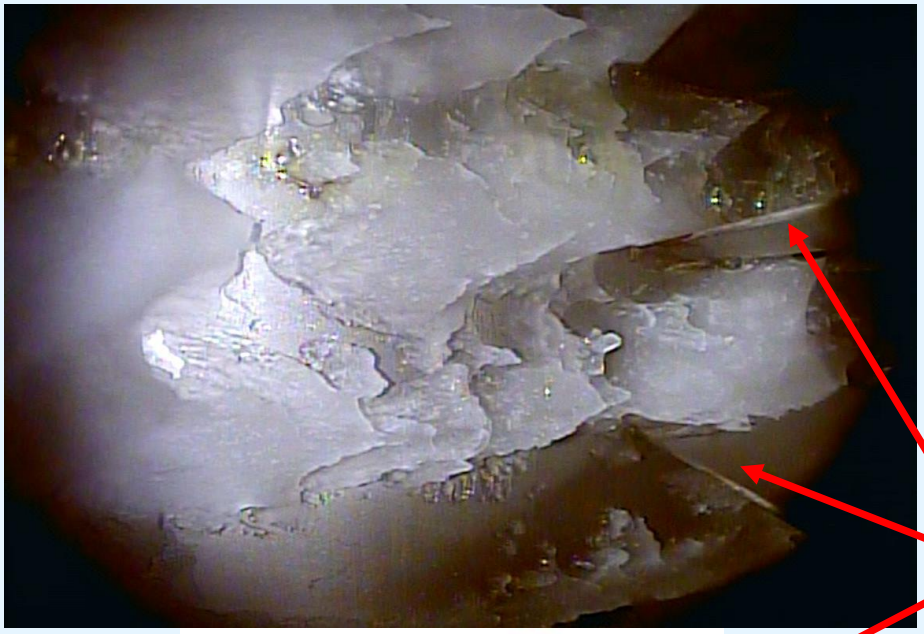
Ice crystal icing on Inlet Guide Vanes*

Flight Conditions: Cruise Alt. and Mach, Tropical Day



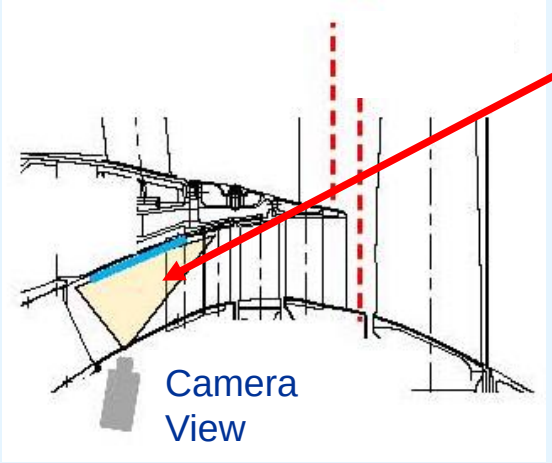
* Engine is NOT in flight operational state (anti-ice turned off)

Ice Accretion in the LPC



Flow

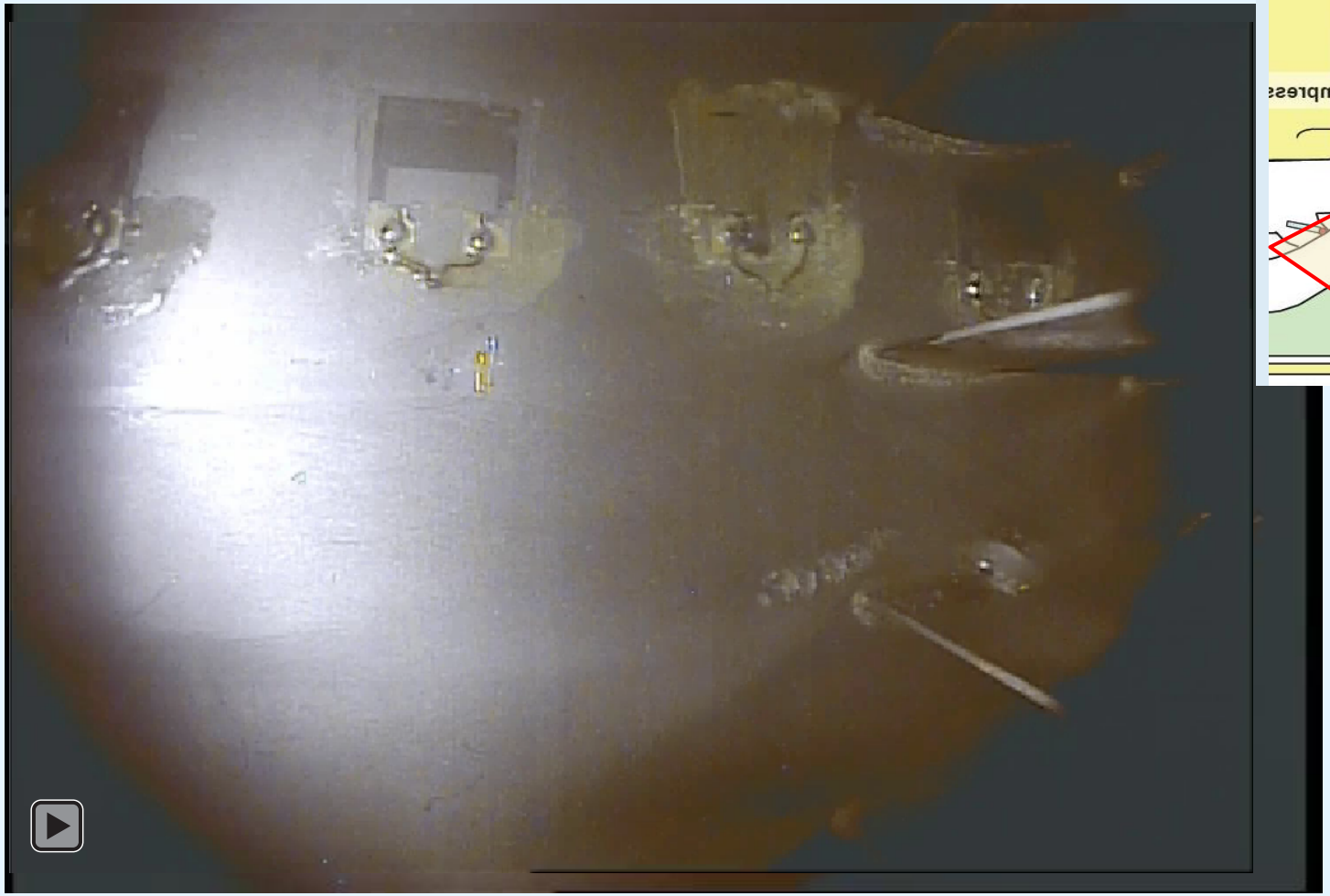
Exit Guide Vanes

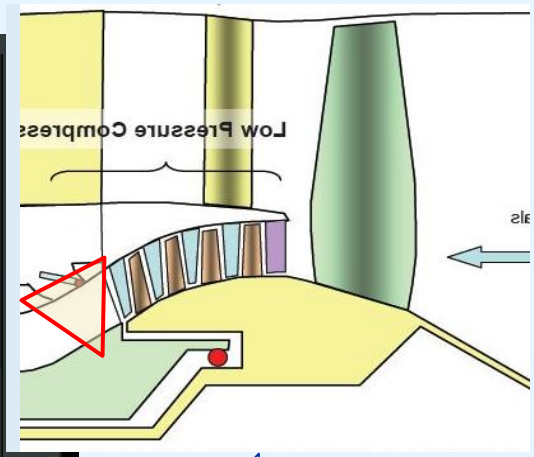


Flow

PSL: Engine Ice Crystal Icing

Time lapse video, looking at outer wall aft of Exit Guide Vanes





Flow

*This Engine is now obsolete

NASA GRC Investments

NASA has made a serious commitment to improving aviation safety and operational efficiency regarding icing.

Two major stimulus funds (ARRA) at Glenn were directed toward icing:

- **Icing Research Tunnel**
  - Upgraded the refrigeration system
- **Propulsion Systems Lab**
  - Added an ice crystal capability

Huge success for both projects!

Questions?





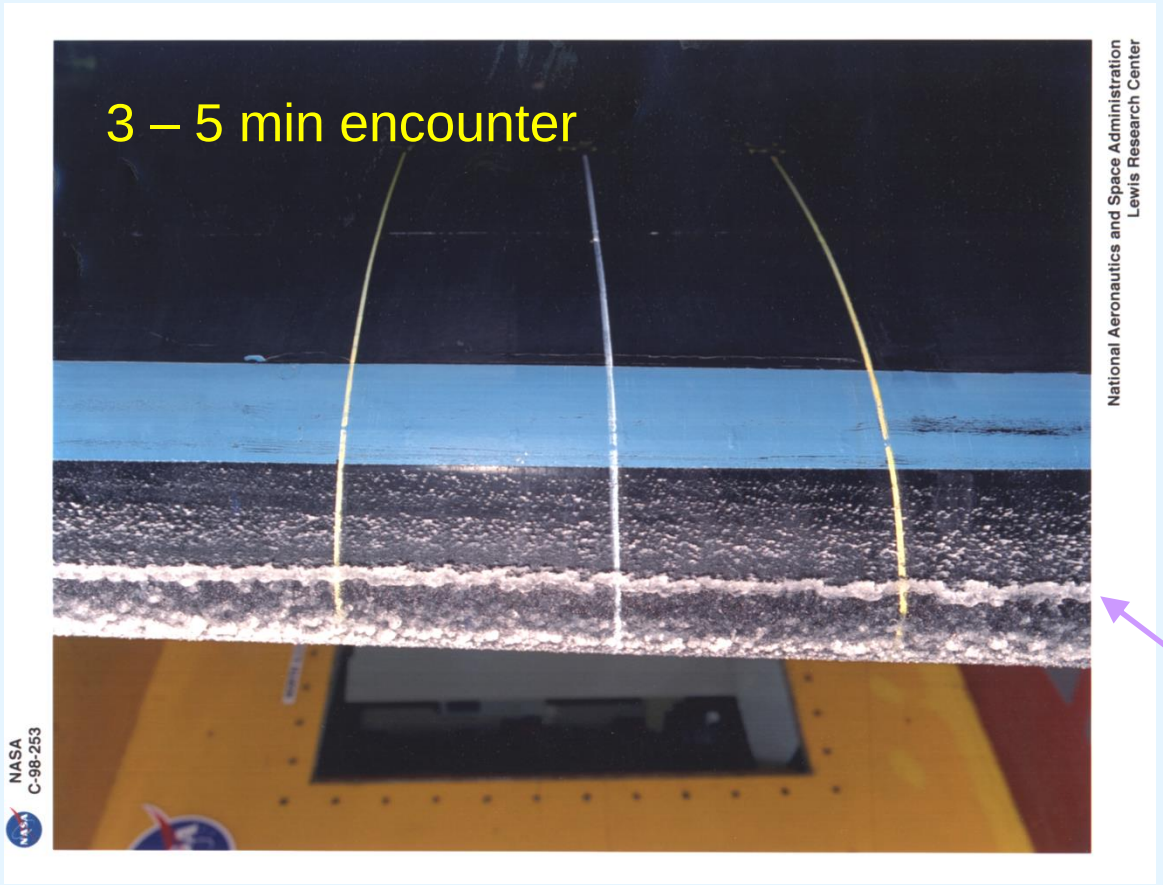
Pilot Training Aids:
http://aircrafticing.nasa.gov/
[*A Pilot's Guide to In-Flight / Ground Icing*]

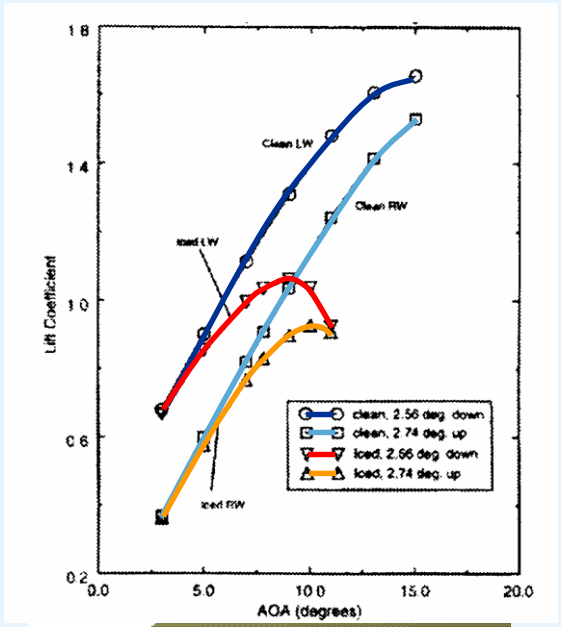
Additional Material

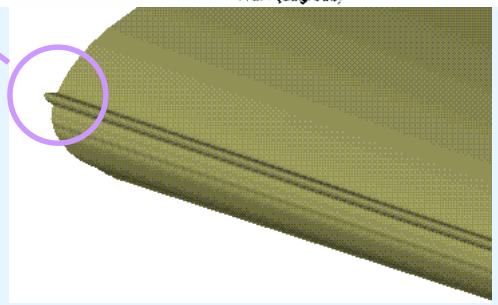


Case Study: In-Flight Icing

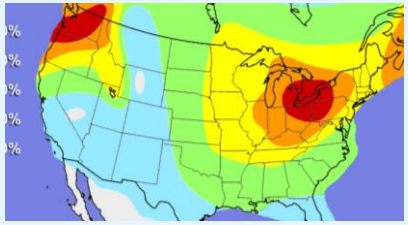
Accident: EMB-120; Monroe, MI; Jan 9, 1997



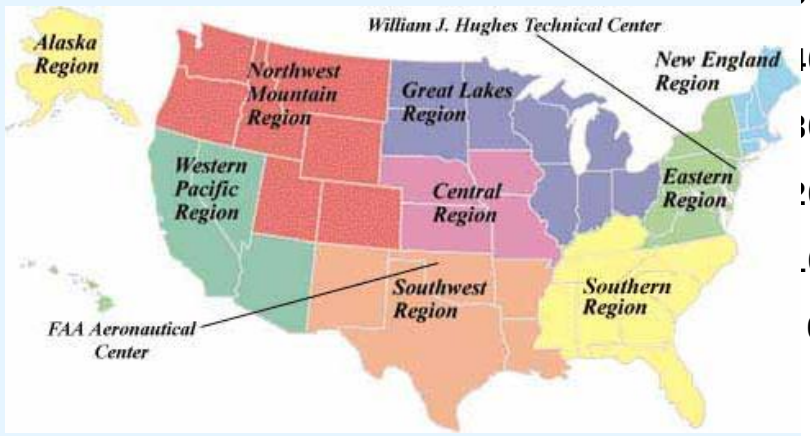


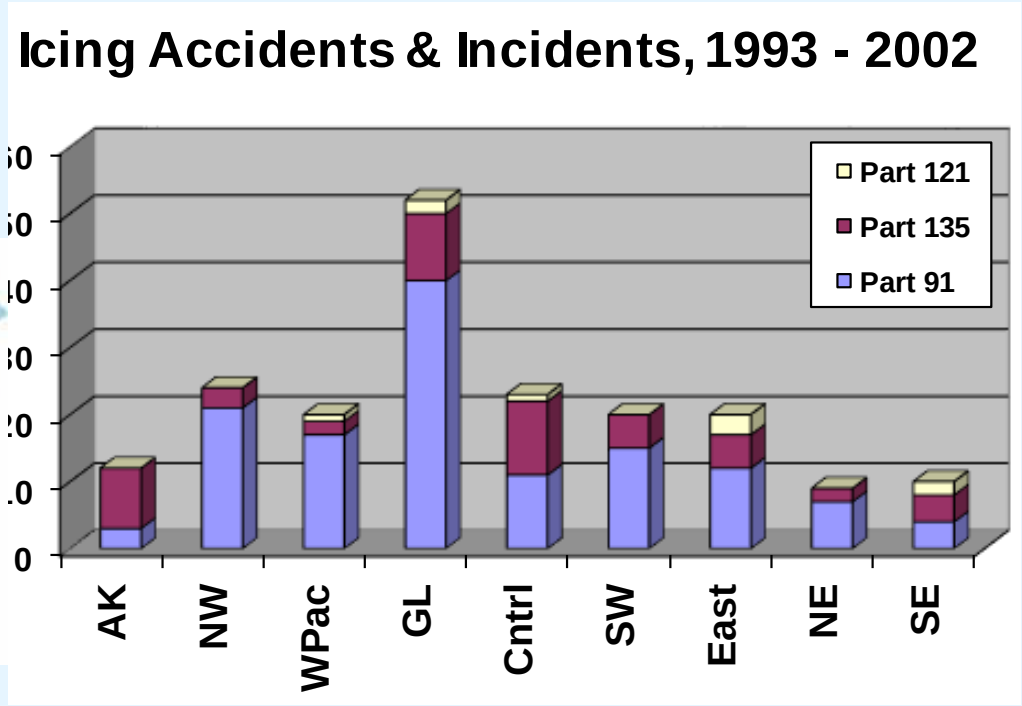


Icing Accidents by Region



FAA Regions





Average Pilot Experience

Part 91: ~ 2500 hrs

60% had over 1000 hrs

Part 135: ~ 5000 hrs

Part 121: ~ 9500 hrs

NASA Commissioned Study: Green, 2004

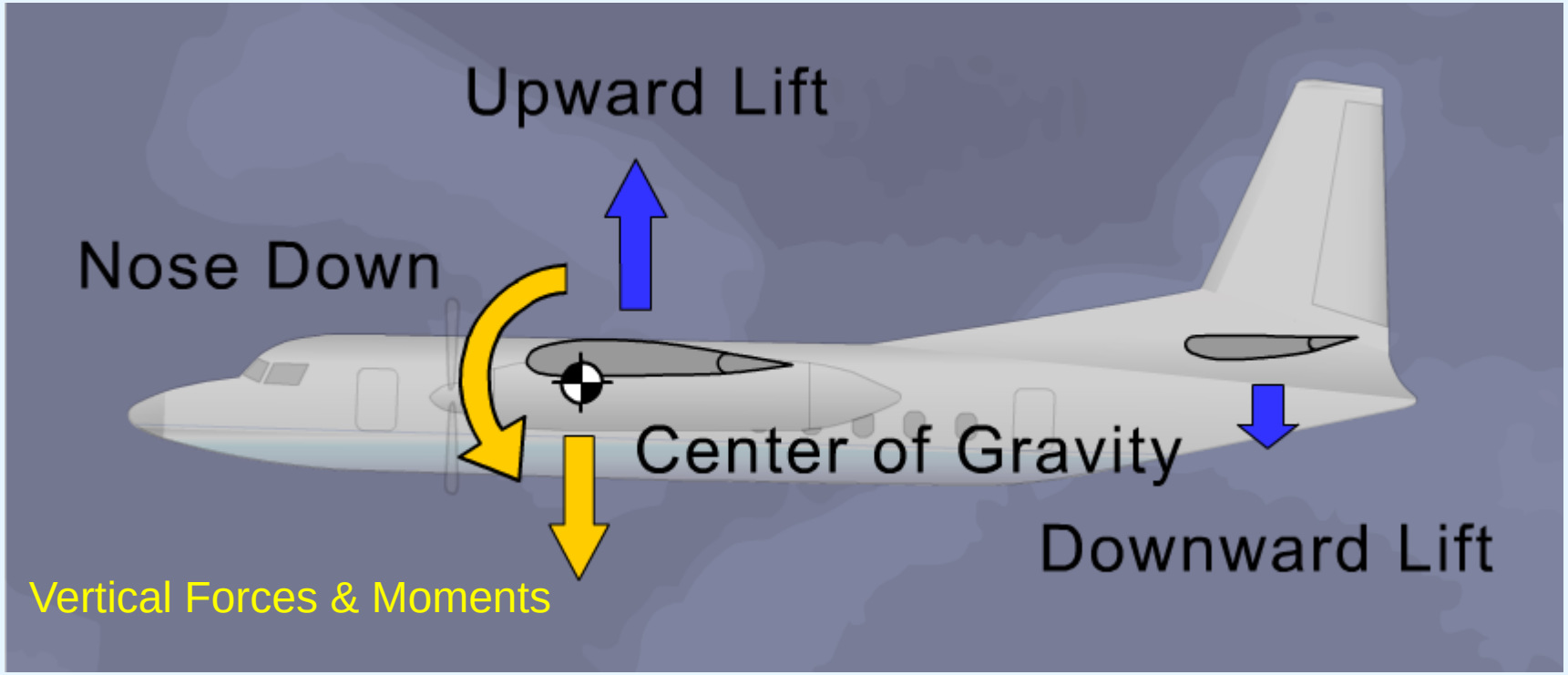
Part 91 ~ General Aviation

Part 135 ~ Commuter & Air Taxi

Part 121 ~ Larger Revenue Service

Note: *Data not normalized by traffic*

Role of the Tailplane

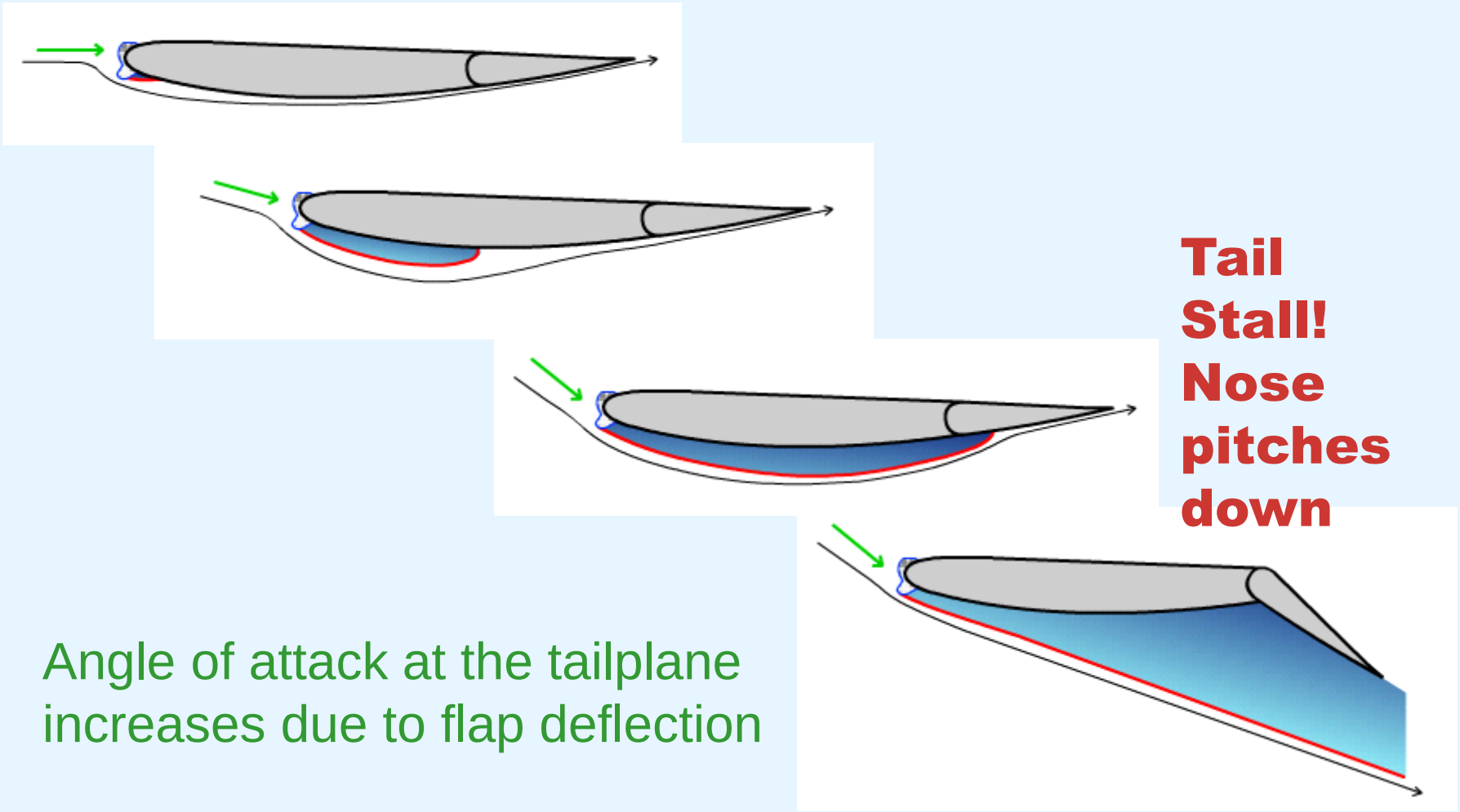


Tail Provides Downward Lift (upside down wing)

Tail is Opposite of Wing

Which aircraft have experienced tail stall? Historically, turboprops w/ large flap deflections and unpowered controls that use aerodynamic balance to trim.

Flow Separation – Ice on the Tailplane



Tail Stall! Nose pitches down

Angle of attack at the tailplane increases due to flap deflection

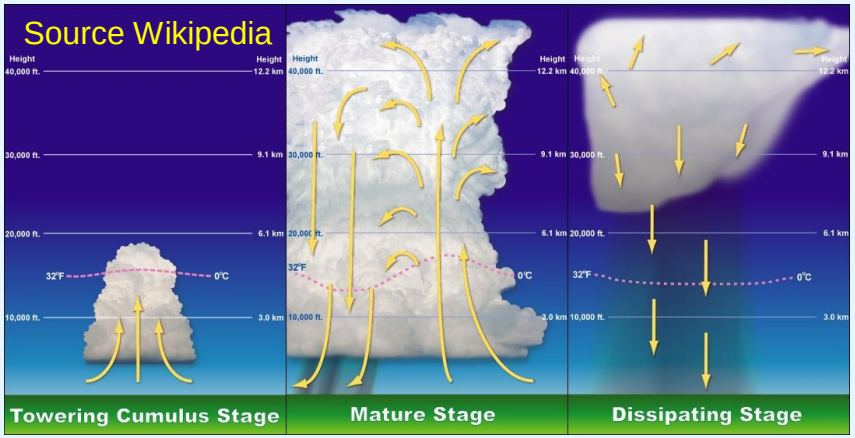
Ice Crystal Environment

- Typically above FL220, where supercooled liquid not likely present.
- Over deep convective activity*: CB, TS…Typhoon

- Light – Mod Turbulence
- No airframe icing
- In visible moisture

  Green or black on

  pilot radar at flight level

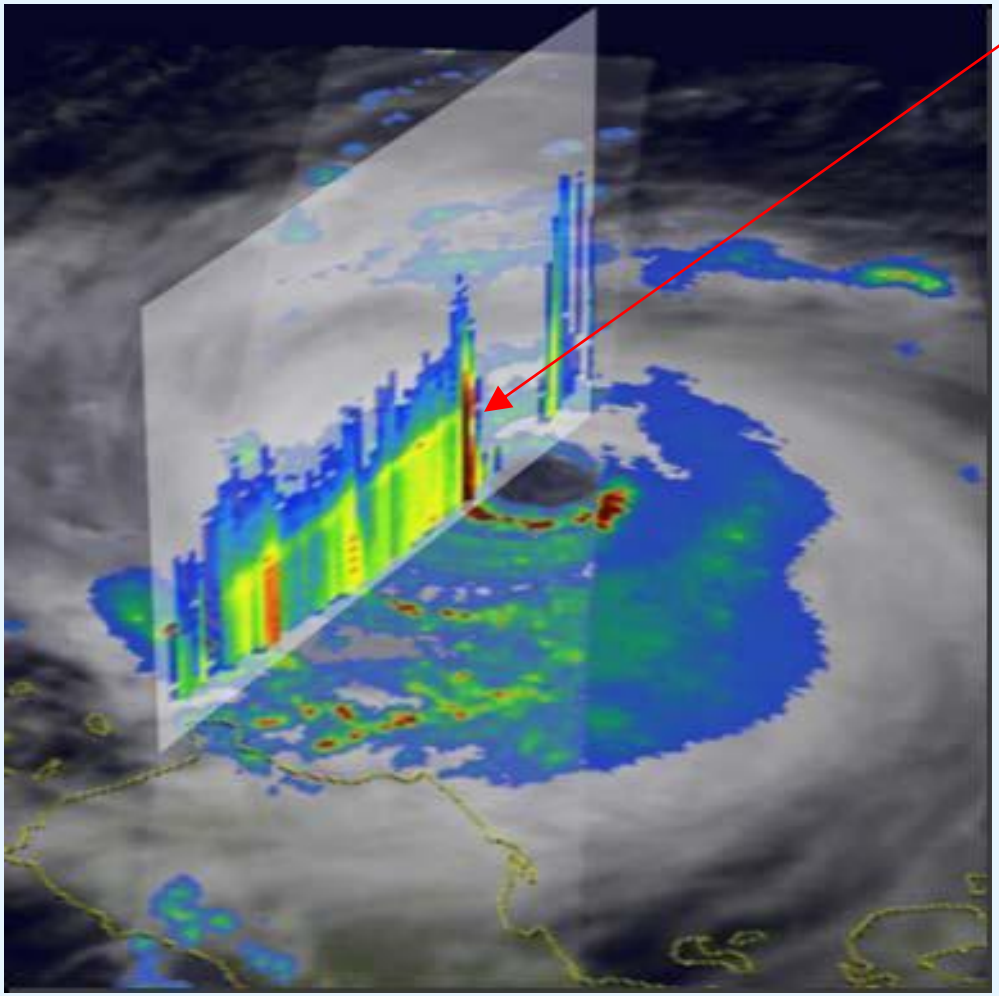


- TAT reading *warmer* than normal

  (ISA + ~10 C, Tropical Day)

* Moisture, lifted up, becomes ice crystals in very large quantities (upto 9 g/m^3), but with sizes too small to trigger typical radar thresholds.

Cross-Section of Convective Activity



Bright band indicates Freezing Level

Satellite & Radar cross-section of an event cloud.
NASA TRMM

Tropical Rainfall Measurement Mission

Moisture lifted up becomes ice crystals in very large quantities (upto 9 g/m^3), aka
High Ice Water Content (HIWC),
but too small to trigger typical radar thresholds.

PSL Engine Ice Crystal tests

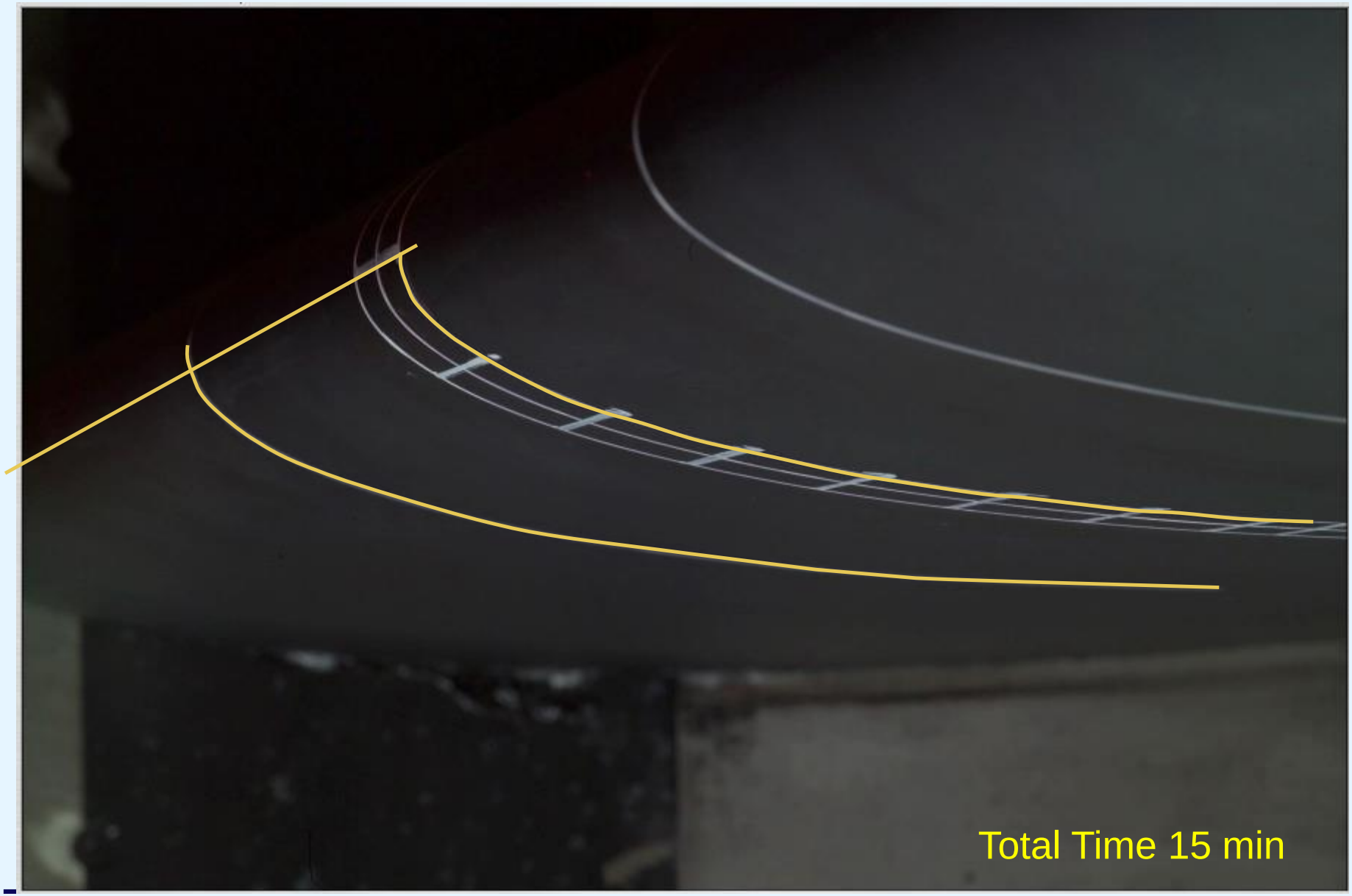
- Honeywell Engine Validation Test, 2013
  - Used the same instrumented engine that had been flight tested in 1998.

    (FAA AD => flight testing => design modification => Solution! The icing-susceptible engine is no longer in service.)
  - Easily recreated (first try) the Engine Rollback Event.

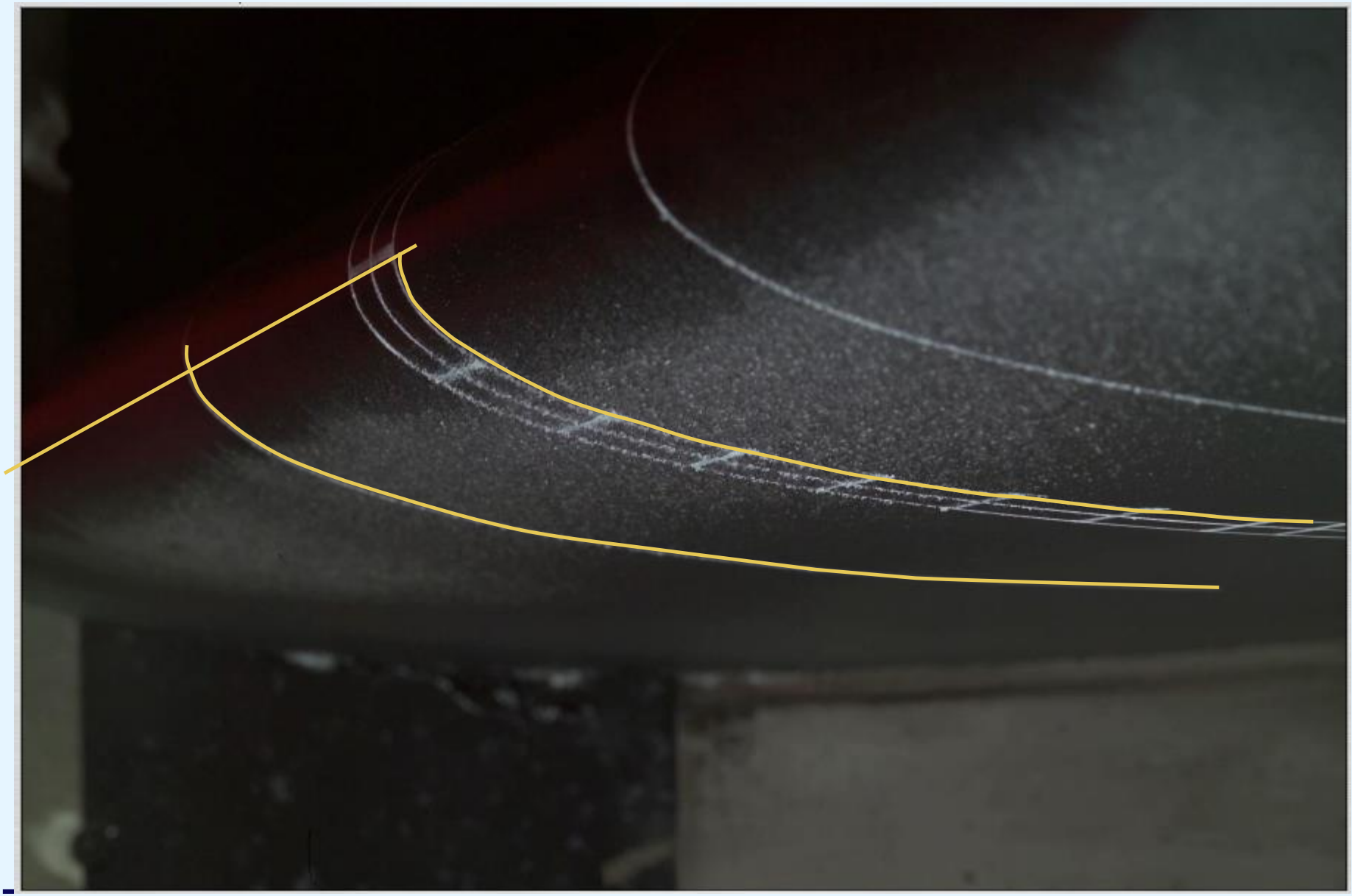
- Customer Driven Rig Test, 2014

- Honeywell Engine Test, 2015
  - Same engine model, more instrumentation – including imaging – in LPC.

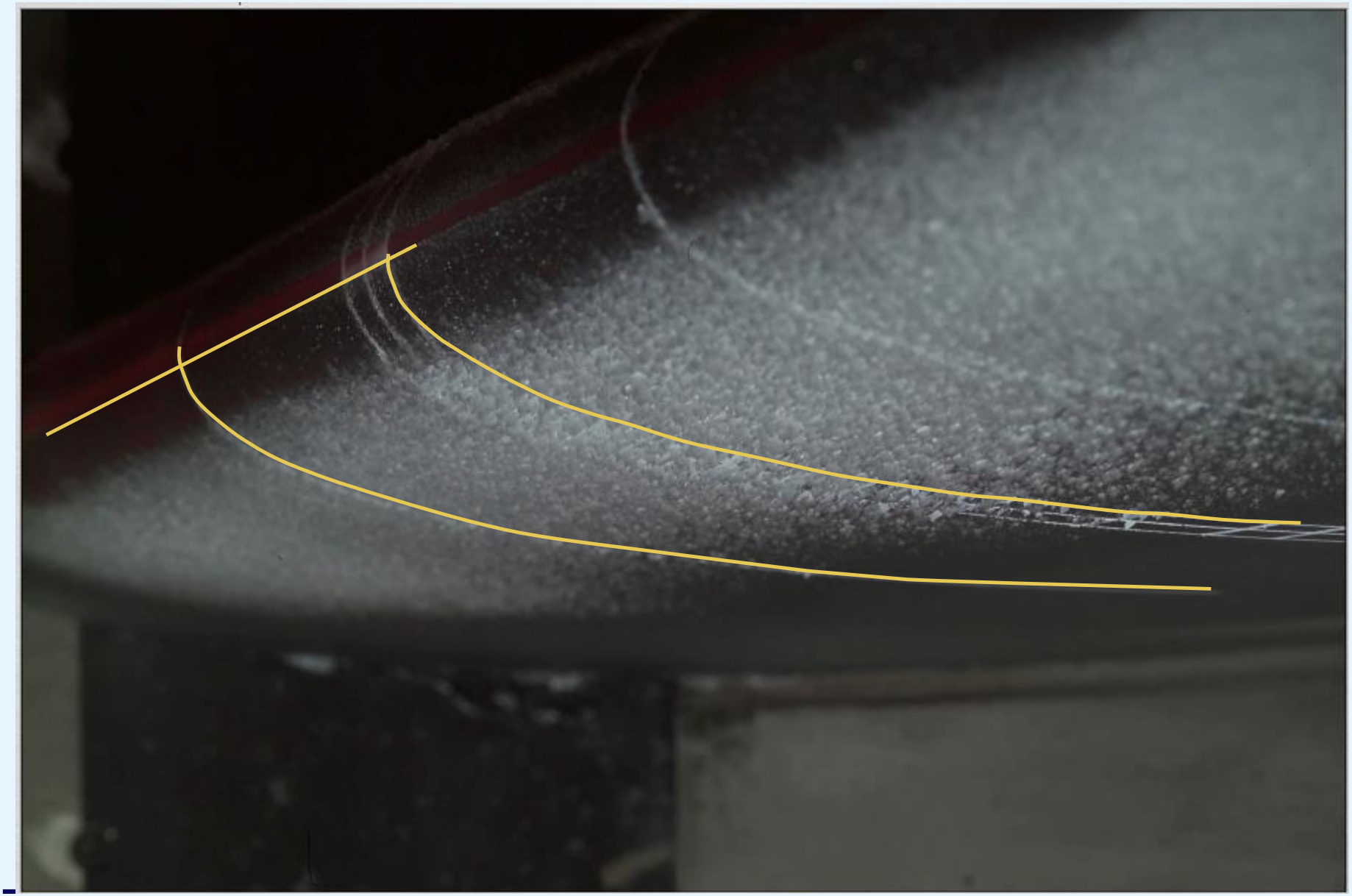
Ice Accretion Video: t= 0 steps



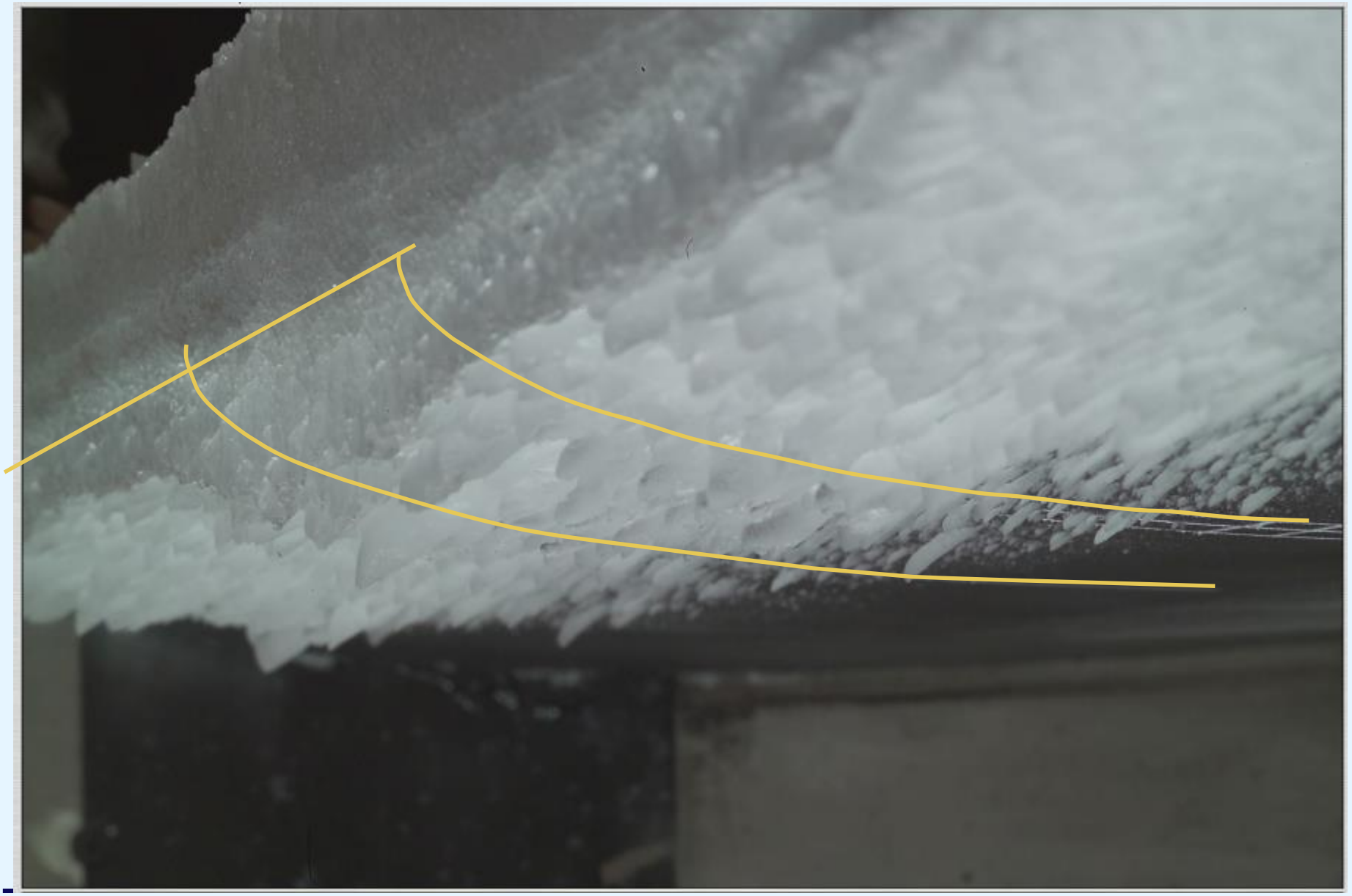
Ice Accretion Video: t= 2 steps



Ice Accretion Video: t= 4 steps



Ice Accretion Video: t= 25 steps



return