Airplane Icing

Accidents That Shaped Our Safety Regulations

Presented to: AE598 UW Aerospace Engineering Colloquium

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Topics

- Icing Basics
- Certification Requirements
- Ice Protection Systems
- Some Icing Generalizations
- Notable Accidents/Resulting Safety Actions
- Readings – For More Information

Icing Basics

- **How does icing occur?**
  - Cold object (airplane surface)
  - Supercooled water drops
    - Water drops in a liquid state below the freezing point
    - Most often in stratiform and cumuliform clouds
  - The airplane surface provides a place for the supercooled water drops to crystalize and form ice

Icing Basics

- **Important Parameters**
  - Atmosphere
    - Liquid Water Content and Size of Cloud
    - Drop Size and Distribution
    - Temperature
  - Airplane
    - Collection Efficiency
    - Speed/Configuration/Temperature

Icing Basics

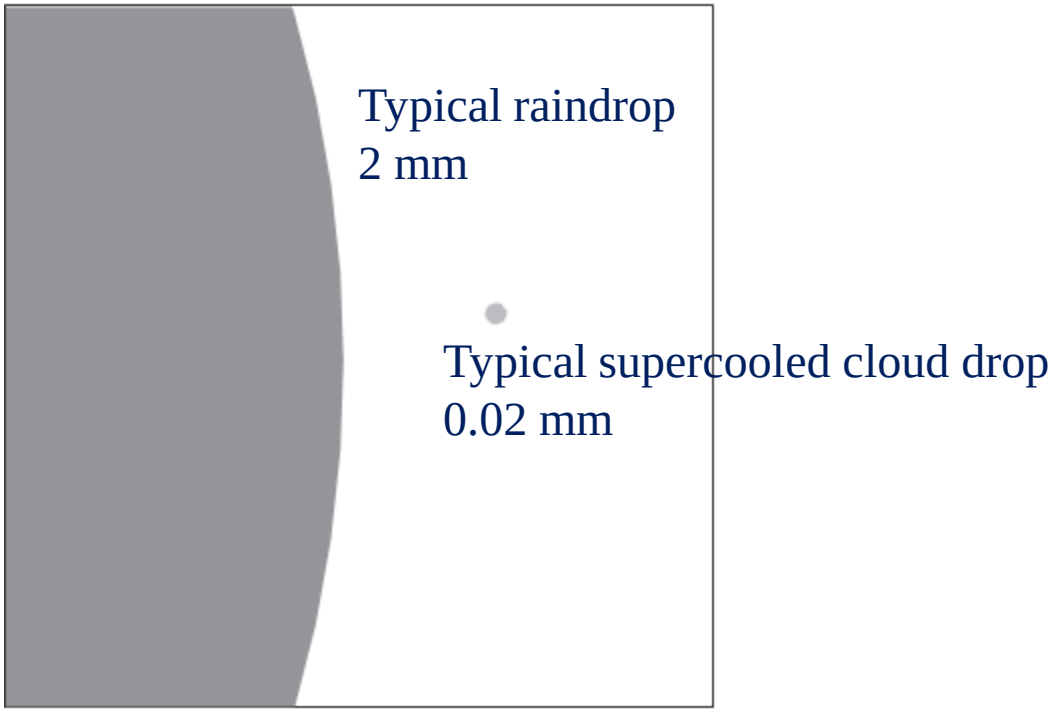
- **Cloud Characteristics**
  - Liquid water content is generally a function of temperature and drop size
    - The colder the cloud, the more ice crystals predominate rather than supercooled water
    - Highest water content near 0º C; below -40º C there is negligible water content
    - Larger drops tend to precipitate out, so liquid water content tends to be greater at smaller drop sizes
  - The average liquid water content decreases with horizontal extent (size) of the cloud

Icing Basics

About Drop Sizes

- Distribution of drop sizes
  - Usually range from 1 to about 50 µm
- Larger drop sizes have greater inertia and will impinge further aft on an airfoil
- Freezing drizzle and freezing rain result in much larger drop sizes
  - Freezing drizzle: 100µm to 500 µm
  - Freezing rain: >500 µm

Drop Size Comparison

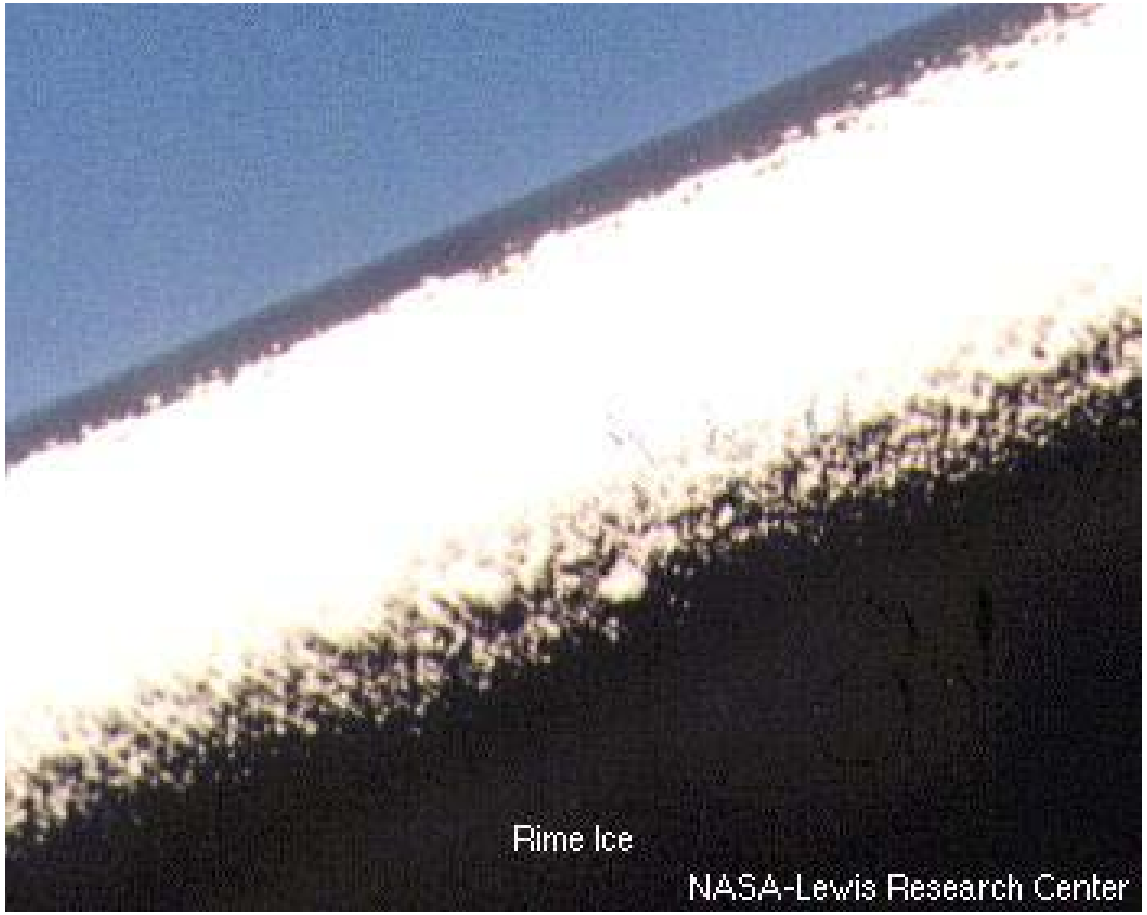


Icing Basics

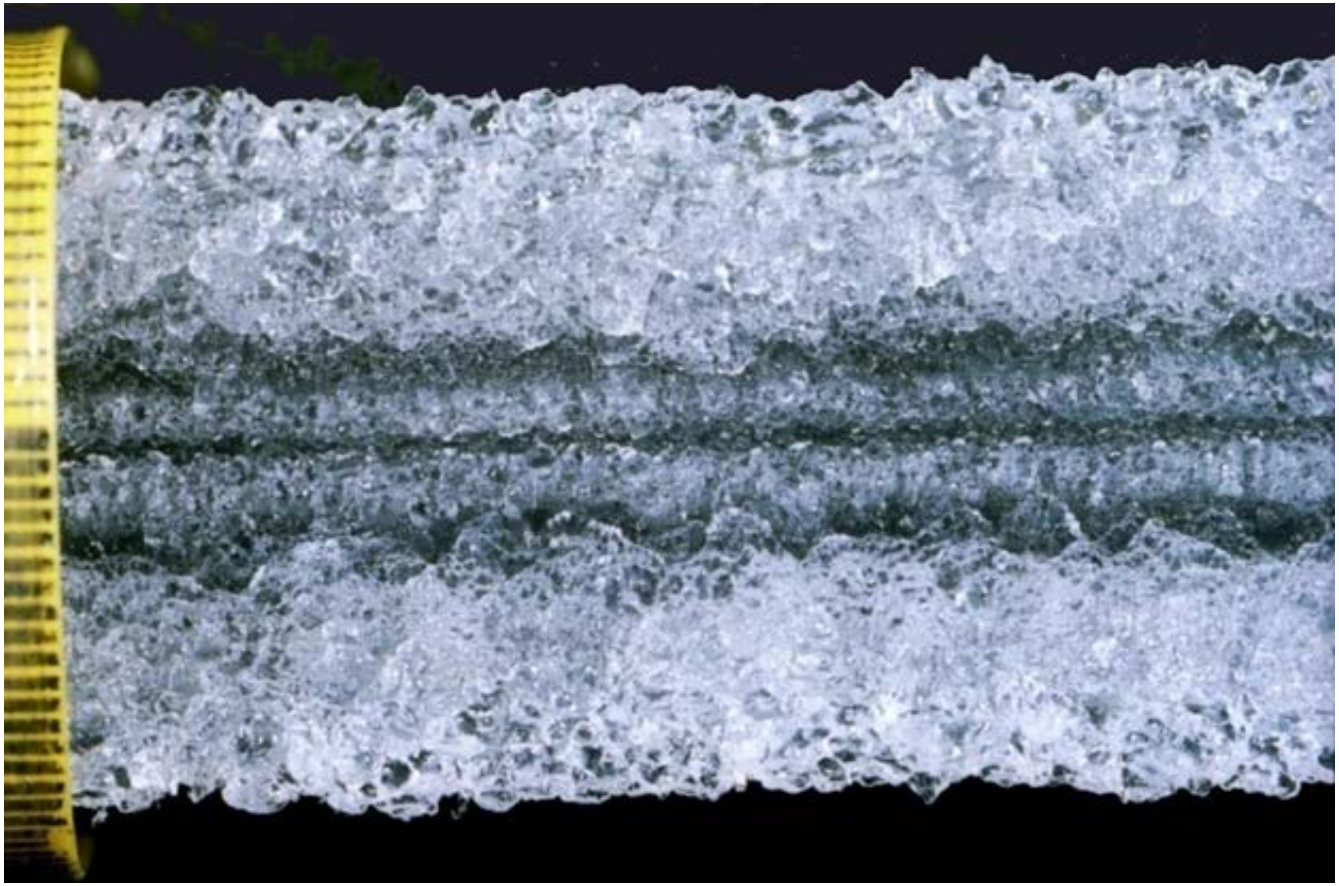
Types of ice accretions

- Rime ice
  - Rough, milky appearance
  - Generally conforms to shape of surface it is on
- Glaze (Clear) Ice
  - Transparent
  - Often flat or concave shape with single or double horns

Rime Ice



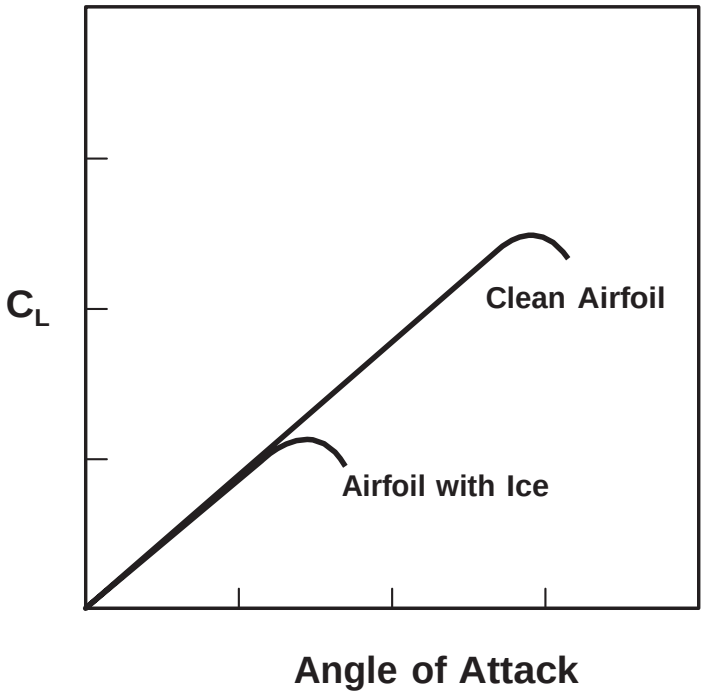
Glaze Ice



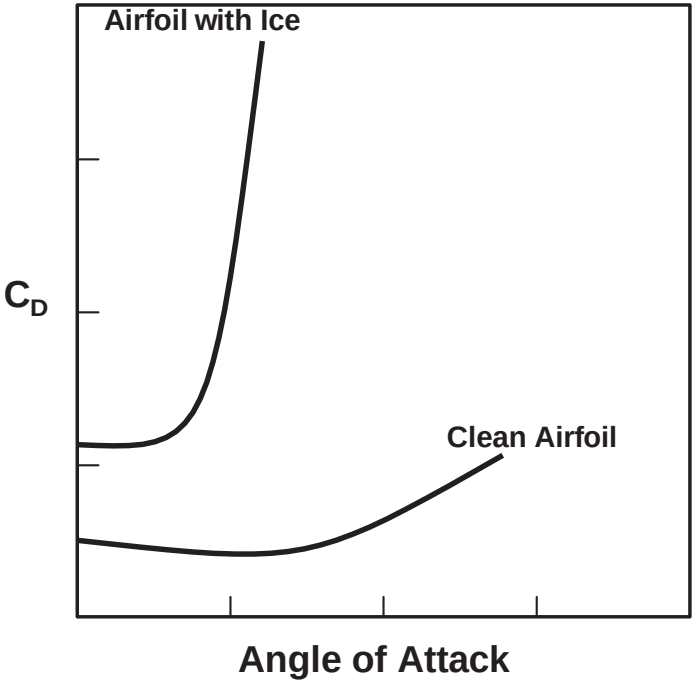
Aerodynamic Effects

Reduces Lift, Increases Drag

Effect on Lift



Effect on Drag



Certification Requirements

- Must determine critical ice accretions, considering the range of atmospheric conditions
  - Mean effective drop diameter
  - Liquid water content
  - Temperature
- Must provide adequate stall warning
- Operating speeds must provide adequate margin to stall warning and stall speeds
- Non-icing controllability requirements must be met in icing conditions
- Some performance degradation permitted

FIGURE 1

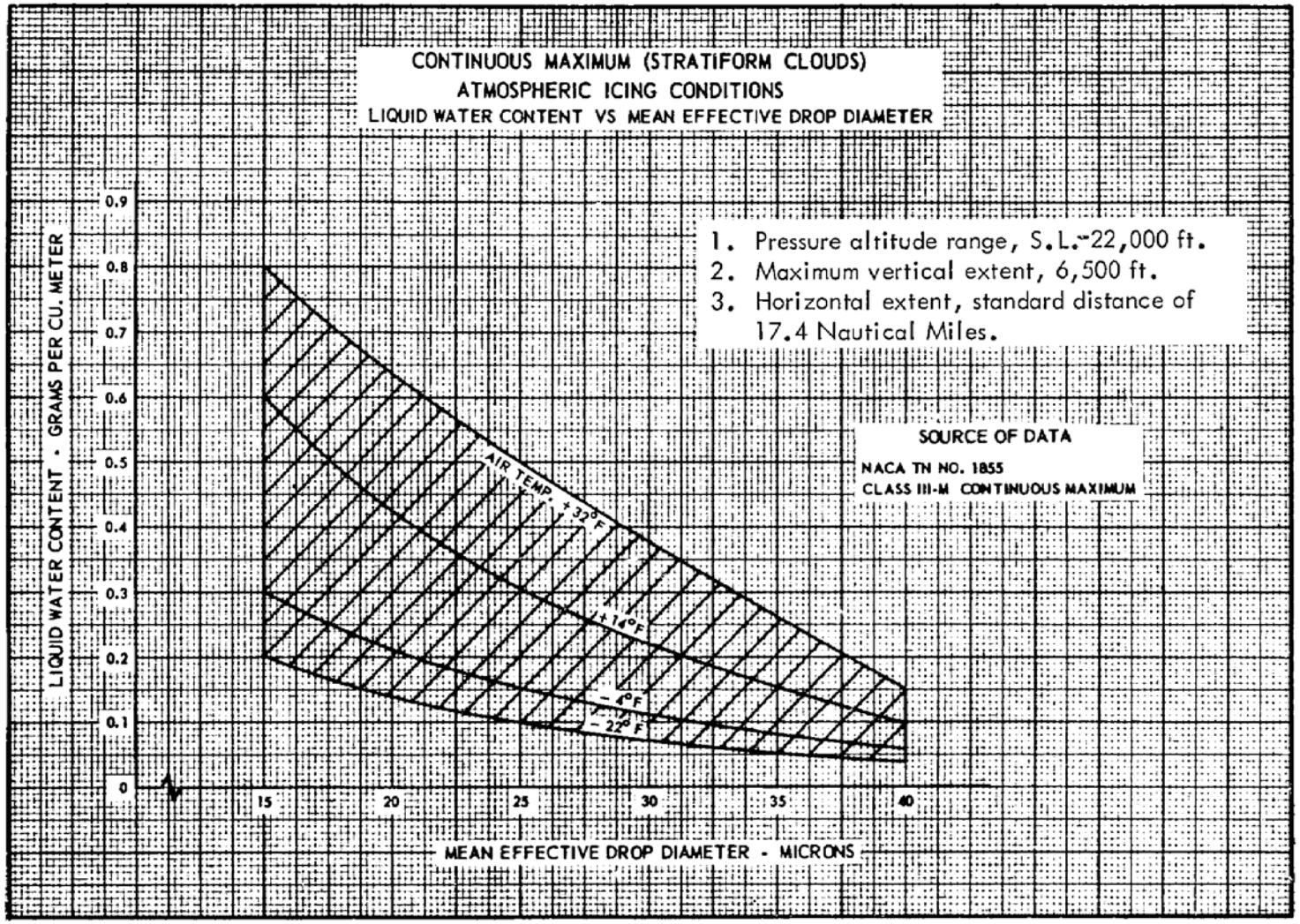
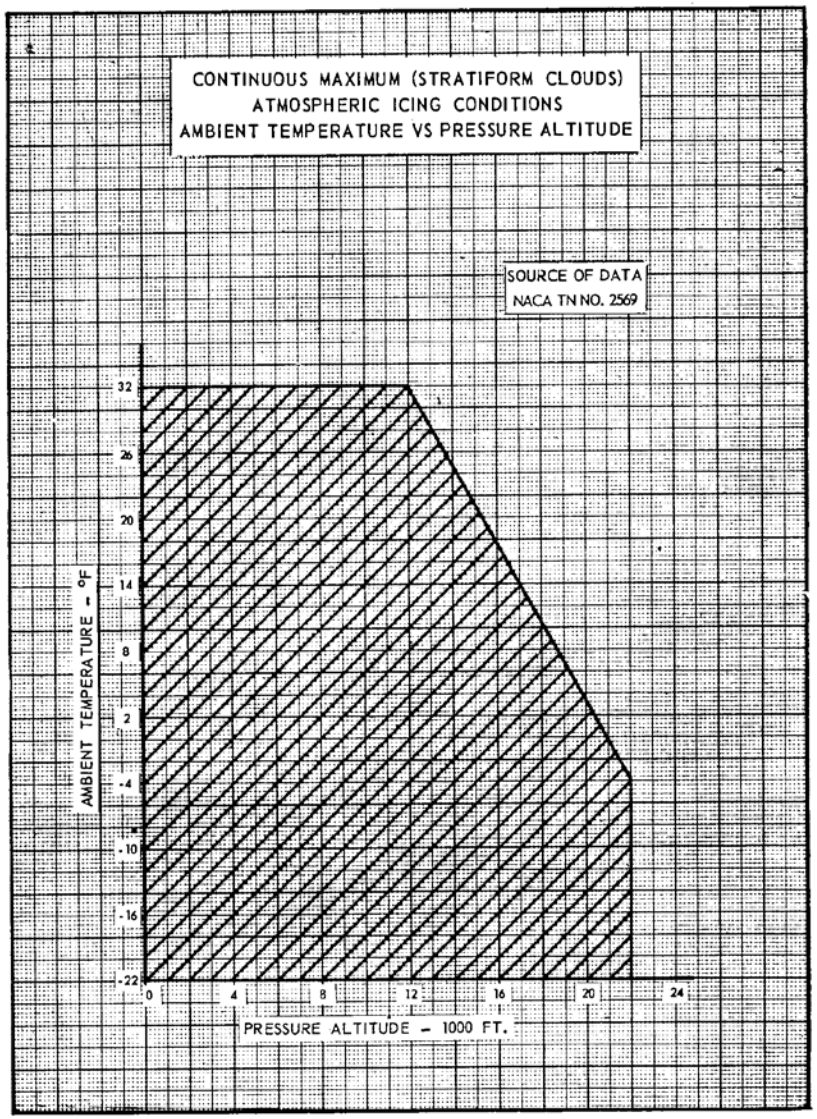

CONTINUOUS MAXIMUM (STRATIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER
1. Pressure altitude range, S.L.-22,000 ft.
2. Maximum vertical extent, 6,500 ft.
3. Horizontal extent, standard distance of 17.4 Nautical Miles.
SOURCE OF DATA
NACA TN NO. 1855
CLASS III-M CONTINUOUS MAXIMUM
AIR TEMP. + 32°F
+ 14°F
- 4°F
- 22°F
LIQUID WATER CONTENT - GRAMS PER CU. METER
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
15
20
25
30
35
40
MEAN EFFECTIVE DROP DIAMETER - MICRONS

FIGURE 2


CONTINUOUS MAXIMUM (STRATIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
AMBIENT TEMPERATURE VS PRESSURE ALTITUDE
SOURCE OF DATA
NACA TN NO. 2569
AMBIENT TEMPERATURE - °F
32
26
20
14
8
2
-4
-10
-16
-22
0
4
8
12
16
20
24
PRESSURE ALTITUDE - 1000 FT.

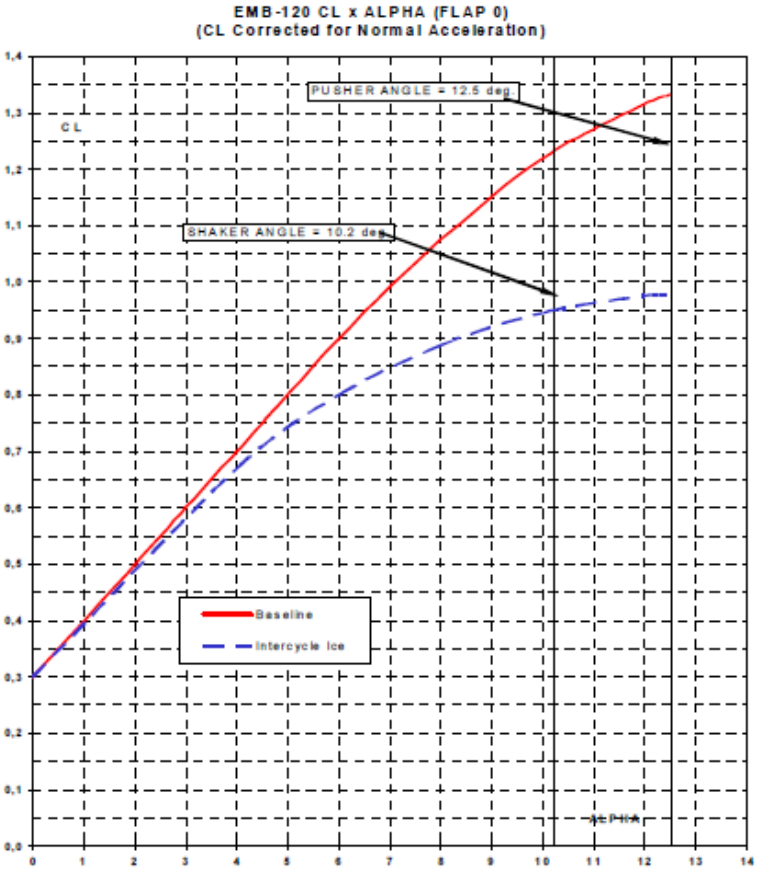
Icing Basics

Critical Ice Accretions

- Protected Areas
  - Pre-activation
  - Intercycle
  - Runback
- Unprotected Areas
  - Sandpaper
  - 45 Minute Hold Condition

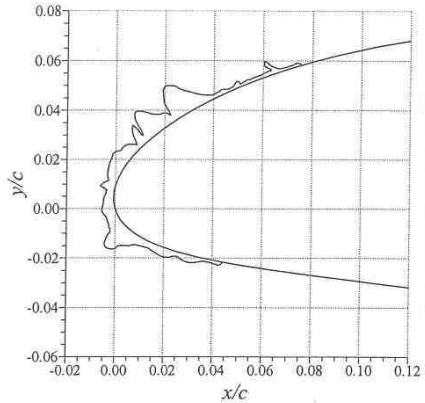
Lift Loss With Intercycle Ice Accretions

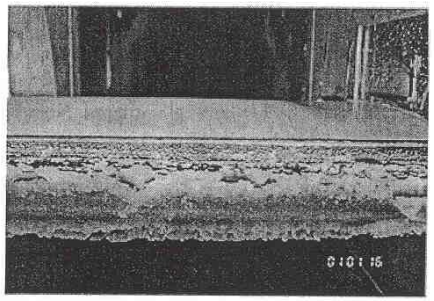
- **DOT/FAA/AR-06/48**

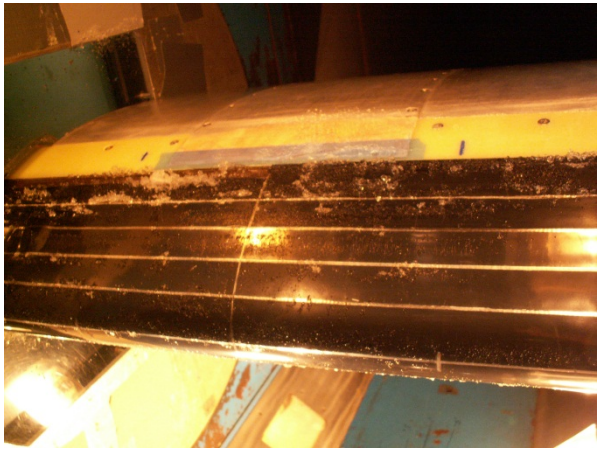


Examples of Critical Ice Accretions

- **Empirically determined**
- **Intercycle**
  - Low airspeed
  - Cold temperatures
  - Roughness







- **Runback**
  - Mechanical systems
    - Temperatures near freezing
  - Thermal systems
    - Codes can’t determine shape and location

Ice Protection Systems

- **Thermal**
  - Hot bleed air
  - Electric
- **Pneumatic Boots**
  - Rubber boot alternately inflated and deflated
  - Airplanes lacking leading edge high lift devices (flaps, slats) on the wings
- **Other**
  - Fluid Protection Systems
  - Electro-Mechanical

Some Icing Generalizations

- **Accretion efficiency depends on location and geometry**
  - Smaller and/or narrower – higher water catch efficiency
- **Airplanes affected comparatively more by icing:**
  - Smaller airplanes
  - Airplanes lacking leading edge high lift devices (flaps, slats) on the wings
  - Airplanes with pneumatic boot ice protection systems

Accidents That Shaped Current Icing Safety Regulations

Notable Icing Accidents

Air Florida 737	Washington, DC	Jan 13, 1982
United Express Jetstream 3101	Pasco, WA	Dec 26, 1989
American Eagle ATR-72	Roselawn, IN	Oct 31, 1994
Comair EMB-120	Monroe, MI	Jan 9, 1997
Challenger 601	Montrose, CO	Nov 28, 2004
Colgan Air DHC-8-400	Clarence Center, NY	Feb 12, 2009

Air Florida 737 Washington National

- Crashed into the Potomac River shortly after takeoff
- Inadequate lift due to ice and snow on the wings
- Significant engine thrust shortfall due to icing of engine pressure probes
- Air Florida crew not experienced in flying in winter weather conditions
- Airplane experienced difficulty in climbing immediately following rotation and subsequently stalled

Air Florida 737 Washington National

Safety Actions Taken:

- Requirements for approved ground deicing/anti-icing programs, including pre-takeoff contamination checks
- Research into improved deicing/anti-icing fluids
- Annual publication of fluid holdover times
- Use of engine anti-ice whenever icing conditions exist or are anticipated on ground or in flight

FAA TYPE I HOLDOVER TIME GUIDELINE

TABLE 1. FAA GUIDELINES FOR HOLDOVER TIMES SAE TYPE I FLUID MIXTURES ON CRITICAL AIRCRAFT SURFACES COMPOSED PREDOMINANTLY OF ALUMINUM AS A FUNCTION OF WEATHER CONDITIONS AND OUTSIDE AIR TEMPERATURE

CAUTION: THIS TABLE IS FOR DEPARTURE PLANNING ONLY AND SHOULD BE USED IN CONJUNCTION WITH PRETAKEOFF CHECK PROCEDURES.

Outside Air Temperature		Wing Surface	Approximate Holdover Times Under Various Weather Conditions (hours: minutes)							
Degrees Celsius	Degrees Fahrenheit		Freezing Fog or Ice Crystals	Snow, Snow Grains or Snow Pellets			Freezing Drizzle[2]	Light Freezing Rain	Rain on Cold Soaked Wing[3]	Other[4]
				Very Light[1]	Light[1]	Moderate				
-3 and above	27 and above	Aluminum	0:11-0:17	0:18-0:22	0:11-0:18	0:06-0:11	0:09-0:13	0:02-0:05	0:02-0:05	
below -3 to -6	below 27 to 21	Aluminum	0:08-0:13	0:14-0:17	0:08-0:14	0:05-0:08	0:05-0:09	0:02-0:05	CAUTION: No holdover time guidelines exist	
below -6 to -10	below 21 to 14	Aluminum	0:06-0:10	0:11-0:13	0:06-0:11	0:04-0:06	0:04-0:07	0:02-0:05		
Below -10	below 14	Aluminum	0:05-0:09	0:07-0:08	0:04-0:07	0:02-0:04				

THE RESPONSIBILITY FOR THE APPLICATION OF THESE DATA REMAINS WITH THE USER.

1 Use light freezing rain holdover times in conditions of very light or light snow mixed with light rain.
2 Use light freezing rain holdover times if positive identification of freezing drizzle is not possible.
3 This column is for use at temperatures above 0 degrees Celsius (32 degrees Fahrenheit) only.
4 Heavy snow, ice pellets, moderate and heavy freezing rain, hail.

SAE Type I fluid/water mixture must be selected so that the freezing point of the mixture is at least 10 °C (18 °F) below OAT.

CAUTIONS:

- The time of protection will be shortened in heavy weather conditions. Heavy precipitation rates or high moisture content, high wind velocity, or jet blast may reduce holdover time below the lowest time stated in the range. Holdover time may be reduced when aircraft skin temperature is lower than OAT.
- SAE TYPE I fluid used during ground deicing/anti-icing is not intended for and does not provide protection during flight.

TABLE 4B. FAA GUIDELINES FOR HOLDOVER TIMES ABAX ECOWING AD-49 TYPE IV FLUID MIXTURES AS A FUNCTION OF WEATHER CONDITIONS AND OUTSIDE AIR TEMPERATURE

CAUTION: THIS TABLE IS FOR DEPARTURE PLANNING ONLY AND SHOULD BE USED IN CONJUNCTION WITH PRETAKEOFF CHECK PROCEDURES.

Outside Air Temperature		Manufacturer Specific Type IV Fluid Concentration Neat-Fluid/Water (Volume %/Volume %)	Approximate Holdover Times Under Various Weather Conditions (hours: minutes)							
Degrees Celsius	Degrees Fahrenheit		Freezing Fog or Ice Crystals	Snow, Snow Grains or Snow Pellets			Freezing Drizzle[2]	Light Freezing Rain	Rain on Cold Soaked Wing[3]	Other[4]
				Very Light[1]	Light[1]	Moderate				
-3 and above	27 and above	100/0	3:20-4:00	2:50-3:00	1:50-2:50	1:10-1:50	1:25-2:00	1:00-1:25	0:10-1:55	
		75/25	2:25-4:00	2:05-2:15	1:40-2:05	1:20-1:40	1:55-2:00	0:50-1:30	0:10-1:40	
		50/50	0:25-0:50	0:40-0:45	0:25-0:40	0:15-0:25	0:15-0:30	0:10-0:15	CAUTION: No holdover time guidelines exist	
below -3 to -14	below 27 to 7	100/0	0:20-1:35	2:50-3:00	1:50-2:50	1:10-1:50	0:25-1:25[5]	0:20-0:25[5]		
		75/25	0:30-1:10	2:05-2:15	1:40-2:05	1:20-1:40	0:15-1:05[5]	0:15-0:25[5]		
below -14 to -26	below 7 to -14.8	100/0	0:25-0:40	0:40-0:50	0:30-0:40	0:15-0:30				

THE RESPONSIBILITY FOR THE APPLICATION OF THESE DATA REMAINS WITH THE USER.

1 Use light freezing rain holdover times in conditions of very light or light snow mixed with light rain.
2 Use light freezing rain holdover times if positive identification of freezing drizzle is not possible.
3 This column is for use at temperatures above 0 °C (32 °F) only.
4 Heavy snow, ice pellets, moderate and heavy freezing rain, and hail.
5 No holdover time guidelines exist for this condition below -10 °C (14 °F).

CAUTIONS:

- The time of protection will be shortened in heavy weather conditions. Heavy precipitation rates or high moisture content, high wind velocity, or jet blast may reduce holdover time below the lowest time stated in the range. Holdover time may be reduced when aircraft skin temperature is lower than OAT.
- ABAX ECOWING AD-49 TYPE IV fluid used during ground deicing/anti-icing is not intended for and does not provide protection during flight.

United Express Jetstream 3101

- Crashed 400 feet short of the runway
- Airplane had been in clouds in icing conditions for 9-1/2 minutes prior to crash
- Tower controller saw airplane nose over and crash short of the runway
- Investigation determined that an accumulation of ice had probably caused a stall of the horizontal stabilizer

Ice Contaminated Tailplane Stall (ICTS)

- Airflow separation on lower surface of tail
- Exacerbated by ice, lowering of flaps, which increases downwash angle on tail
- Reduction or loss in pitch control or pitch stability
- Can cause elevator hinge moment reversal, which may cause control column to suddenly move forward
- Recovery action is opposite to that for a wing stall

United Express Jetstream 3101

Safety Actions Taken:

- Ice Contaminated Tailplane Stall (ICST) study conducted
- Airplanes deemed to be potentially susceptible were tested
- New certification requirement to test airplanes for ICTS susceptibility

ATR-72 Roselawn

- Airplane was in a holding pattern at around 8,000 feet in icing conditions
- Investigation determined that freezing drizzle was encountered, which has larger drop sizes than used for airplane certification
- A ridge of ice formed on one wing aft of the de-icing boots and in front of the aileron
- Caused a sudden aileron reversal, subsequent roll, and loss of control

ATR-72 Roselawn

Safety Actions Taken:

- Turboprop airplanes with deicing boots tested for susceptibility to roll upset
- Pilot cues developed to identify when an airplane is in severe icing conditions and mandatory procedures required an immediate exit
- New certification requirements developed that require consideration of supercooled large drops for a certain class of airplanes (final adoption expected this summer)

Comair EMB-120 Monroe

- Crashed after a rapid descent after an uncommanded roll excursion
- Combination of ice accretions on the wings and low airspeed
- Ice protection system (boots) not activated because crew felt icing was not significant
- Stall warning system did not provide an adequate warning due to the effects of ice accretion (which were not taken into account in the design)
- The autopilot was being used, which may have masked the deteriorating roll performance

Comair EMB-120 Monroe

Safety Actions Taken:

- New requirements for:
  - Activation of ice protection systems
  - Stall warning for icing conditions
  - Minimum airspeeds in icing conditions

Activation of Ice Protection Systems

- In many accidents, the ice protection system had not been activated
  - “Trace” or “light” icing
  - Ice bridging
  - Less effective shedding until enough ice is present
- Interim guidance, training, procedures emphasized early activation of ice protection – at first sign of ice accretion
- New regulations require one of 3 methods:
  - Primary ice detector
  - Advisory ice detector plus first sign of ice accretion
  - Defined conditions conducive to icing

Challenger 601 Montrose

- Crashed during takeoff in snowy conditions
- Airplane had been parked before the flight while wet snow fell for about 45 minutes
- Airplane was not de-iced before takeoff
- Supercritical airfoil, no leading edge high lift devices

Challenger 601 Montrose

Safety Actions Taken:

- "Clean" wing concept re-emphasized – no amount of ice on critical surfaces is acceptable before takeoff
- Requirement for pilots of turbojet airplanes without leading edge high lift devices to verify, visually and tactilely (hands on surface), there is no ice on wing leading edges or upper surfaces before takeoff in conditions conducive to icing
- Rule removed that had allowed takeoff with frost if that frost is "polished"

Colgan Air DHC-8-400

- On approach into Buffalo-Niagara Airport, airplane entered into a stall from which it did not recover
- Airplane encountered icing, but the icing was of minimal effect
- Planned approach speed inconsistent with speeds for icing conditions
- Stall warning (stick shaker) activated at higher than expected speed
- Pilot reacted by pulling back on the control column, leading to several stick pusher activations
- Pilot continued pulling back, more forcefully after each pusher activation

Colgan Air DHC-8-400

Safety Actions Taken:

- Ensure that tailplane stall recovery procedures are not included in manuals, training, and procedures for airplanes not susceptible to ICTS
- For airplanes not susceptible to ICTS, explicitly state that the airplane is not susceptible to ICTS

Readings – For More Information

AC 20-73A, Aircraft Ice Protection	http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/0/96cc6215cf1dfa72862571d4006cdea2/$FILE/AC20-73A.pdf
FAA Inflight Icing Webinar	https://www.faasafety.gov/gslac/ALC/course_content.aspx?cID=33&sID=148&preview=true
NASA Icing Training Courses	http://aircrafticing.grc.nasa.gov/courses.html
BAE Systems Booklet, Think Ice!	http://www.regional-services.com/Files/Pdf/pwk_0161-Think-Ice.pdf
AC 25.1419-1A, Certification of Transport Category Airplanes for Flight in Icing Conditions	http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/0/81a657cc460ec9c586256ec300692df2/$FILE/AC25-1419-1A.pdf
AC 91-74A, Pilot Guide: Flight in Icing Conditions	http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/0/4c8192bb0b733862862573d2005e7151/$FILE/AC%2091-74A.pdf

QUESTIONS?