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

Typical raindrop
2 mm

Typical supercooled cloud drop
0.02 mm
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

\[ C_L \]

Clean Airfoil

Airfoil with Ice

Effect on Drag

\[ C_D \]

Airfoil with Ice

Clean Airfoil

Angle of Attack
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

LIQUID WATER CONTENT - GRAMS PER CU. METER

MEAN EFFECTIVE DROP DIAMETER - MICRONS
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

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

<table>
<thead>
<tr>
<th>Outside Air Temperature</th>
<th>Wing Surface</th>
<th>Approximate Holdover Times Under Various Weather Conditions (hours: minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees Celsius</td>
<td>Degrees Fahrenheit</td>
<td>Freezing Fog or Ice Crystals</td>
</tr>
<tr>
<td>-3 and above</td>
<td>27 and above</td>
<td>Aluminum</td>
</tr>
<tr>
<td>below -3 to -6</td>
<td>below 27 to 21</td>
<td>Aluminum</td>
</tr>
<tr>
<td>below -6 to -10</td>
<td>below 21 to 14</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Below -10</td>
<td>below 14</td>
<td>Aluminum</td>
</tr>
</tbody>
</table>

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 9 degrees Celsius (16 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 PRETAKEOF CHECK PROCEDURES.

<table>
<thead>
<tr>
<th>Outside Air Temperature</th>
<th>Manufacturer Specific Type IV Fluid Concentration (Volume %):</th>
<th>Approximate Holdover Times Under Various Weather Conditions (hours: minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-2014 Holdover Times Tables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees Celsius</td>
<td>Degrees Fahrenheit</td>
<td>Neat-Fluid/Water (Volume %:Volume %)</td>
</tr>
<tr>
<td>-3 and above</td>
<td>27 and above</td>
<td>100/0</td>
</tr>
<tr>
<td>-3 to -14</td>
<td>below 27 to 7</td>
<td>75/25</td>
</tr>
<tr>
<td>-14 to -26</td>
<td>below 7 to -14</td>
<td>50/50</td>
</tr>
</tbody>
</table>

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 tactiley (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

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<tr>
<td>NASA Icing Training Courses</td>
<td><a href="http://aircrafticing.grc.nasa.gov/courses.html">http://aircrafticing.grc.nasa.gov/courses.html</a></td>
</tr>
<tr>
<td>BAE Systems Booklet, Think Ice!</td>
<td><a href="http://www.regional-services.com/Files/Pdf/pwk_0161-Think-Ice.pdf">http://www.regional-services.com/Files/Pdf/pwk_0161-Think-Ice.pdf</a></td>
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QUESTIONS?