Engine Icing in High Ice Water Content Environments

Overview and Research Initiatives

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By: Dr. James T. Riley

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OUTLINE

- Engine Harmonization Working Group
- Database of Engine Icing Events
- Research on High Ice Water Content Environments
- Proposed Appendix D to Part 33
- Overview of EHWG Mixed-Phase/Glaciated Icing Technology Plan
- Summary

Engine Harmonization Working Group (EHWG)

- **Power Plant Installation Working Group (PPIHWG)**
- **Under Aviation Rulemaking Advisory Committee (ARAC)**
- **Chairs of EHWG:**
  - Jeanne Mason – Boeing
  - Robert Mazzawy – Trebor Systems
- **Participating Organizations include GE, PW, Rolls Royce, Honeywell, Snelma, Boeing, Cessna, FAA, TC, CAA**

EHWG Database of Engine Icing Events in Commercial Service, 1988-2003

- **Over 100 in-service engine events over the period 1988 to 2003**
  - many resulting in powerloss
  - 6 resulted in multiple engine flameouts
  - Damage from core compressor ice shed in some events
  - No accidents
  - Near anvil of thunderstorms, tropical storms
  - Many events in Southeast Asia
- **See also AIAA-2006-0206 by Mason, et. al.**

Common Observations During Events

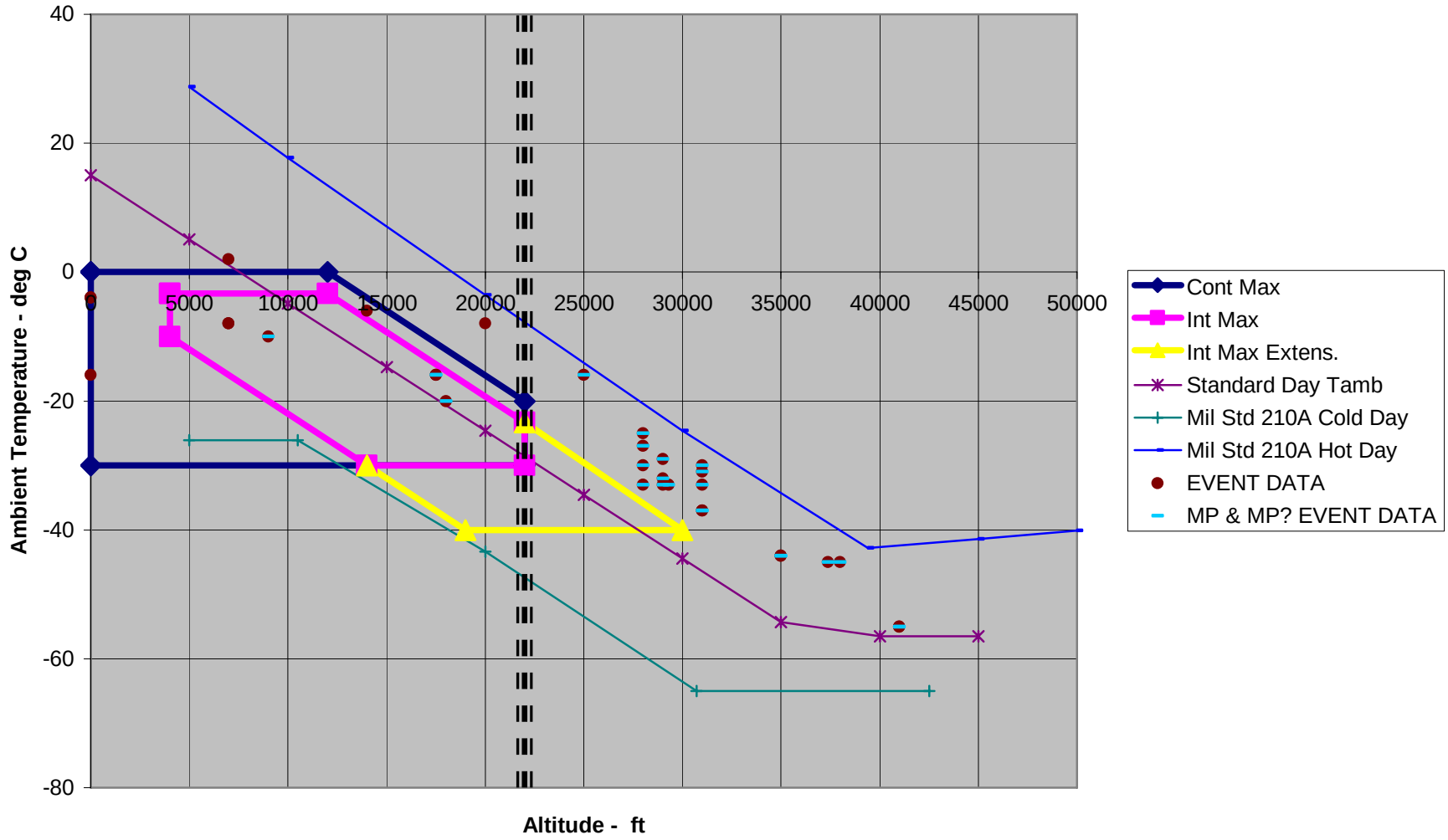
- Aircraft flying in the vicinity of a thunderstorm or tropical storm
- Temperatures usually 10-15 degrees warmer than a standard atmosphere
- TAT probe freezing often occurs
- Usually no significant airframe icing; sometimes ice detector indicates presence of liquid, but usually not
- Pilots report apparent “heavy rain” on the windscreen
- Usually between 20000 – 30000’, but as high as 38,000’ and as low as 9,000’
- Often flying around a heavy-echo region, but typically only in the green-echo or no-echo region

Interpretation of Common Observations

- Very high IWC regions near the cores of thunderstorms or in tropical storms composed mainly of small ice particles that do not produce significant radar echoes
- Probably not associated with much liquid water, although liquid can be present
- Reported “heavy-rain on windscreen” almost certainly very high mass of small ice particles melting on windscreen (cold temperatures, sometimes colder than –40 C preclude rain, and pilots in one case noted the lack of sound of rain normally heard)
- Type of TAT freezing observed is known to be caused by ingestion of ice particles

Altitude and Temperature of Engine Icing Events

Commercial Service Data Base of Icing Events compared with FAR Part 25 Appendix C Icing Envelope Limits



MIXED-PHASE/GLACIATED CONDITIONS

- **Stratiform clouds**
  - Extensive in-flight research, especially in recent years
  - Ice water content (IWC) measurements low to moderate
    - rarely measured as more than .5 g/m3, usually much lower
  - Not believed to be associated with engine problems
- **Deep Convective Clouds**
  - Data limited
  - High IWCs measured, calculated
  - Believed to be associated with engine problems

MIXED-PHASE/GLACIATED CONDITIONS STRATIFORM CLOUDS

- **Research dating back to early 1980s relied mainly on 2D OAPs**
  - DOT/FAA/AR-97/66 by Jeck surveys this data
  - IWCs for stratiform clouds rarely reported to be more than .5 g/m3 and typically much less
- **More recent research (late 1990s and later) by Environment Canada (EC) using Convair 580 employed Nevzorov Probe as well as 2D OAPs**
  - Airspeeds about 100 m/s
  - IWCs rarely measured as more than .5 g/m3 and typically much less

MIXED-PHASE/GLACIATED CONDITIONS DEEP CONVECTIVE CLOUDS

- **Based on examination of engine icing events in commercial service**
- **Events tend to occur in deep convective complexes**
  - Anvils of thunderstorms
  - Tropical storms
- **Airspeeds on order of 200 m/s**
- **IWCs may reach 5 g/m3 or higher (theoretically 10 g/m3)**
- **High Ice Water Content Environments**

RESEARCH ON ICING CONDITIONS IN DEEP CONVECTIVE CLOUDS

- **McNaughtan Data - *Mech. Eng. 283,* 1959.**
- **Extensive data set – 101 flights, 44.5 hrs of in-cloud data**
- **Some very high IWCs (7 g/m3) reported**
- **However, in Task 1 of the Plan the sampling is described as "non-ideal" with several correction factors that can no longer be traced. Thus the "accuracy … can no longer be confirmed."**
- **More recent research is limited**
  - AIAA-1999-0498 by Strapp, et. al.,
  - J. Aircraft 1998 by Lawson, et. al.

PROPOSED APPENDIX D TO PART 33 Mixed Phase and Ice Crystal Icing Envelope (Deep Convective Clouds)

- **Figure D-1 is largely based on event database**
- **Figure D-2 is based on**
  - adiabatic calculation
  - McNaughtan data
- **Figure D-3 is based on McNaughtan data**
- **Analysis by Walter Strapp of EC**

Figure D-1 FAR 33 Appendix D Icing Envelope Limits

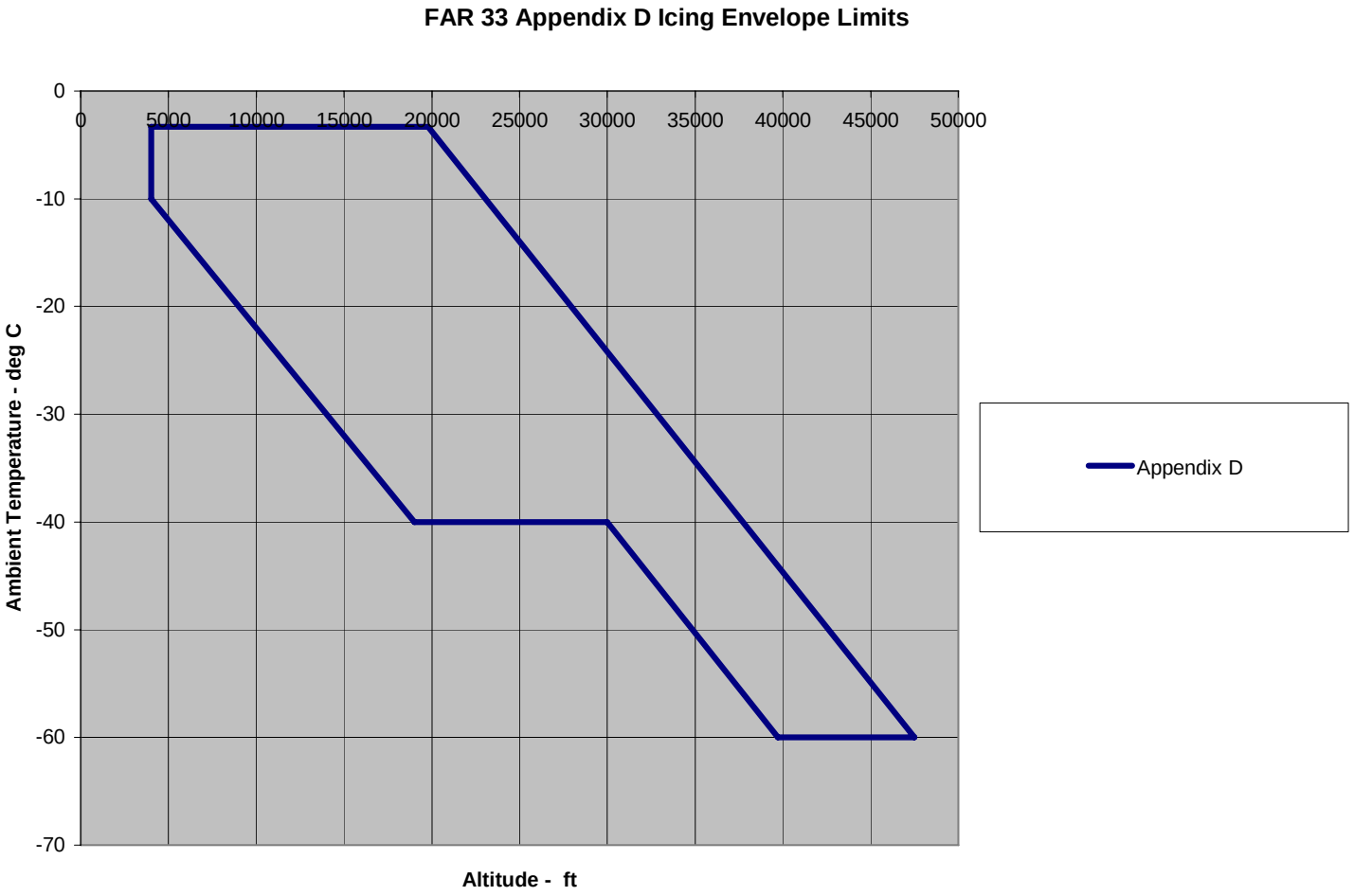


Figure D-2

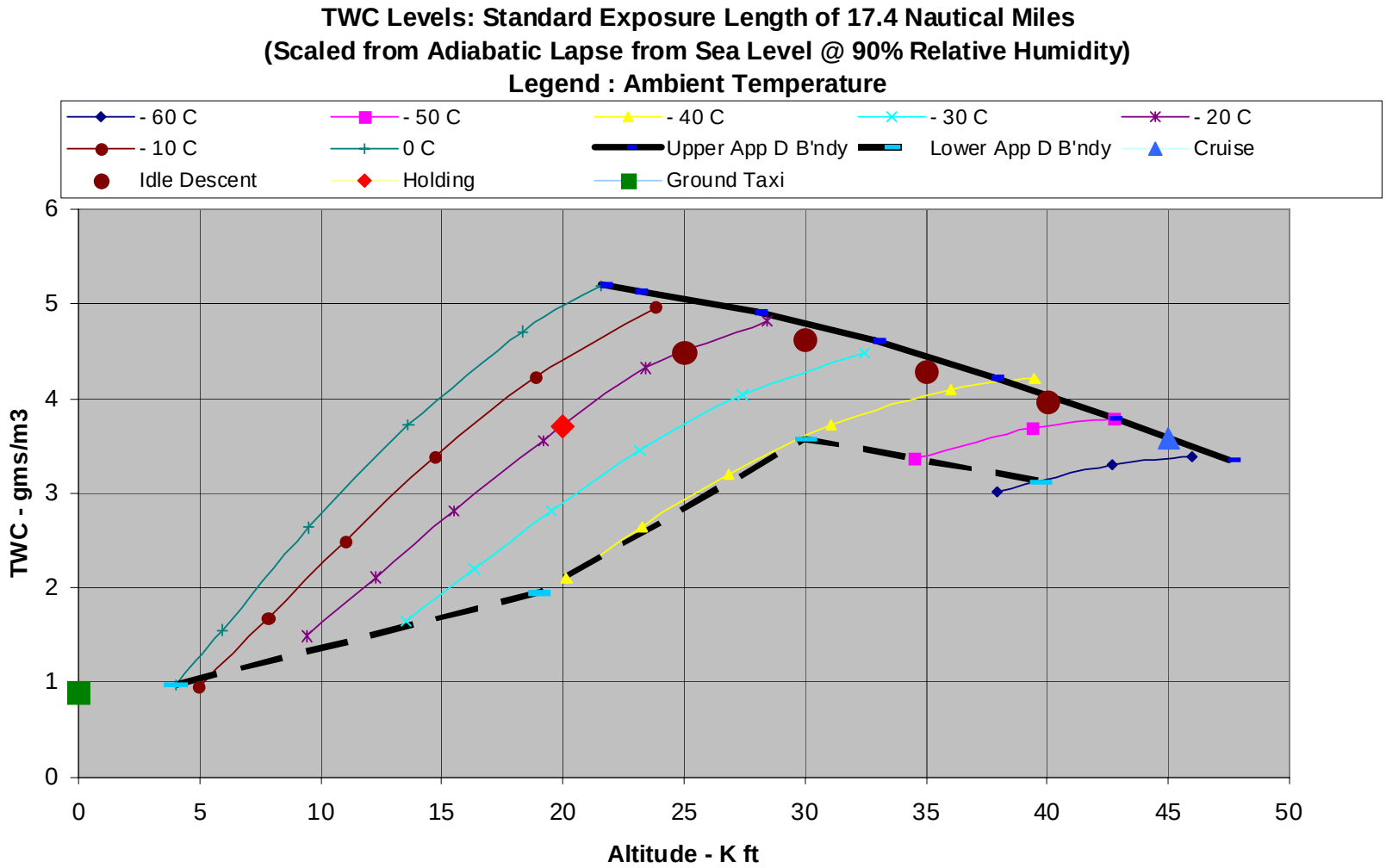
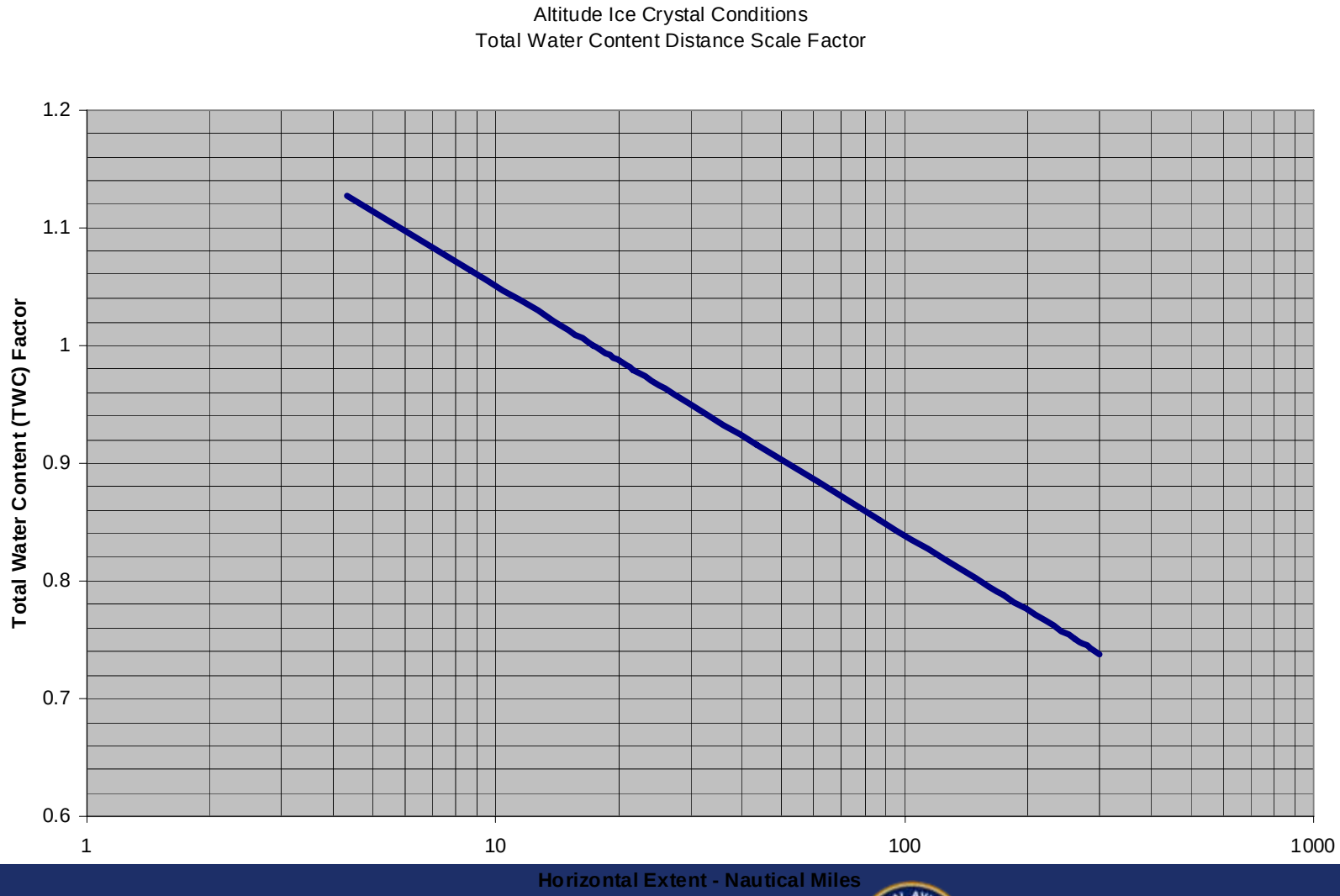

TWC Levels: Standard Exposure Length of 17.4 Nautical Miles
(Scaled from Adiabatic Lapse from Sea Level @ 90% Relative Humidity)
Legend : Ambient Temperature
- 60 C
- 50 C
- 40 C
- 30 C
- 20 C
- 10 C
0 C
Upper App D B'ndy
Lower App D B'ndy
Cruise
Idle Descent
Holding
Ground Taxi
TWC - gms/m3
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
50
Altitude - K ft

Figure D-3 Exposure Length Influence on TWC



Adiabatic Calculation for Figure D-2

- **Calculate the TWC for undiluted air parcel rise**
  - Initial surface conditions from 0°C to 35°C.
- **A relative humidity of 90% assumed at the surface**
  - Maximize the TWC
  - Maintain a realistic surface boundary condition.

Adjustment for Figure D-2 using McNaughtan Data Set

- Data set has a mean sortie altitude and temperature of about 20,000 ft and -9°C respectively.
- The calculated adiabatic TWC for this condition is about 6.7 gm-3
- The 99% McNaughtan TWC at 17.4 nmi is 4.4 gm-3, a factor of 0.65 of adiabatic. (17.4 nmi is consistent with Appendix C. See next slide.)
- 99% value chosen as prudent engine test guideline.
- Then appropriate test point for 20,000' and –9 C for a distance scale of <u>17.4 nmi</u> would be <u>4.4 gm-3</u>
- For other temperatures and altitudes, the same scale factor of 0.65 is assumed to apply

Determination of Figure D-3 using McNaughtan Data Set

- The general slope of the TWC reduction with distance scale is calculated from the McNaughtan data set for the 99% TWC.
- A standard distance scale of 17.4 nmi chosen as normalization point, same as for Appendix C continuous maximum conditions.
- This scale also roughly represents a typical onset time for an engine event after the recognition of a total air temperature (TAT) anomaly, which is accepted as common indicator of the presence of high TWC.

Overview of EHWG Mixed-Phase/Glaciated Icing Technology Plan

- **RESEARCH PARTNERS**

- **TASKS**

RESEARCH PARTNERS

- NATIONAL RESOURCE COUNCIL (NRC) OF CANADA
- ENVIRONMENT CANADA
- TRANSPORT CANADA
- FAA
- NASA
- INDUSTRY
- OTHERS

TASKS

1 Instrumentation development and evaluation for

high ice water content

2 Flight test research for characterization of high ice water content environments.

3 Experimental testing in support of ice accretion model development and validation for high ice water content environments.

4 Test facilities requirements for demonstrating engine compliance with Appendix D requirements

Task 1. Instrumentation development and evaluation for high ice water content

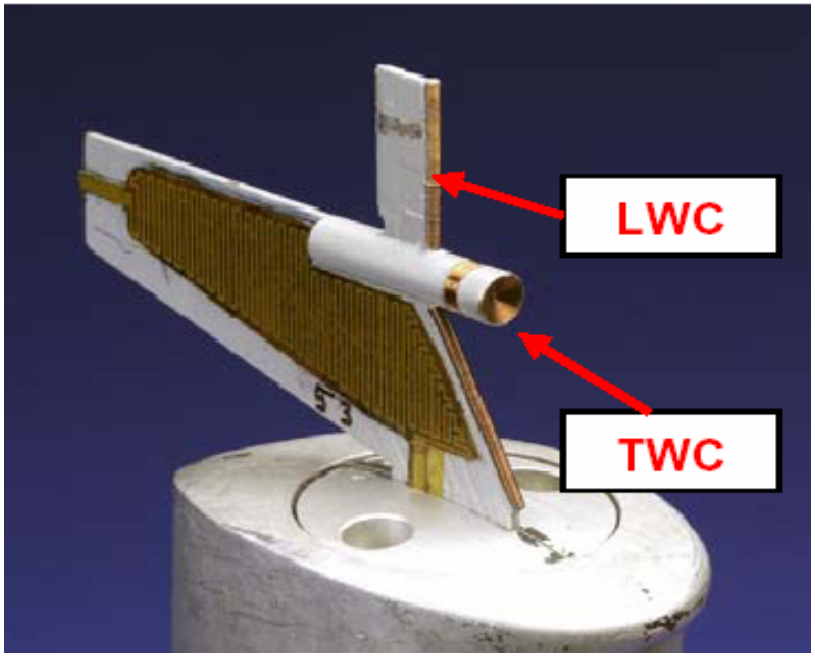
- **Essential to successful execution of Task 1, and also needed for Tasks 3 and 4**
- **Existing instrumentation is for much lower airspeeds and ice water contents than will be required**
- **Existing instrumentation will have to be modified or new instrumentation introduced.**

Task 1. Instrumentation development and evaluation for high ice water content (cont.)

- Instrumentation should be tested and evaluated in icing facilities
- Requires facilities that can achieve sufficiently high ice water contents and airspeeds
- Hot wire instruments
- Evaporators
- Others

Task 1. Instrumentation development and evaluation for high ice water content (cont.)
Hot Wire Instruments

•PMS King



•Nevzorov

Task 1. Instrumentation development and evaluation for high ice water content (cont.)
Evaporators

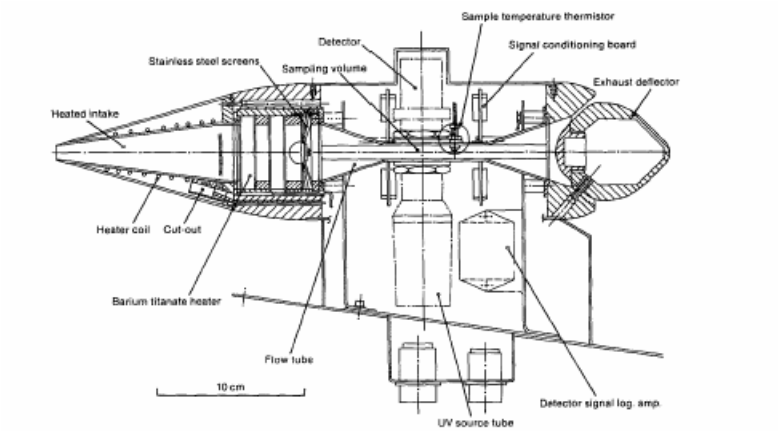


FIG. 1. A cross-sectional diagram of the total water content probe, showing the main internal components (after Nicholls et al. 1990).

- UK Met Office Evaporator
- DMT CVI

Task 1. Instrumentation development and evaluation for high ice water content (cont.)

- Work has begun in the Cox & Co. Tunnel – EC, NASA, FAA, Cox & Co.
- Work has also begun by NRC in their tunnel
- Instrumentation needs to be ready for flight research by summer 2007 for flight check of instrumentation functionality at high true airspeeds, etc.

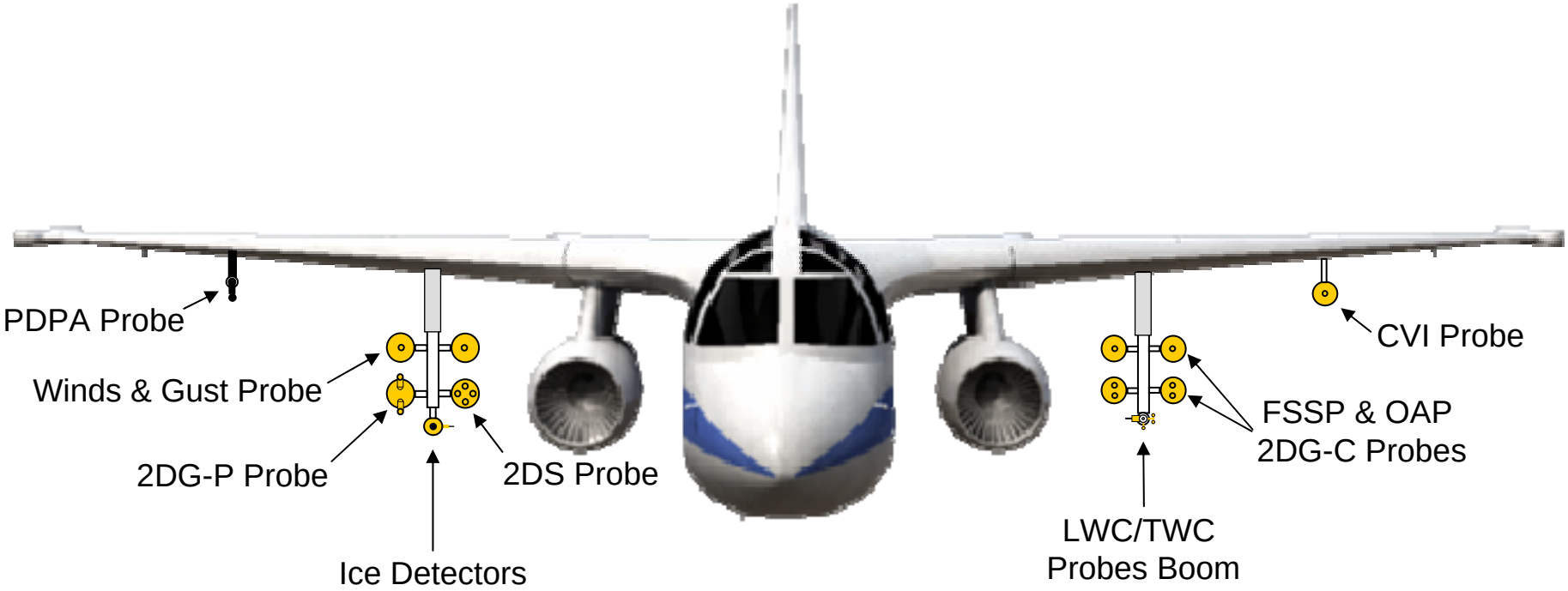
Task 2. Flight test research to characterize high ice water content environments

- Goal: Acquire data for a revised Appendix D
- Plan envisions use of NASA S-3B
- Detailed planning has begun by NASA and EC

Task 2. Flight test research to characterize high ice water content environments (cont) NASA S-3B

- Ceiling: ≈ 40,000 ft
- Speed: ≈ 155-450 knots at 30,000 feet
- Range: ≈ 1800 n mi

Task 2. Flight test research to characterize high ice water content environments (cont) NASA S-3B



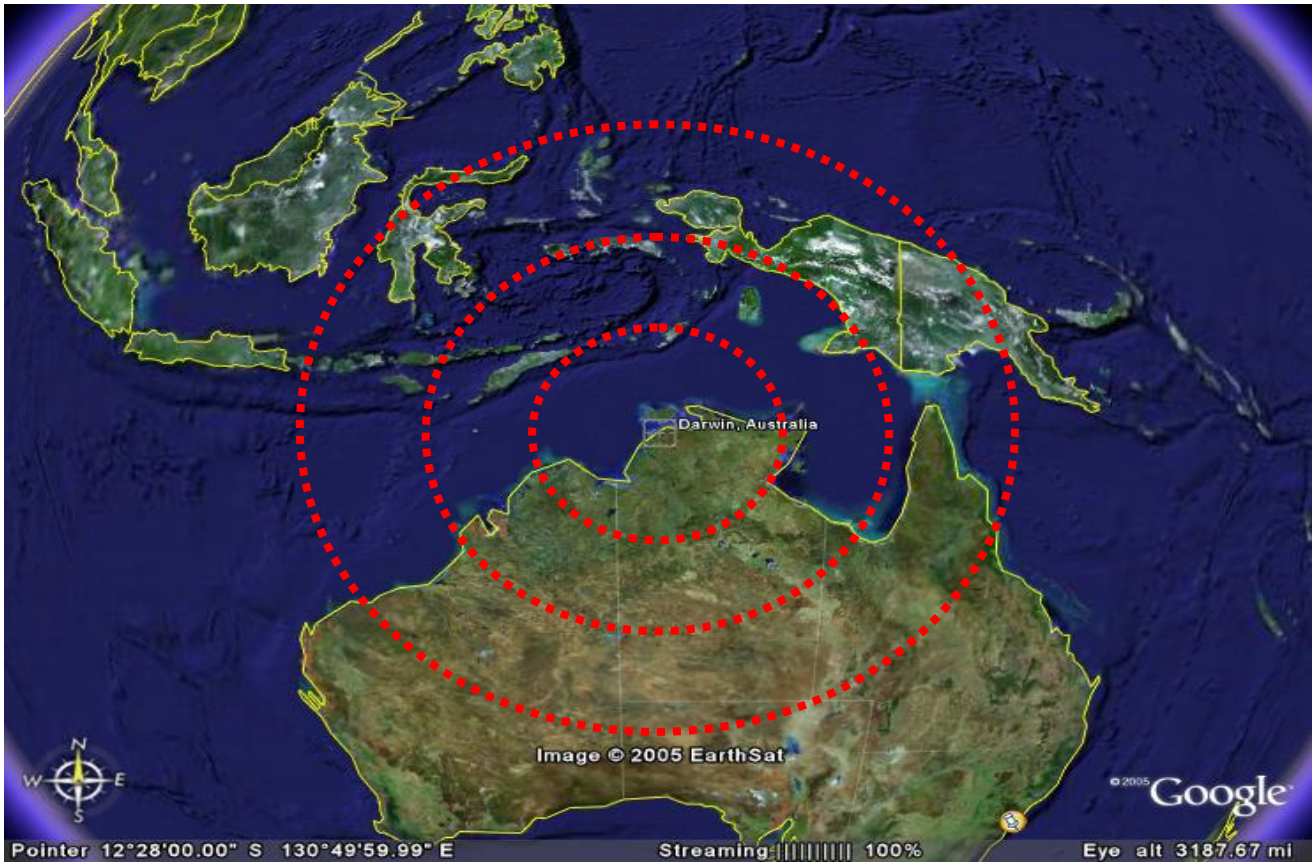
Task 2. Flight test research to characterize high ice water content environments (cont.)

- **Flights in Cleveland area – proposed Summer 2007**
  - Cirrus or very cold clouds
  - Check instrumentation functionality at high true airspeeds
- **Flights of North American East Coast – proposed Fall 2007**
  - Vicinity of Storms
    - High IWC, little lightning
  - Check instrumentation functionality at high true airspeeds in “target environment”

Task 2. Flight test research to characterize high ice water content environments (cont.)

- **Trial Campaign based in Costa Rica - proposed Summer 2008**
  - Deep tropical convection similar to that associated with many engine events
  - Preparation for “full-up” campaign; some characterization data can be acquired
- **“Full-Up’ Campaign based in Northern Australia – proposed Winter 2009**
  - High sea surface temperatures fuel deep convection
  - Many of the engine events have taken place in this area
  - Much of McNaughtan data was collected in this area
  - Primary site for collection of characterization data

Task 2. Flight test research to characterize high ice water content environments (cont.) Projected Australia Field Campaign



Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments

- **Goal: Provide data and other information for engine manufacturers in their efforts to construct ice accretion analysis tools for certification of new engines to high ice water content conditions**

Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments(cont.)

- **Key Question: How does ice accrete "deep" in engine on an initially warm surface in a warm environment?**
- **Answer will require experiments to investigate at least some of following:**
  - Ice crystal melting, sticking, bouncing, splashing on wet surface
  - Thermodynamics and heat transfer
  - Erosion of ice accretion by ice particles

Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments(cont.)

- **May Include:**
  - Component Testing
  - Cascade Testing
  - Rotating Rig Testing
  - Engine testing
- **Some testing must be done in warm environment**
- **Detailed plans have not been worked out**

Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments(cont.)

- **May Include:**
  - Component Testing
  - Cascade Testing
  - Rotating Rig Testing
  - Engine testing
- **Some testing must be done in warm environment**
- **Detailed plans have not been worked out**
- **Projected use of NASA PSL for later stages of Research**

Task 4. Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements

- **Objective: Define test facility requirements**
- **High ice water content environment**
- **Demonstrate compliance for safe operation in environment**
- **This task should benefit from Tasks 1 and 2 and, especially, Task 3**

SUMMARY

- **Key Role of Engine Harmonization Working Group**
- **Developed Database of Engine Icing Events**
- **Concluded Events Were Associated With High Ice Water Content Environments**
- **Proposed New Icing Envelopes**
- **Identified Technology Needs in Plan**

REFERENCES

EHWG, "Mixed-Phase/Glaciated Icing Technology Plan," Version 1.0, Dec. 2005

Mason, J. G.; Strapp, J.W.; and Chow, P., "The Ice Particle Threat to Engines in Flight," AIAA-2006-0206.

McNaughtan, I.I.,"The Analysis of Measurements of Free Ice and Ice/Water Concentrations in the Atmosphere of the Equatorial Zone," *Royal Aircraft Establishment (Farnborough) Technical Note No. : Mech. Eng. 283,* 1959.

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Lawson, R.P., Angus, L.J., and Heymsfield, A..J., "Cloud Particle Measurements in Thunderstorm anvils and Possible Threat to Aviation," *J. Aircraft*, *Vol. 35, No. 1*, 1998, pp. 113-121.