June 20-22, 2023
Vienna, Austria

SAE INTERNATIONAL

International Conference on Icing of Aircraft, Engines, and Structures

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Icing Wind Tunnel Testing for App C and App O Icing Conditions

Matthew Hamman, El Hassan Ridouane (Collins Aerospace)
Venkateshwar Bora Reddy (TUBS), David Orchard (NRC)
Johannes Lucke, Tina Jurkat-Witschas (DLR)

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SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

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20-22 June 2023

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Outline

- SENS4ICE IWT Campaign Objectives
- IWT Campaign Planning
- IWT Owners Achievements and Lessons Learned
- Reference Measurements

SENS4ICE IWT Campaign Objectives

- Plan Measurement Campaigns in Icing Wind Tunnels
- Perform IWT tests of direct sensors that are being developed in SENS4ICE
- Evaluate direct sensors measurements against reference probes based on ability to measure/detect/discriminate App. C and App. O
- Provide IWT test results for sensor selection at Gate 2 in June 2021
- Testing took place between Nov 2020 and March 2021

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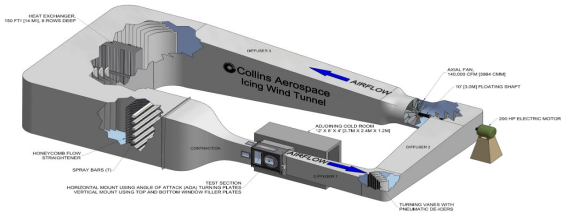
IWT Campaign Planning

Sensor Developers Achievements

- Sensor ICD completed
- Test matrix developed for each IWT facility
- Standard test procedure developed
- Hardware shipped and installed in IWT facilities
- Tests performed
- Data analyzed and reported for Gate 2 evaluation

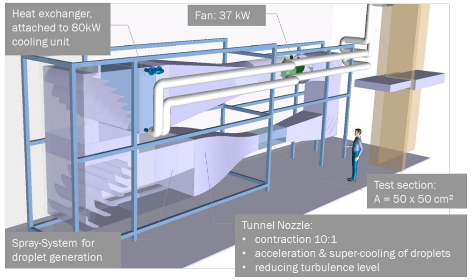
Overview of SENS4ICE IWT Capabilities

Collins Aerospace, USA



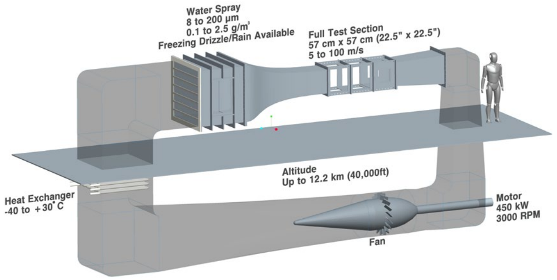
- MVD 15-190 micron droplets
- LWC between 0.15 and 3.0 g/m3
- Temperature 0°C to -30°C
- Sustained speed 14-103 m/s
- Test section: 152×56×112 cm3
- Calibrated per SAE ARP 5905
- Controls and power supplies can simulate aircraft controls

TU Braunschweig, Germany



- MVD 9-60 micron droplets
- LWC between 0.1 and 1.5 g/m3
- Temperature 30°C to -20°C
- Sustained speed 10-40 m/s
- Test section: 150×50×50 cm3
- Calibrated per SAE ARP 5905
- Short spray transients ~ 15s
- Bi-modal SLD and mixed phase capability

NRC, Canada



- 8-200 micron droplets
- LWC between 0.1 and 2.5 g/m3
- Supercooled Water: 10 to > 200 µm (incl. SLD bi-modal)
- Temperature +30°C to -40°C
- Sustained speed 5-100 m/s
- Test section: 57×57 cm2 (52x33 cm2 with insert)
- Sea level < Altitude < 40,000ft
- Calibrated per SAE ARP 5905

Sensors & IWT Pairing

- Test status and distribution of sensors between IWT facilities

Developer	Sensor	Sensor Type	IWT Name	IWT Test Status
AEROTEX	AIP	Atmospheric	NRC	Complete
COLLINS	IDS	Atmospheric	Collins, NRC	Complete
DLR	LILD	Accretion	TUBS	Complete
DLR	CM2D [BCPD]	Atmospheric	TUBS	Complete
DLR	CM2D [Nevzorov]	Atmospheric	TUBS	Complete
HONEYWELL	SRP	Atmospheric	Collins, NRC	Complete
INTA	FOD	Accretion	NRC	Complete
ONERA	AHDEL	Atmospheric	TUBS	Complete
ONERA	AMPERA	Atmospheric	N/A	N/A
SAFRAN	AOD	Atmospheric	TUBS	Cancelled
SAFRAN	PFIDS	Accretion	TUBS	Complete

Test Matrices

- Three IWT test facilities were used by the sensor developers to complete testing for Gate 2:
  - Collins IWT, USA
  - TUBS IWT, Germany
  - NRC IWT, Canada
- Test Matrices development followed guidelines of ED-103.
- Different capabilities offered by each IWT facility, with very limited overlap.
- The overlap allowed for common test points between all or some of the facilities

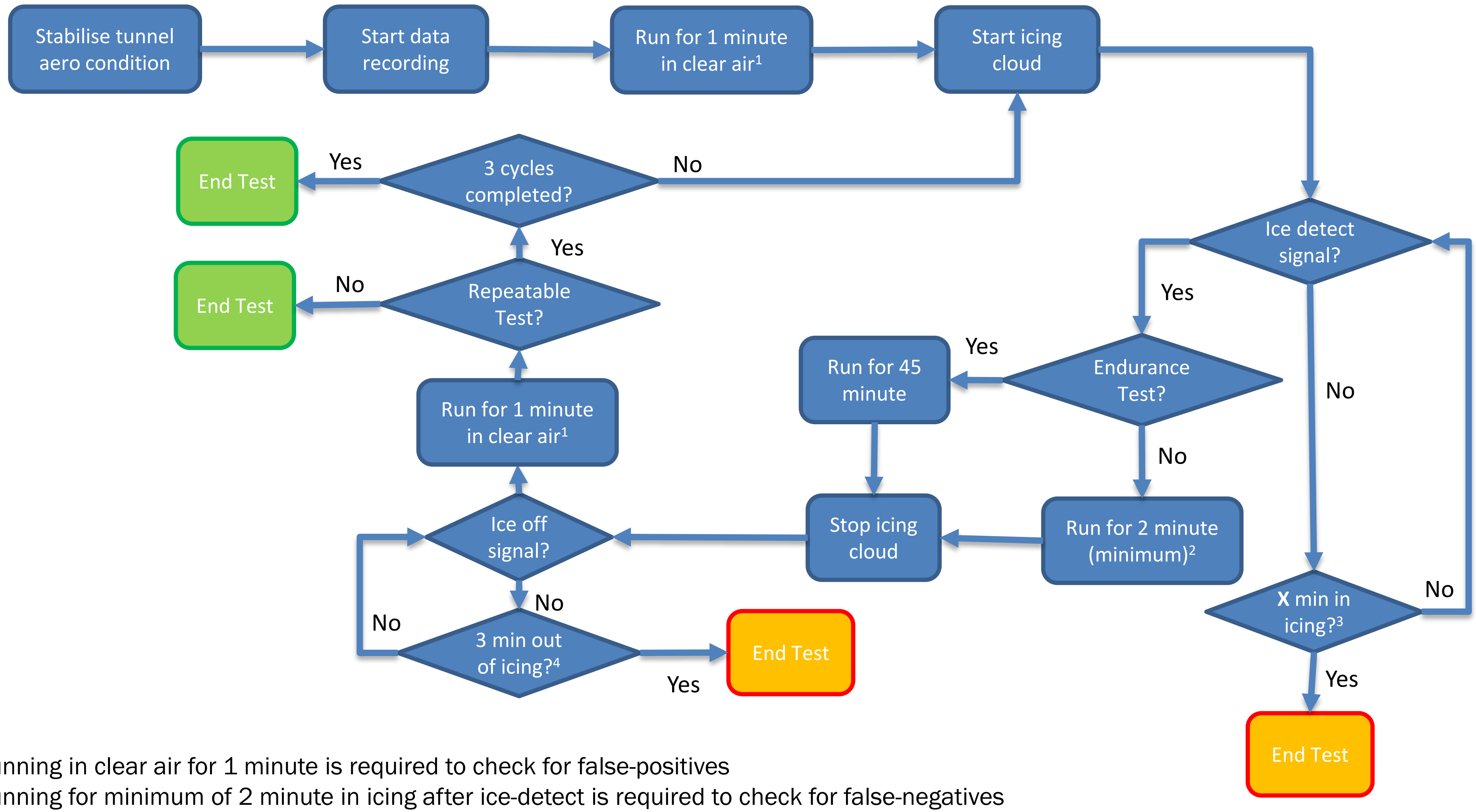
IWT Name	App C						App O					
	Total Test Points	Test Points Common with All Tunnels	Test Points Common with Two Tunnels	Test Points Used Only at One Tunnel	CM Test Points	IM Test Points	Total Test Points	Points Common with All Tunnels	Points Common with One Tunnel	Test Points Used Only at One Tunnel	Total Points [unimodal]	Total Points [bimodal]
TUBS	19	4	1	14	10	9	18	0	1	17	0	18
Collins	18	4	3	10	9	9	6	0	1	5	6	0
NRC	19	4	4	11	9	10	17	0	2	15	4	13

Test Matrices

- Standard Test Points of Test Matrix: Example Test Matrix - NRC
  - Standard tests for atmospheric sensors
  - Includes required response time (LW:Enter) as per ED-103
  - Includes required discrimination time (LW_O:Enter) as per ED-103
  - Colour coding follows ED-103:
    - Green for App. C – CM
    - Blue for App. C – IM
    - Dark orange for FZDZ, MVD>40 µm
    - Light orange for FZDZ, MVD<40 µm

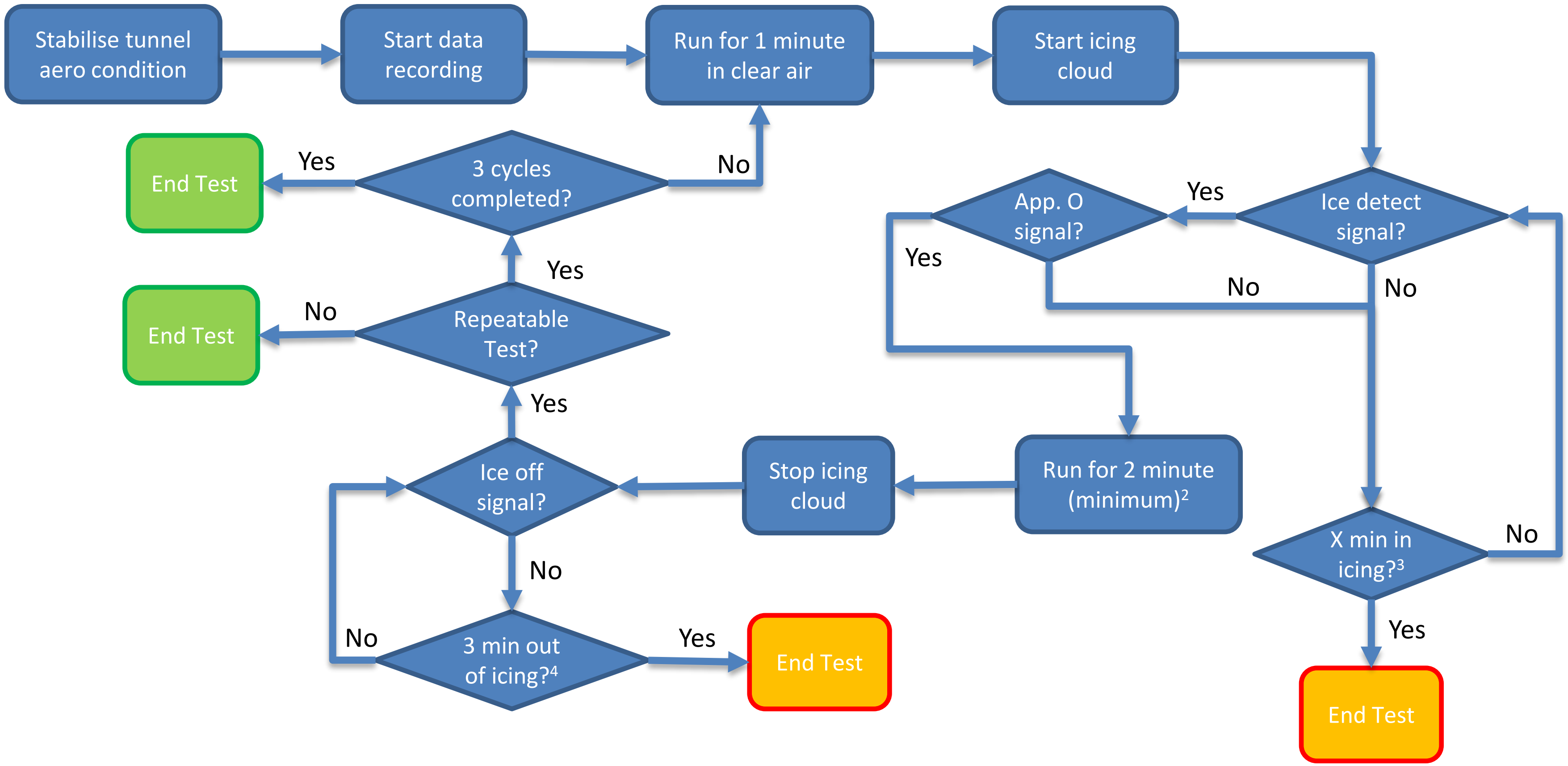
NRC Atmospheric Sensors Results Table - Standard Tests																	
Conditions								Requirements		Measurements / Results							
Case	Test Type	Condition	Airspeed	Static Temp.	Altitude	MVD	LWC	LW: Enter	LW_O: Enter	LW: Enter	LW: Exit	LW_O: Enter	LW_O: Exit	False Alarm	LWC	MVD	DMAX
[-]	[-]	[-]	[m/s]	[deg. C]	[feet]	[microns]	[g/m³]	[s]	[s]	[s]	[s]	[s]	[s]	[-]	[g/m³]	[microns]	[microns]
1	Repeat 2	LW-C CM	40.1	-20	0	15	0.3	36	-								
2	Endurance	LW-C CM	40.1	-10	0	20	0.42	23	-								
3	Standard	LW-C CM	84.9	-10	0	23	0.34	11	-								
4	Repeat 3	LW-C CM	40.1	0	0	23	0.54	126	-								
5	Standard	LW-C CM	84.9	-20	0	30	0.11	33	-								
6	Standard	LW-C CM	84.9	-10	0	40	0.1	36	-								
7	Standard	LW-C CM	84.9	-10	0	35	0.15	24	-								
8	Standard	LW-C CM	84.9	-30	0	35	0.05	72	-								
9	Standard	LW-C CM	84.9	-3.5	0	30	0.35	29	-								
10	Repeat 1	LW-C IM	40.1	-20	0	22	1.5	6	-								
11	Standard	LW-C IM	40.1	-10	0	28	1.2	10	-								
12	Standard	LW-C IM	84.9	-20	0	23	1.3	3	-								
13	Standard	LW-C IM	40.1	-20	0	42	0.3	26	-								
14	Standard	LW-C IM	84.9	-20	0	20	1.75	3	-								
15	Standard	LW-C IM	84.9	-10	0	20	2.25	5	-								
16	Standard	LW-C IM	84.9	-10	0	20	0.5	8	-								
17	Standard	LW-C IM	84.9	-20	0	31	0.75	5	-								
18	Standard	LW-C IM	84.9	0	0	20	2.5	57	-								
19	Standard	LW-C IM	84.9	-3.5	0	35	1	25	-								
20	Standard	unimodal	76.1	-17.7	0	163.5	0.82	4	5								
21	Standard	unimodal	40.1	-17.7	0	122	0.46	15	24								
22	Repeat 4	LW-FZDZ	79.7	-20	0	106	0.4	9	17								
23	Standard	LW-FZDZ	79.7	-25	0	20	0.29	15	169								
24	Standard	LW-FZDZ	84.9	-15	0	20	0.35	12	132								
25	Standard	LW-FZDZ	84.9	-10	0	20	0.38	11	122								
26	Standard	LW-FZDZ	84.9	-3.5	0	20	0.42	28	110								
27	Standard	LW-FZDZ	84.9	-25	0	20	0.15	27	308								
28	Standard	LW-FZDZ	84.9	-15	0	20	0.18	22	257								
29	Standard	LW-FZDZ	84.9	-10	0	20	0.2	20	231								
30	Standard	LW-FZDZ	84.9	-3.5	0	20	0.21	29	221								
31	Standard	LW-FZDZ	84.9	-25	0	110	0.18	18	35								
32	Standard	LW-FZDZ	84.9	-15	0	110	0.22	15	29								
33	Standard	LW-FZDZ	84.9	-10	0	110	0.23	14	28								
34	Standard	LW-FZDZ	84.9	-3.5	0	110	0.26	28	29								
35	Standard	unimodal	84.9	-10	0	180	0.25	13	15								
36	Standard	unimodal	84.9	-10	0	220	0.25	13	14								

Test Procedures – App C Conditions



Notes:
1. Running in clear air for 1 minute is required to check for false-positives
2. Running for minimum of 2 minute in icing after ice-detect is required to check for false-negatives
3. X is the target calculated detection time + 1 minute
4. Based on AS5498A time to detect exit being a maximum of 3 minutes

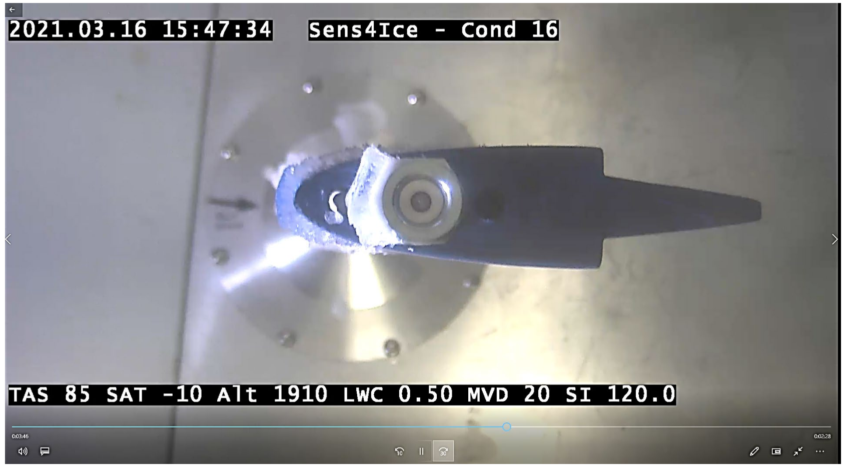
Test Procedures – App O Conditions



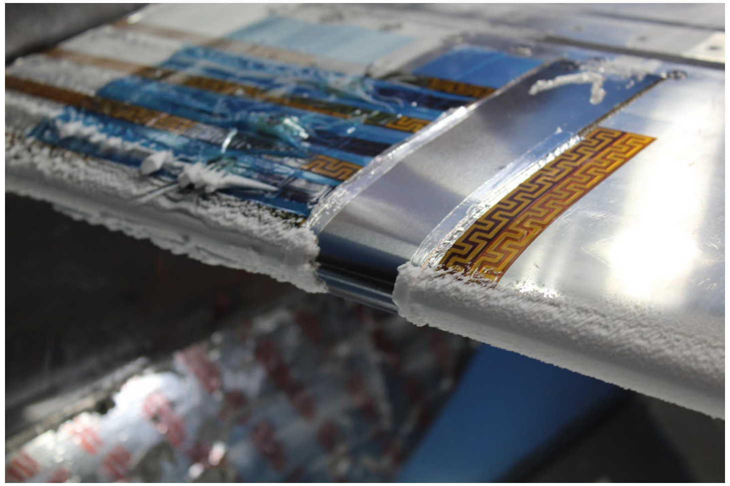
Notes:
1. Running in clear air for 1 minute is required to check for false-positives
2. Running for minimum of 2 minute in icing after ice-detect is required to check for false-negatives
3. X is the target calculated detection time + 1 minute
4. Based on AS5498A time to detect exit being a maximum of 3 minutes

Hardware shipped and installed for Testing

INTA FOD at NRC

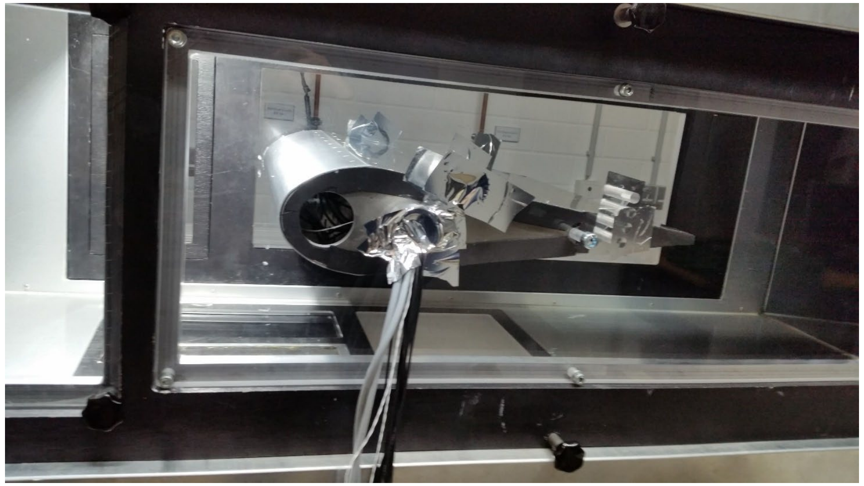


Collins-IDS at Collins



ATX–AIP at NRC

DLR LILD at TUBS



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Key Achievements by IWT Operators

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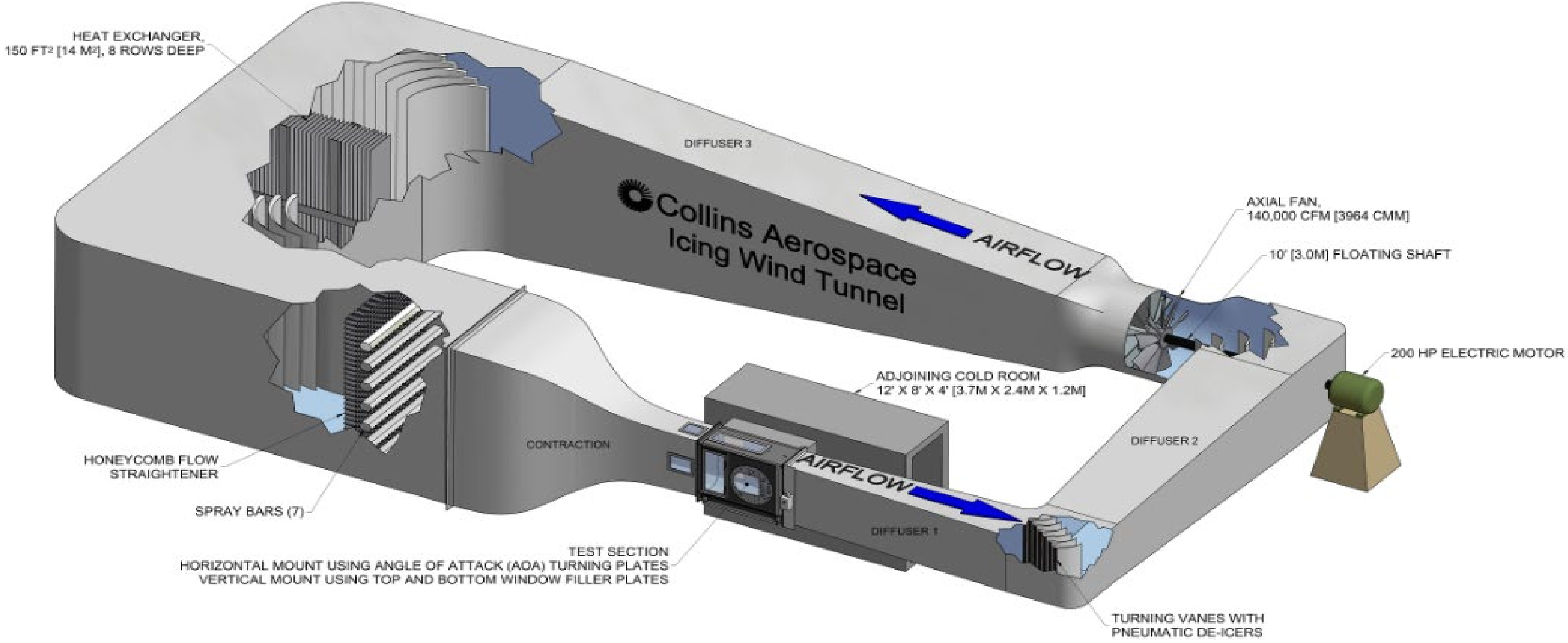
Collins Aerospace Icing Wind Tunnel

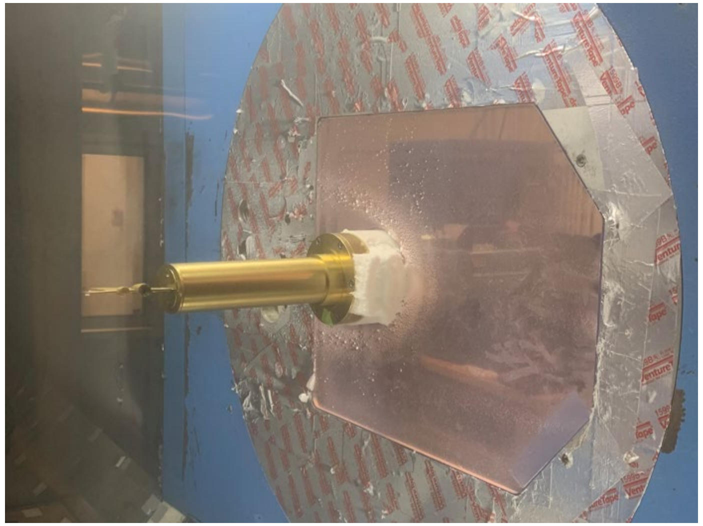
Collins Aerospace: Goodrich Icing Wind Tunnel



Summary of Experiences

- Initial work was focused on characterizing the App O and App C capabilities of the Collins IWT.
  - The App C calibration procedure is based on the best practices outlined in SAE ARP5905. An icing blade and PDI laser system was utilized to calibrate centerline LWC and droplet MVD respectively.
  - For App O conditions an SEA Multi-Element Probe was used to characterize LWC. The PDI system was coupled with a 1000mm focal length lens and used to characterizing SLD.
- The Collins IWT was further characterized/baselined by DLR using the Nevzorov and CCP probes.
  - The Nevzorov testing was performed with DLR participating remotely, from Germany, via Zoom (Nov. 2020).
  - The CCP testing was performed with CloudSci on site at the IWT on behalf of DLR (Feb. 2021).

Nevzorov Probe

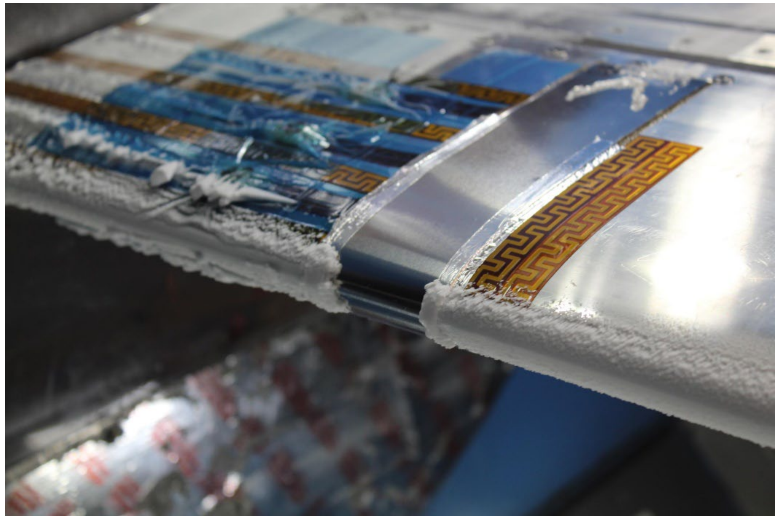


CCP Probe

Summary of Experiences

- Two Different Sensor Developers performed testing in the Collins IWT.
  - Honeywell: Spent one week testing the Honeywell sensor in the IWT (Jan. 2021). The sensor was installed by Honeywell and the testing was carried out with them on site (not pictured).
  - Collins: Spent two weeks testing the Collins Ice Differentiator System (IDS) in the IWT (Nov. 2020 & Jan. 2021). The testing was performed with the Collins IDS team participating remotely, from Ireland, via Zoom.

Collins-IDS



Summary of Experiences

- Challenges
  - App O condition characterization required an extensive testing campaign.
  - COVID posed many unique challenges, for example:
    - COVID forced Collins to develop remote test capabilities.
    - Created logistical challenges regarding scheduling and the shipment of equipment.
    - Social distancing and facemask requirements were mandated to ensure wind tunnel operator and sensor developer safety.
- Lessons Learned and Takeaways
  - Gained further understanding of IWT characterization equipment, such as the Nevzorov and CCP probes, and measurement methodologies, such as using the SEA Multi-Element Probe half-pipe to measure App O Conditions.
  - Importance of international collaboration between experts in the icing community.
  - Recommend a global App O harmonization effort like the Golden Model, which was done in the 2000's.

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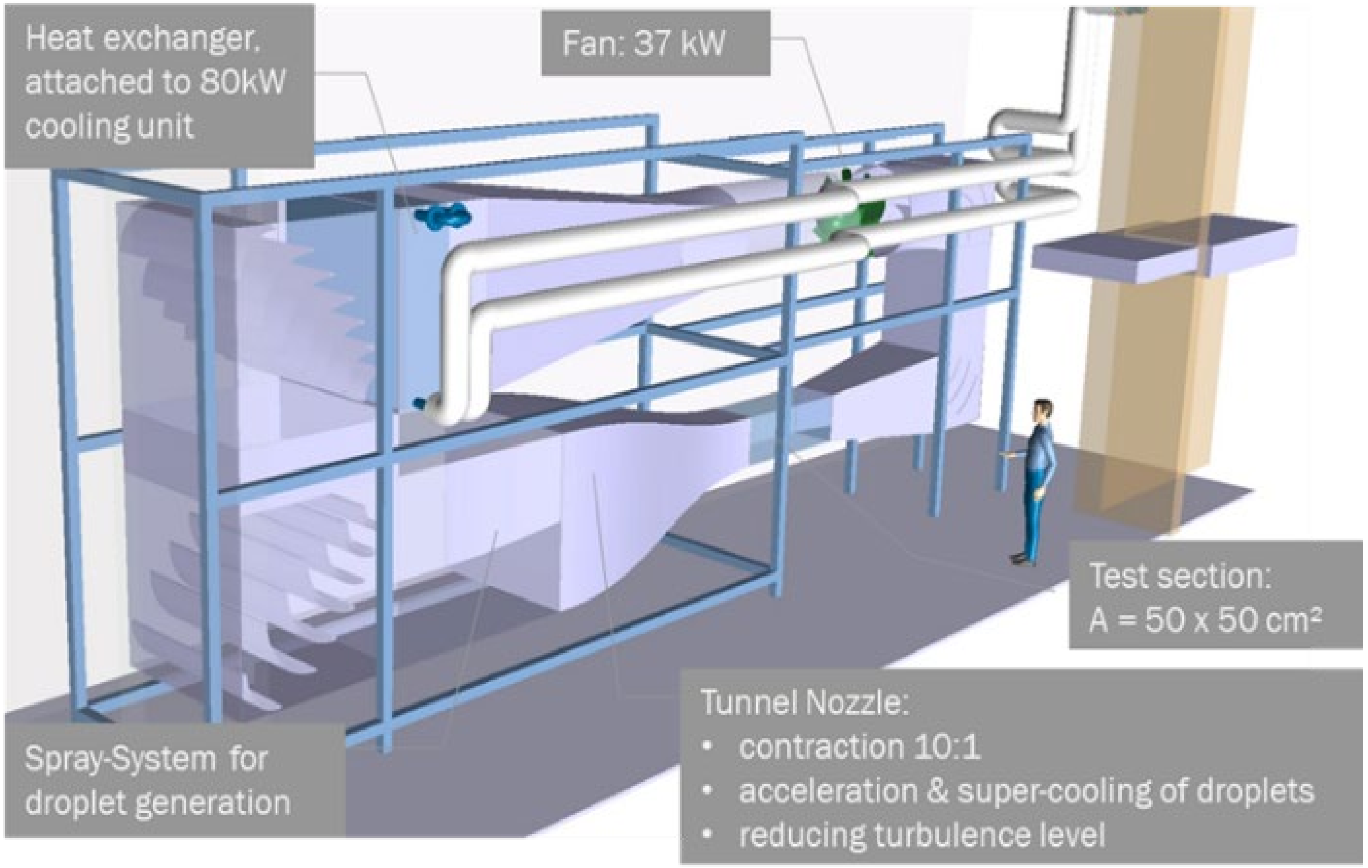
TUBS Icing Wind Tunnel

Braunschweig Icing Wind Tunnel (BIWT)

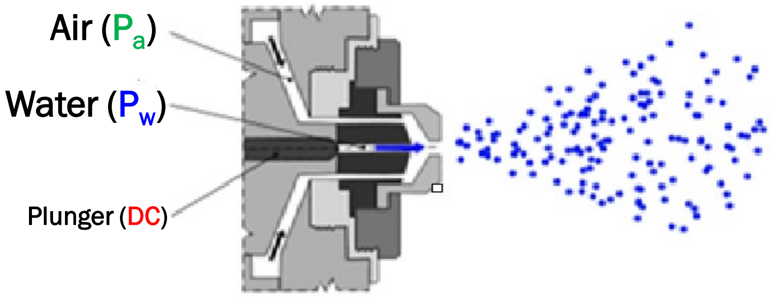


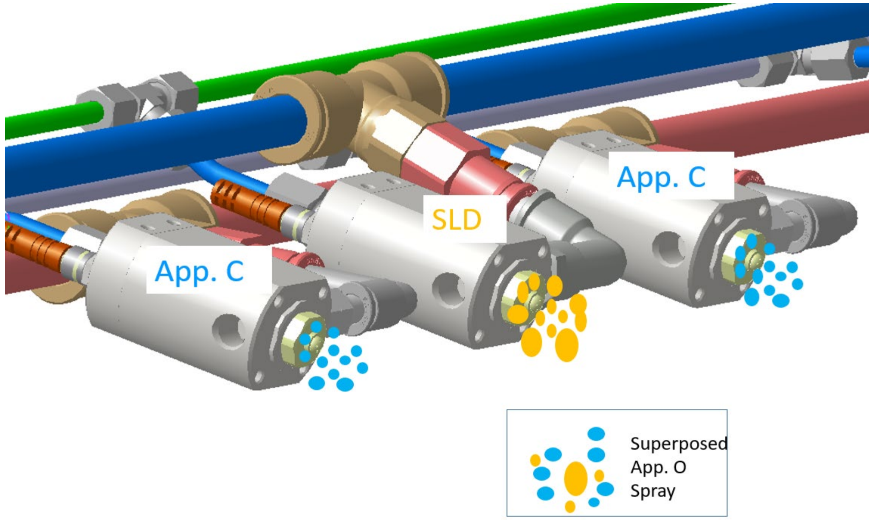
- Salient Features
  - Velocity:10 to 40 m/s
  - Temperature: -20 to +30 °C
  - Turbulence intensity 1.2% with spray
- Icing Conditions
  - App. C and App. O FZDZ conditions
  - 1<D<450 μm
  - LWC = 0.1 to 1.5 g/m³
  - Shorter spray transients (≈15s)
  - Ice crystal icing
    - Realistic shape and density produced in cloud chamber

Capable of simulating supercooled droplet icing , ice crystal icing and mixed phase icing

Upgrade to App. O Conditions

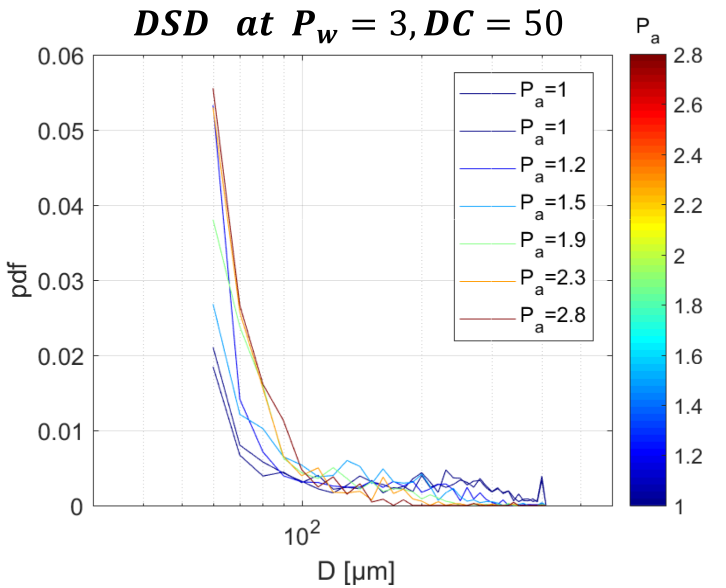
- Shortlisting of atomizers
  - Electrically actuated pulse width modulated air-assisted atomizers
  - DSD controlled by water Pressure P_w, air Pressure P_a
  - PWM Duty cycle (DC)enables control of LWC
  - D_{max} 450 µm
- Atomizers layout
  - Two sets of atomizers in the top two rows
  - Bimodality from the superposition of sprays
  - Each atomizer set can be actuated independently
  - App. C, App. O and only SLD clouds can be generated

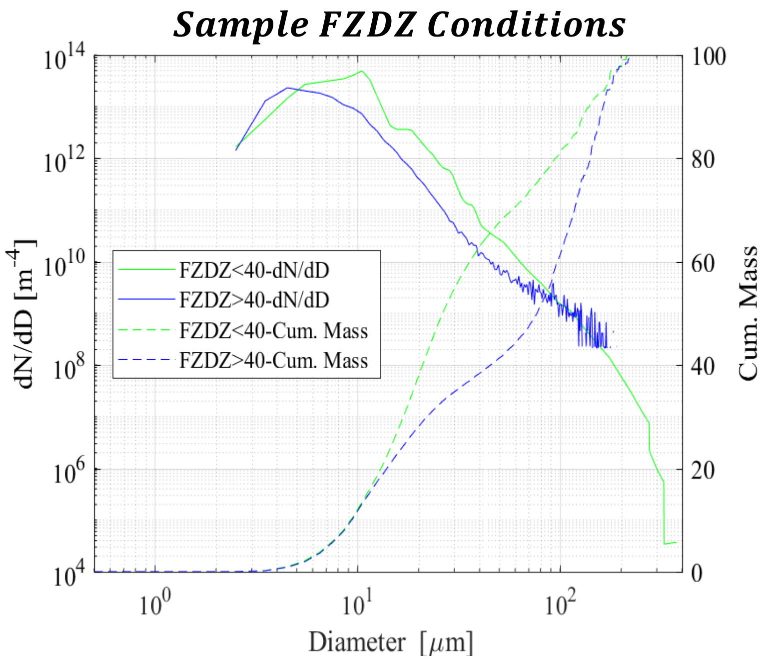




Cloud Calibration

- DSD Characterization
  - CCP
  - PDI
  - Shadowgraphy
- LWC Characterization
  - Nevzorov
  - CU-IKP
  - Coriolis flow meter (accuracy ±0.5ml/min)
  - Rotating Cylinder
- Uniformity
  - Grid Tests
  - Accretion Tests
  - Traversing Nevzorov
- Quantified SLD aero-thermal uncertainties





Sensor Testing

1. CCP - DLR (reference measurements)
2. Nevzorov - DLR (reference measurements)
3. AHDEL – ONERA
4. AIP – AeroTex
5. CM2D - DLR
6. LILD – DLR
7. PFIDS - SAFRAN

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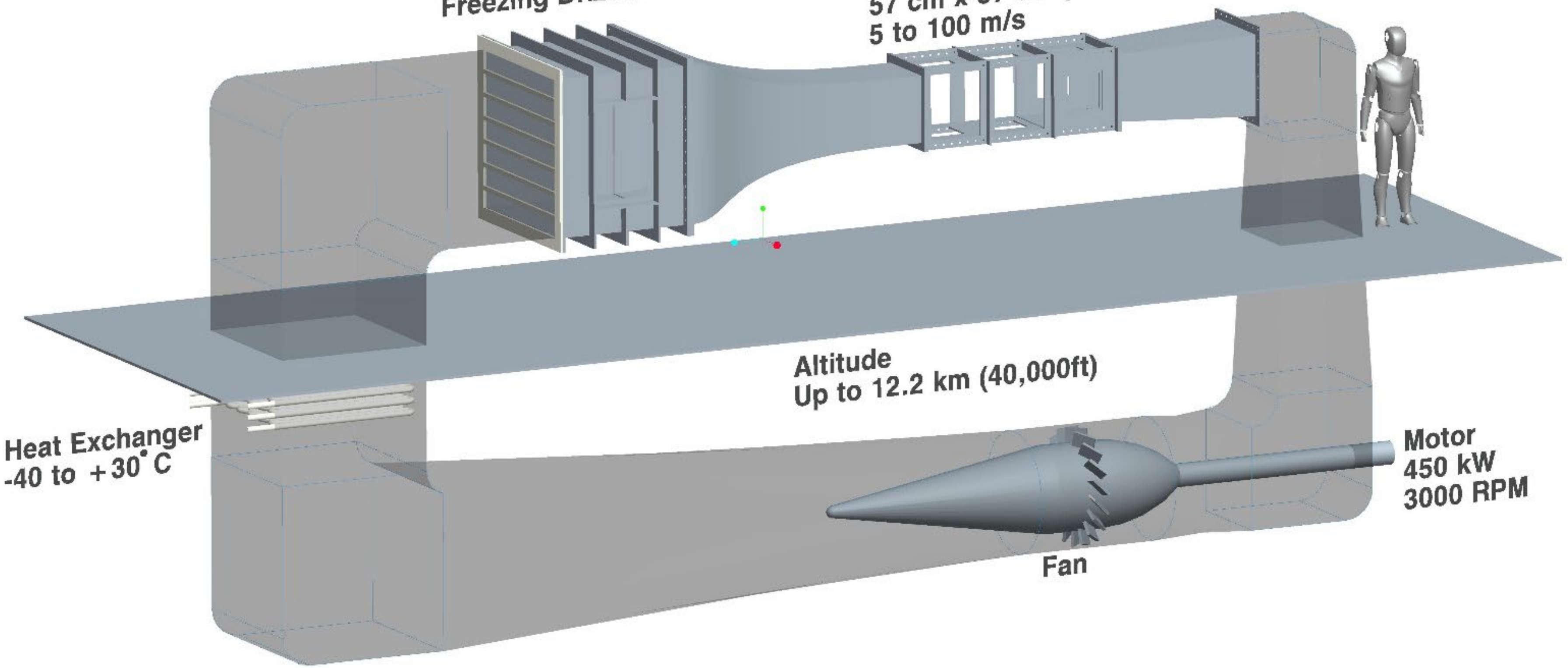
NRC Icing Wind Tunnel

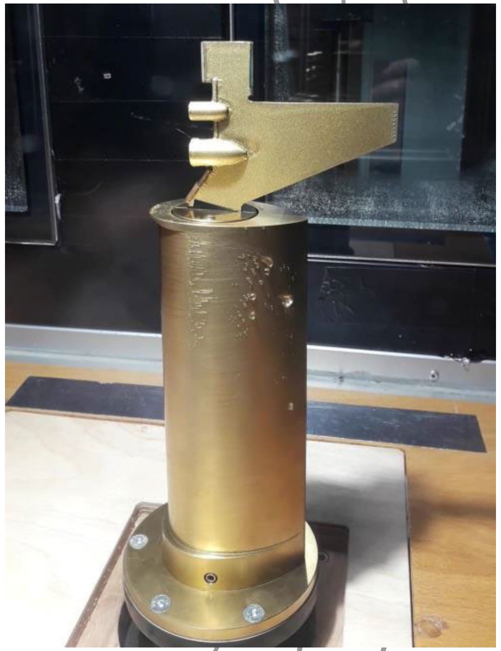
National Research Council: Altitude Icing Wind Tunnel (AIWT)



National Research Council: Altitude Icing Wind Tunnel (AIWT)

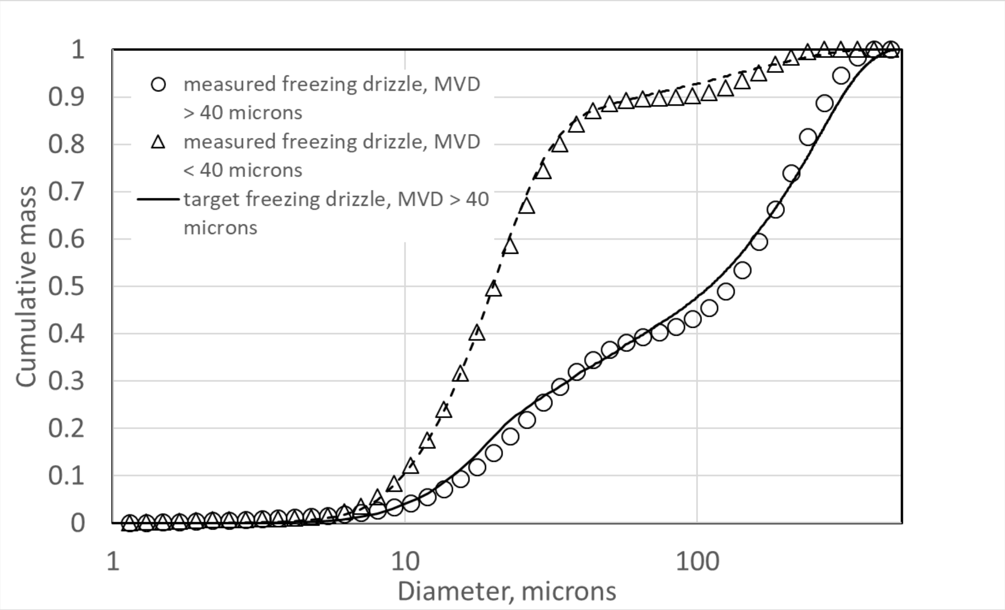
March / April, 2021:

- ❑ **Wind tunnel test completed**
  - Collins Aerospace
  - Honeywell
  - INTA
  - Aerotex UK
- ❑ **Full dataset delivered**
  - Appendix C and O conditions
  - Common test points between Collins and TUBS wind tunnels
  - Reference measurements with DLR (Nevzorov) probe completed



AIWT: Supercooled Large Drop conditions

- **AIWT can achieve SLD in full bi-modal freezing drizzle**
- **No standards exist for tunnel operational capabilities and reference instruments for SLD**
- **Further collaborative efforts are needed to standardize icing wind tunnels for SLD conditions**
- **Necessary for future product development and certification**



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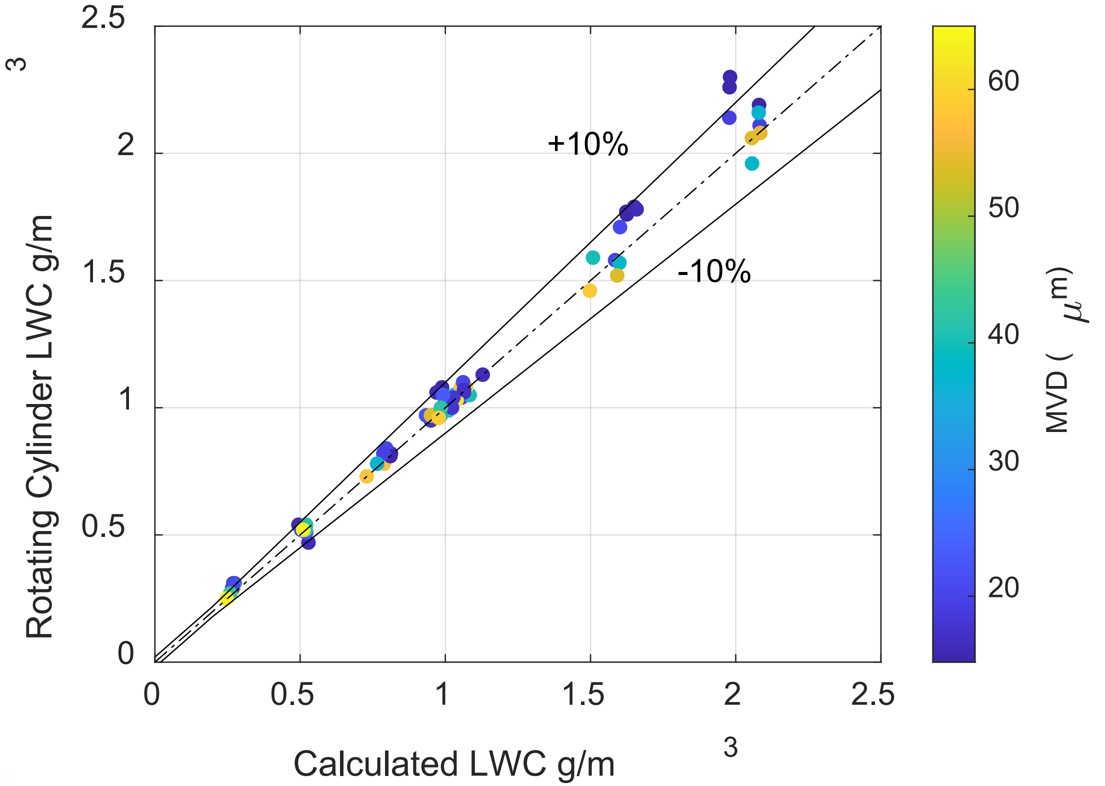
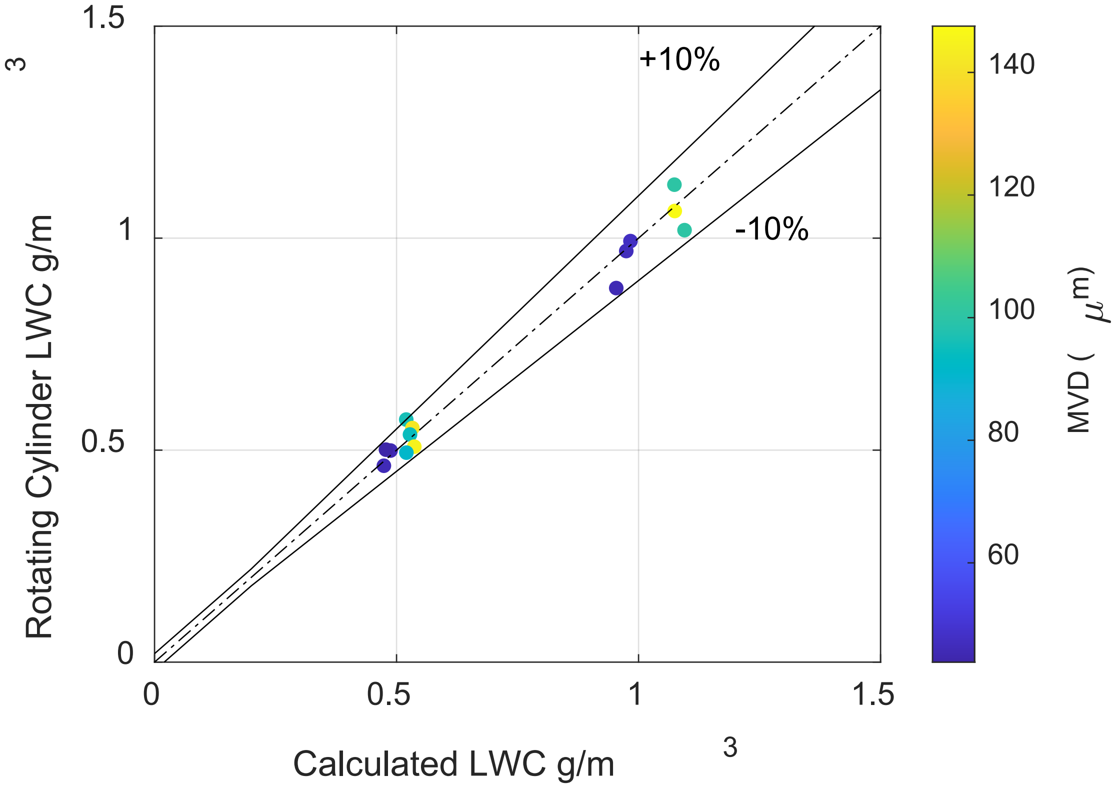
Reference Measurements

LWC measurements at AIWT

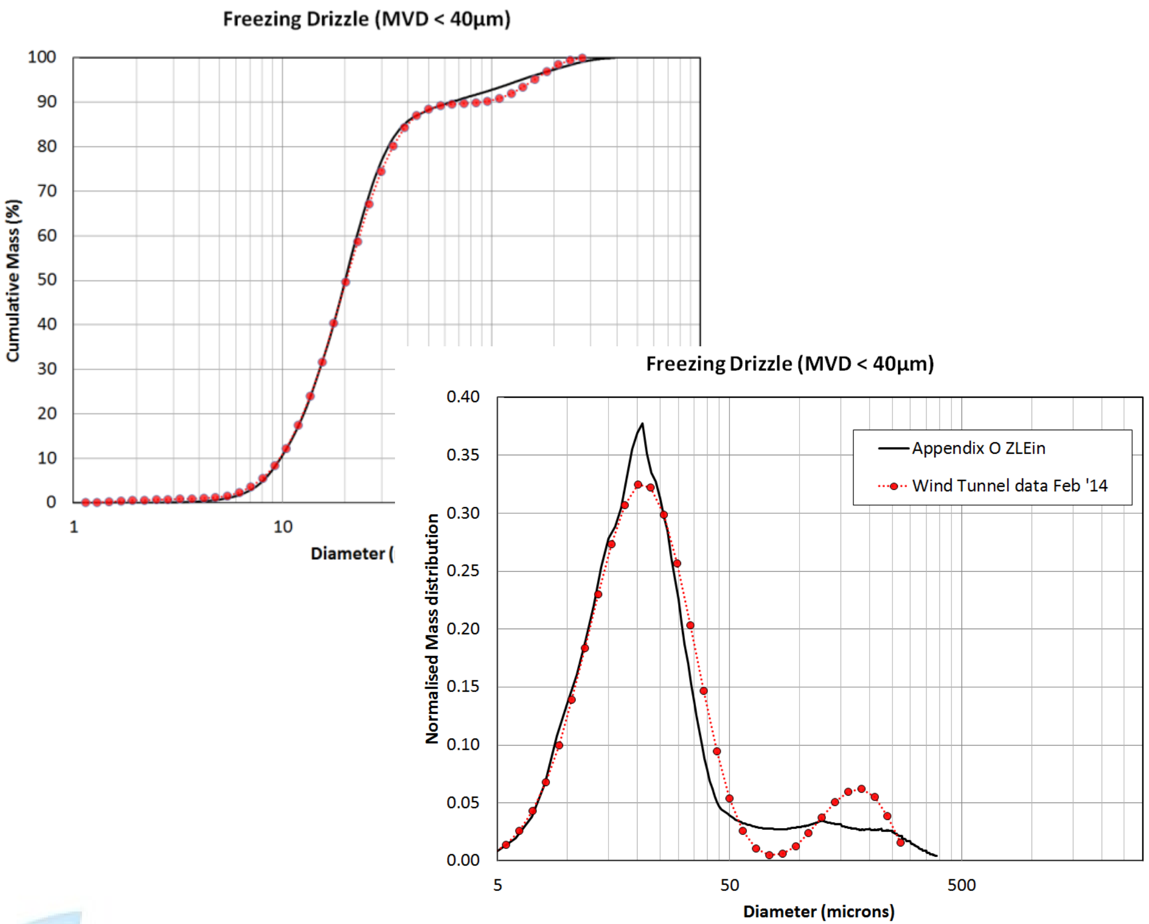
- Rotating cylinder facility main LWC measurement techniques
- Some evidence that LWC may be underpredicted at larger drop sizes.
  - → requires further investigation

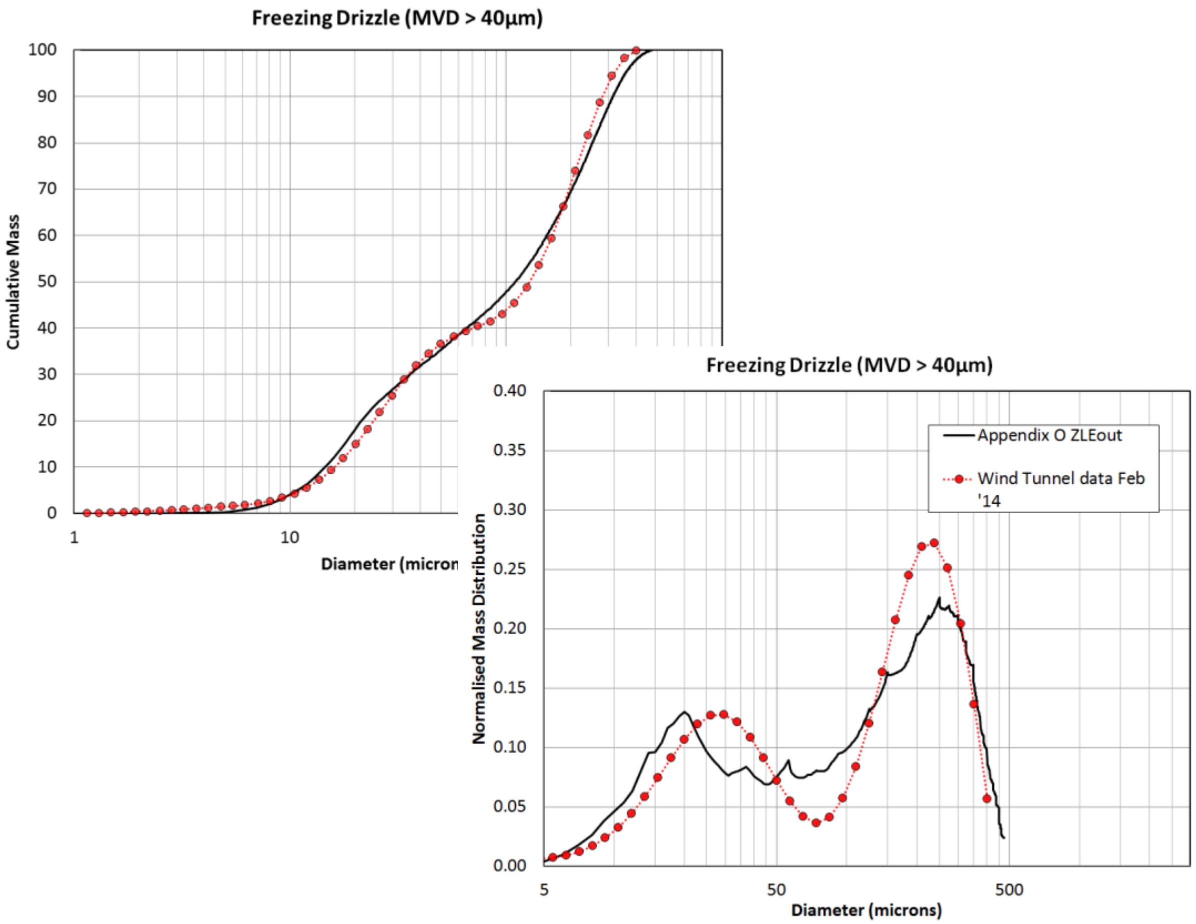




Bi-modal Distribution AIWT

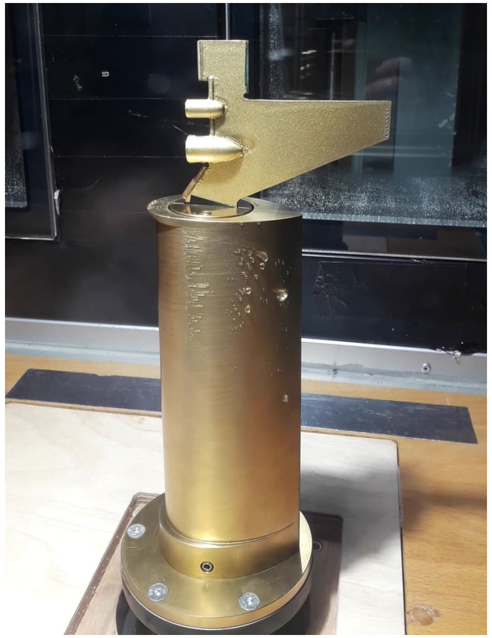
- Malvern Spraytec main drop size measurement technique
- Freezing Drizzle profiles with MVD < 40 µm & MVD > 40 µm





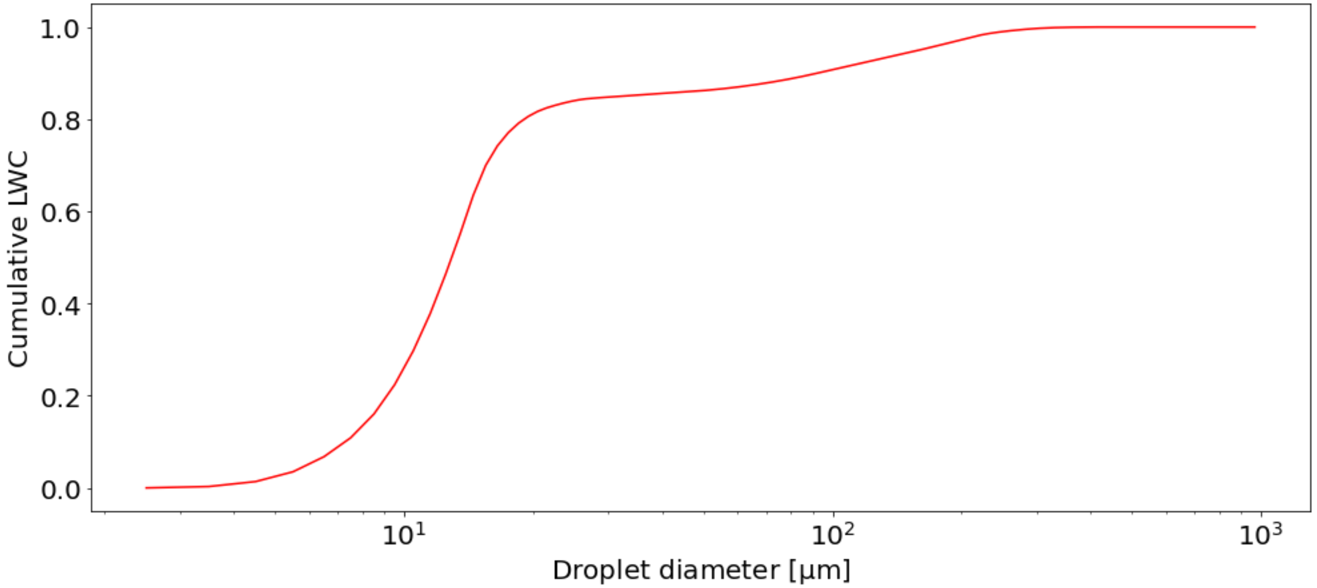
Reference measurements

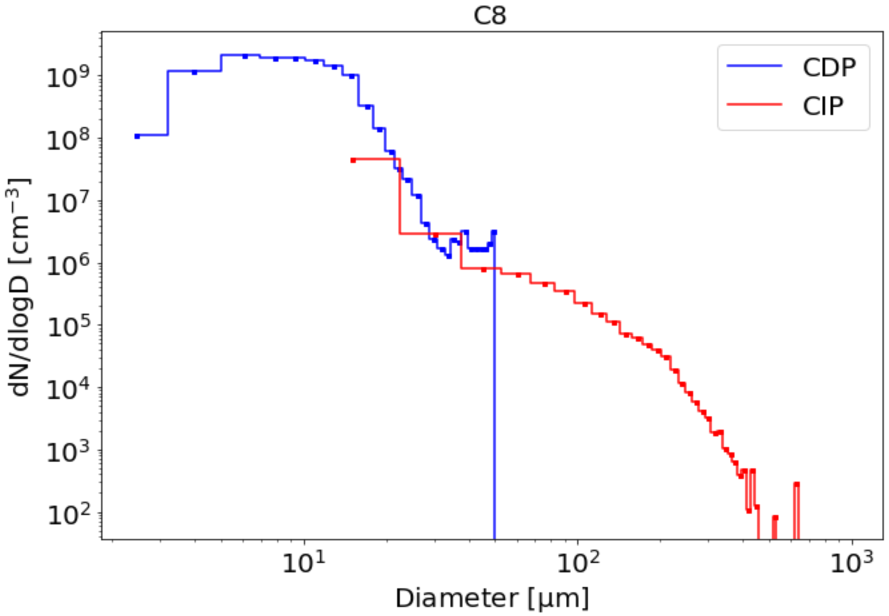
- Reference measurements were carried out at TUBS and at Collins.
- Scientific instrumentation for airborne experiments was used and compared to tunnel in-house measurements.
- No established method for measurements of Appendix O conditions exists.



Observations at Collins

- In very few cases nominal Appendix C conditions showed a large droplet mode. This may cause sensors to identify the condition as Appendix O.
- The second mode could be due to recirculation, but this has not been proven and requires further investigation.

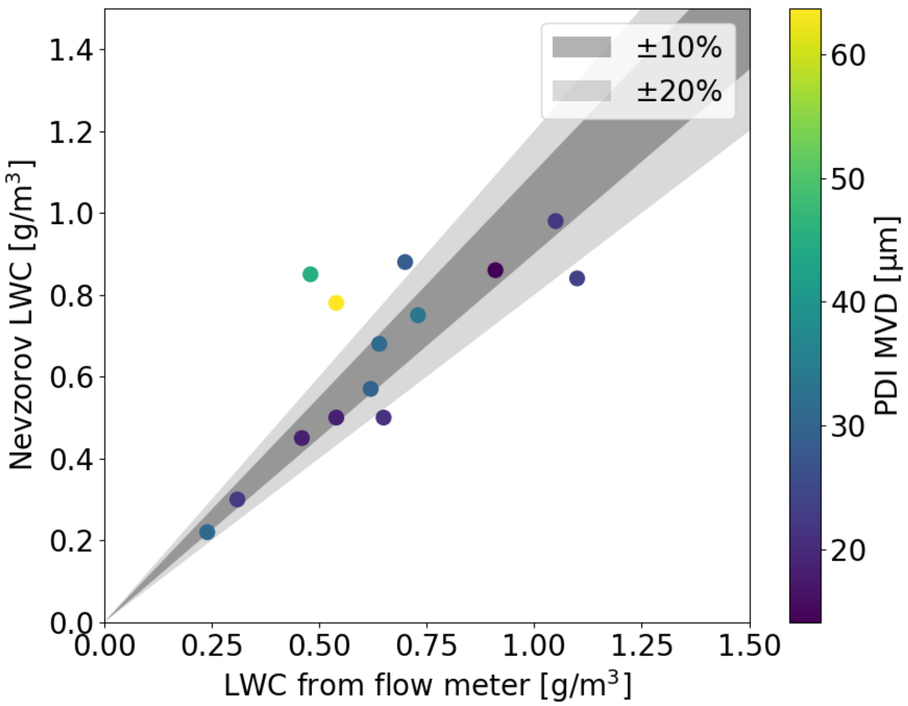


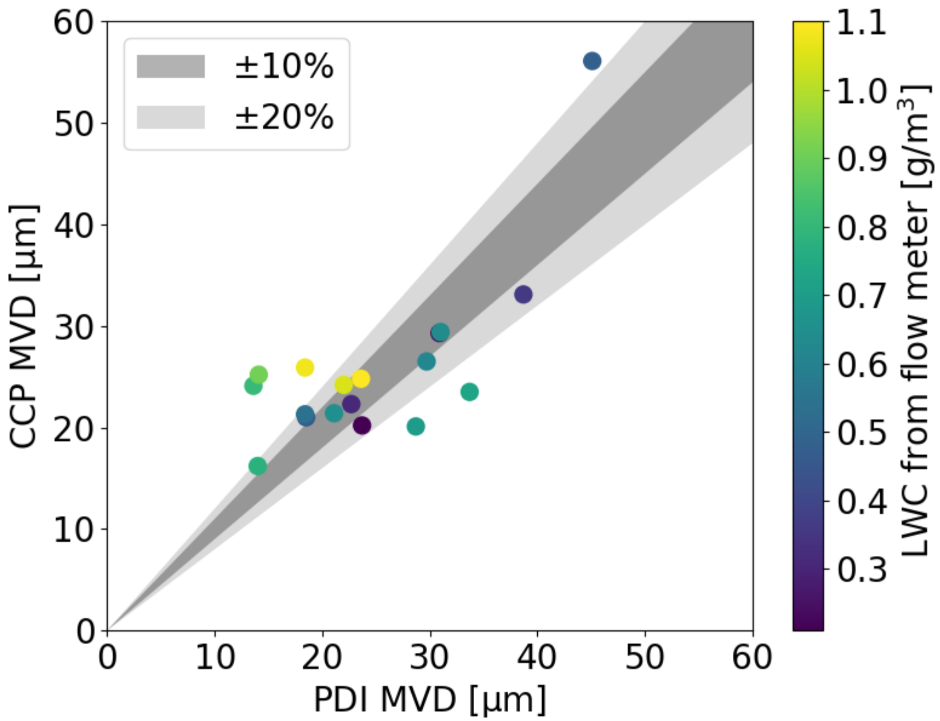


Appendix C conditions at TUBS

- Agreement within ±20% for LWC for all but five conditions.
- Larger disagreement between tunnel and reference measurements of MVD.

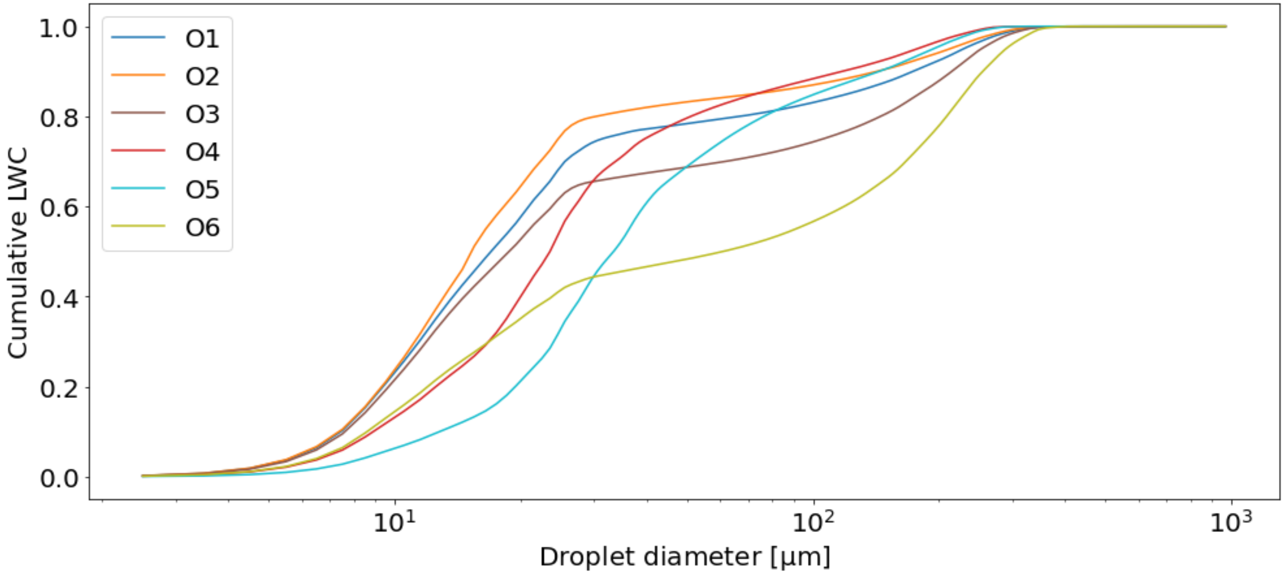
  → requires further investigation





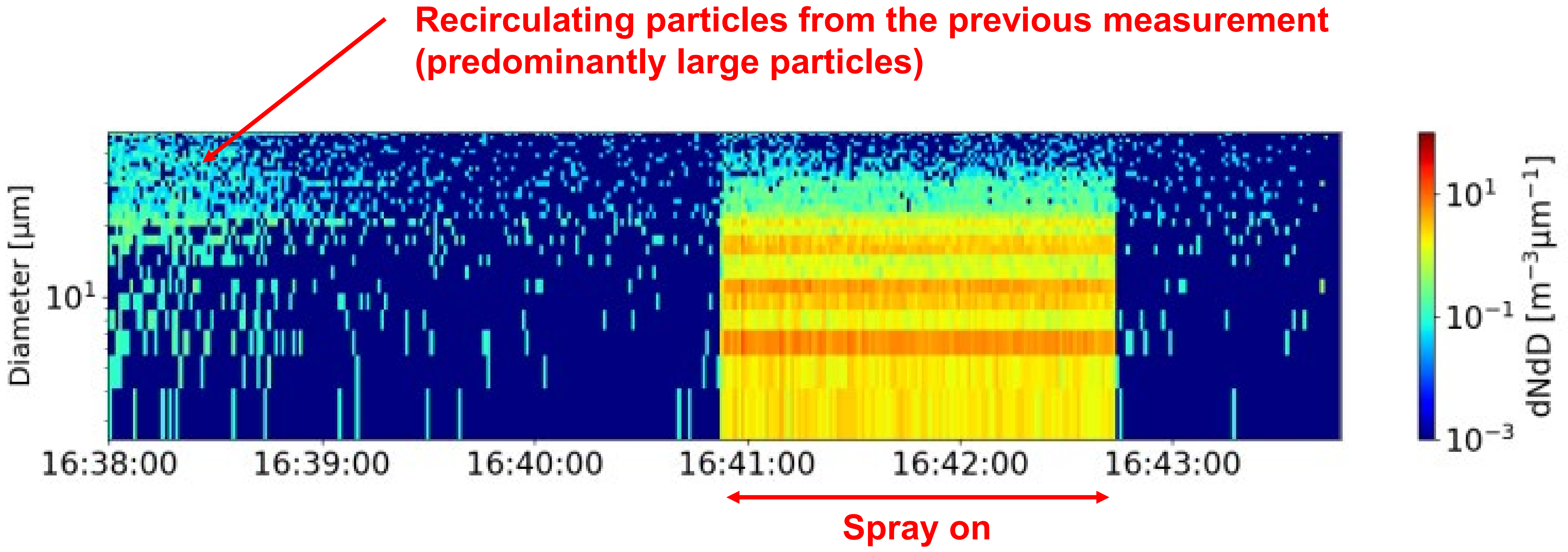
Appendix O conditions at TUBS

- TUBS achieved bimodal distributions.
- Small droplet mode is centered between 15-30 µm.
- Percentage of LWC in SLD mode is only in one case larger than 20%.
- For IWT tests it is acceptable to have larger LWC, therefore also larger percentages of SLD could be possible.
- MVD in Appendix O conditions has high uncertainty!



Observations at TUBS

- Recirculation is a problem at TUBS which requires further attention.
- Recirculation is especially apparent when the tunnel has been running for a long time.



Conclusions

- Two successful reference measurement campaigns were conducted.
- Both ‘Collins and TUBS’ tunnels were able to produce stable SLD conditions.
- The data from the campaigns enabled us to decrease the uncertainties of the icing conditions in the tunnels.
- For the assessment of SLD conditions the size distribution is more meaningful than the MVD.
- Knowledge about the suitability of different measuring techniques in Appendix O conditions was gained.
- Additional measurement campaigns are required to decrease uncertainties in LWC and the size distribution even further.

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