SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

Supercooled Large Droplet (SLD) Icing Wind Tunnel Tests Results

FINAL DISSEMINATION EVENT OF SENS4ICE PROJECT

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Directorate General for Research and Innovation, Brussels, Belgium – 29 November 2023

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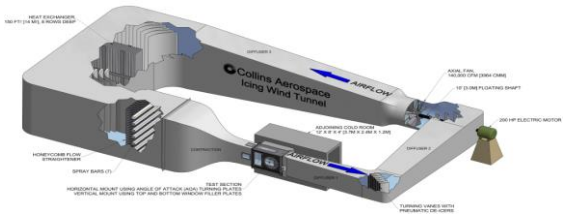
Icing Wind Tunnel Activities in SENS4ICE

- Sensor Interface Control Document (ICD) complete
- Icing Wind Tunnel (IWT) facilities upgrade for SLD conditions complete
- 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 technology evaluation

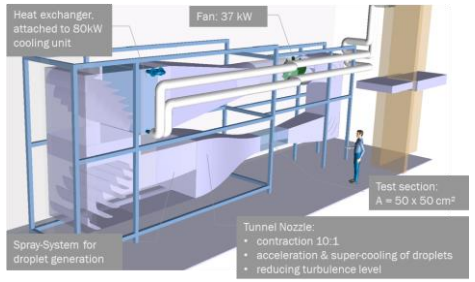
Overview of SENS4ICE IWT Capabilities

Collins Aerospace, USA



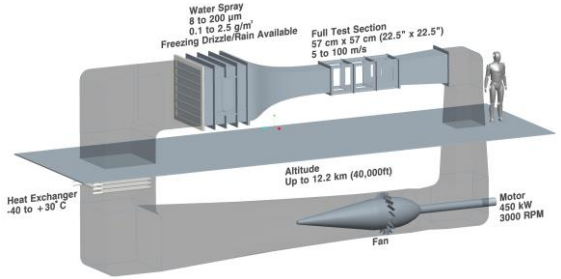
- MVD 15-190 micron droplets
- LWC between 0.15 and 3.0 g/m3
- Temperature 0°C to -30°C
- Sustained speed 14-103 m/s
- Test section: 152×56×112 cm3
- Controls and power supplies can simulate aircraft controls
- Calibrated per SAE ARP 5905

TU Braunschweig (TUBS), 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
- Short spray transients ~ 15s
- Bi-modal SLD and mixed phase capability
- Calibrated per SAE ARP 5905

NRC, Canada

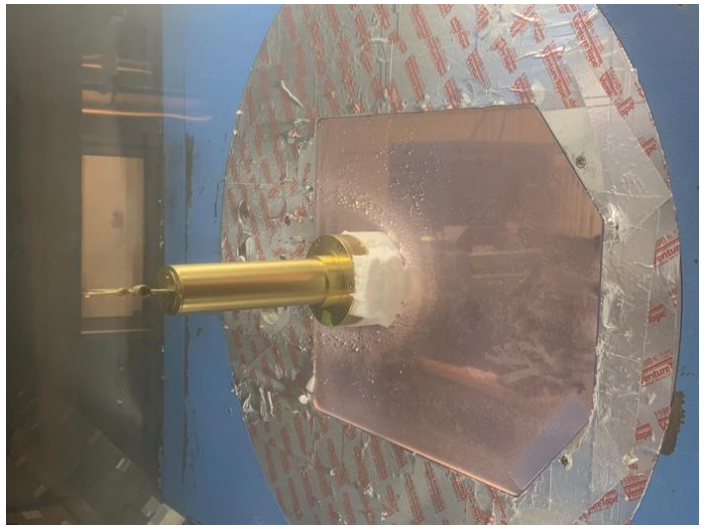


- MVD 8-200 micron droplets
- LWC between 0.1 and 2.5 g/m3
- Temperature +30°C to -40°C
- Sustained speed 5-100 m/s
- Test section: 57×57 cm2 (52x33 cm2 with insert)
- Supercooled Water: 10 to > 200 µm (incl. SLD bi-modal)
- Sea level < Altitude < 40,000ft
- Calibrated per SAE ARP 5905

Collins IWT Characterization

- 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).

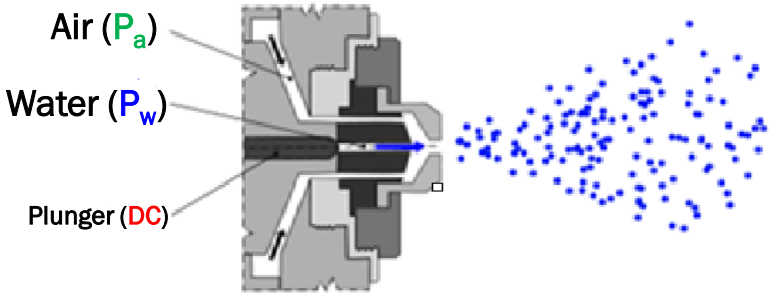
Nevzorov Probe



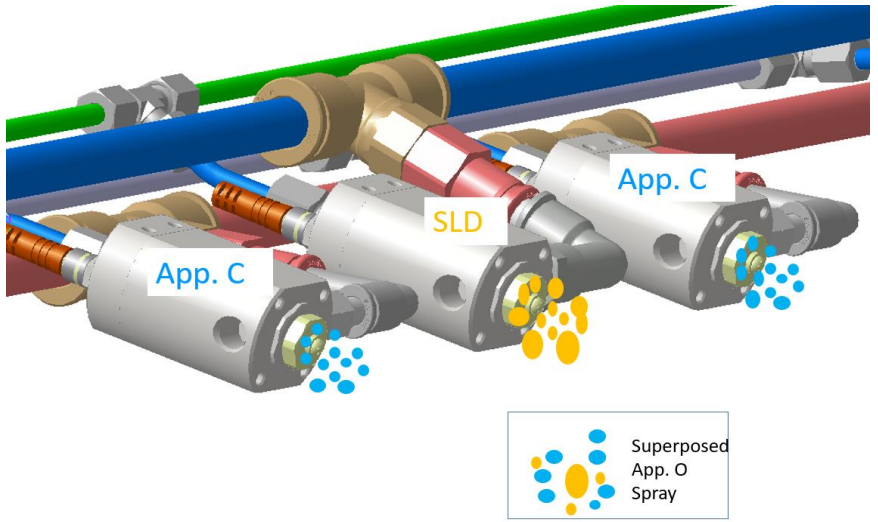
CCP Probe

TUBS IWT 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

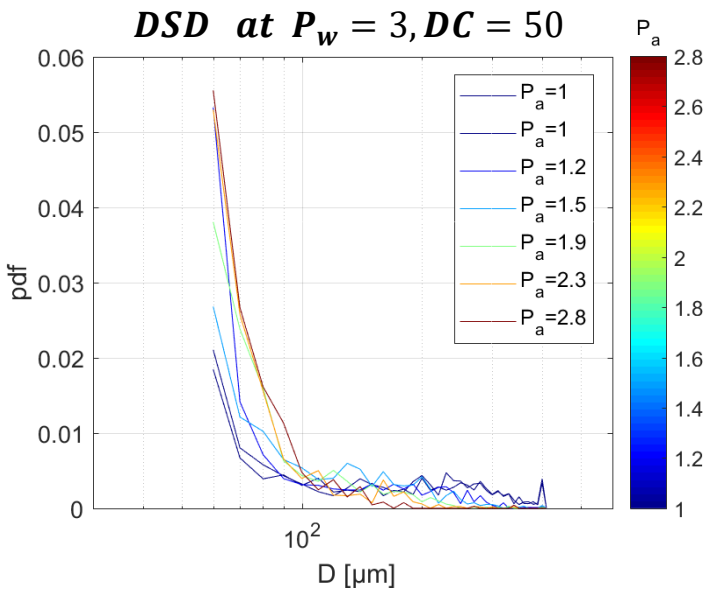


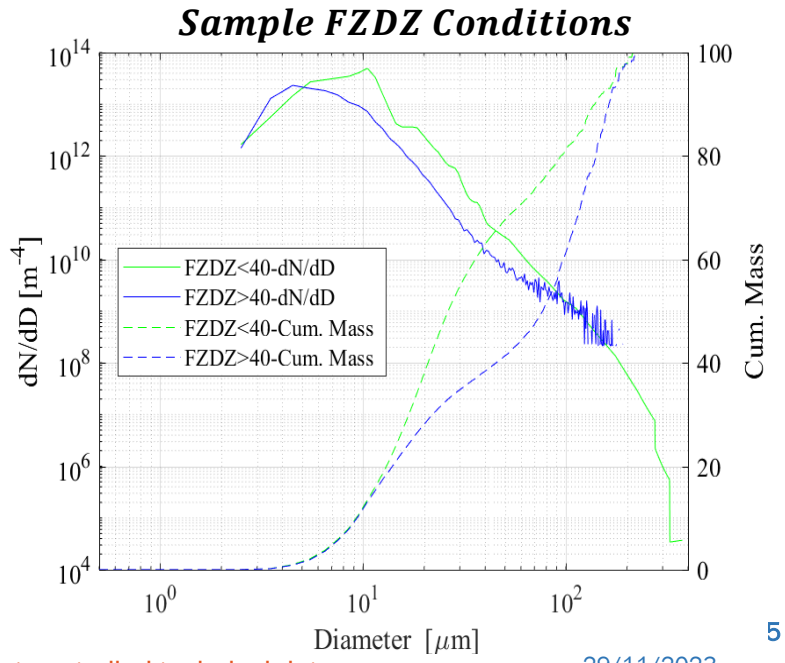
- Atomizers layout
  - Two sets of atomizers in the top two rows
  - Bimodality from the superposition of sprays
  - Each atomizer set can be actuated independently
  - App. C, App. O and only SLD clouds can be generated



TUBS IWT 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





Sensors & IWT Pairing

- Summary of sensor technologies and distribution between IWT facilities

Developer	Sensor Acronym	Sensor Type	Sensor Principle	IWT Name	IWT Test Status
AEROTEX	AIP	Atmospheric	Isothermal with inertial separation at different sensors along aircraft	NRC, TUBS	Complete
COLLINS	IDS	Atmospheric	Thermal response to heat impulse	Collins, NRC	Complete
DLR	LILD	Accretion	Ultrasonic wave attenuation / phase change	TUBS	Complete
DLR	CM2D [BCPD]	Atmospheric	Single particle optical backscatter	TUBS	Complete
DLR	CM2D [Nevzorov]	Atmospheric	Isothermal measurement of water content	TUBS	Complete
HONEYWELL	SRP	Atmospheric	Collecting backscattered light from particles	Collins, NRC	Complete
INTA	FOD	Accretion	Latent heat measured with fiber optic	NRC	Complete
ONERA	AHDEL	Atmospheric	Particle charging and subsequent measurement of the charge	TUBS	Complete
ONERA	AMPERA	Atmospheric	Measurement of aircraft electric potential	N/A	N/A
SAFRAN	AOD	Atmospheric	Shadowgraphy	TUBS	Cancelled
SAFRAN	PFIDS	Accretion	Optical reflection from accretion	TUBS	Complete

Icing Wind Tunnel 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.

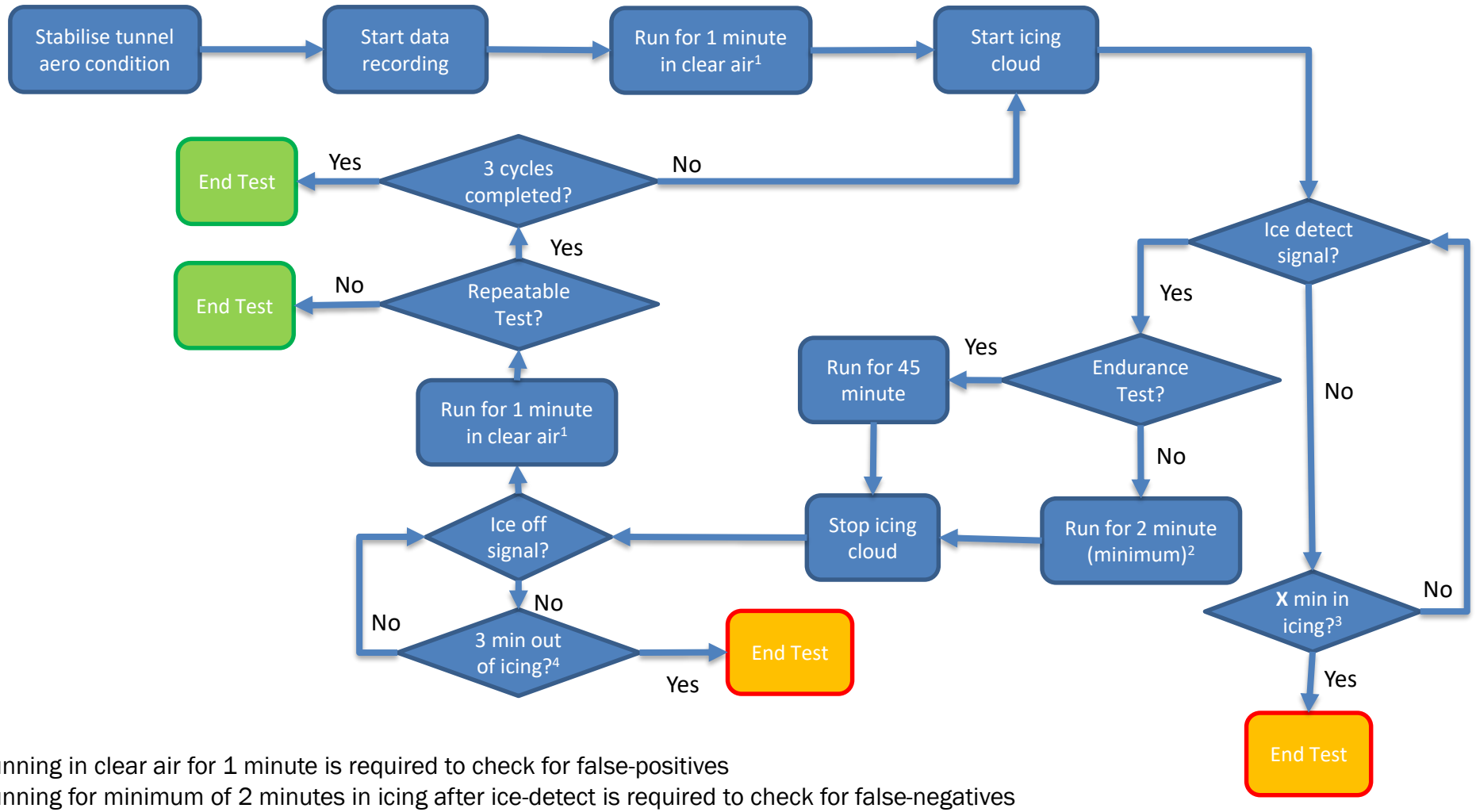
IWT Name	App C						App O					
	Total Test Points	Test Points Common with All Tunnels	Test Points Common with Two Tunnels	Test Points Used Only at One Tunnel	CM Test Points	IM Test Points	Total Test Points	Points Common with All Tunnels	Points Common with One Tunnel	Test Points Used Only at One Tunnel	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/m^3]	[s]	[s]	[s]	[s]	[s]	[s]	[-]	[g/m^3]	[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								

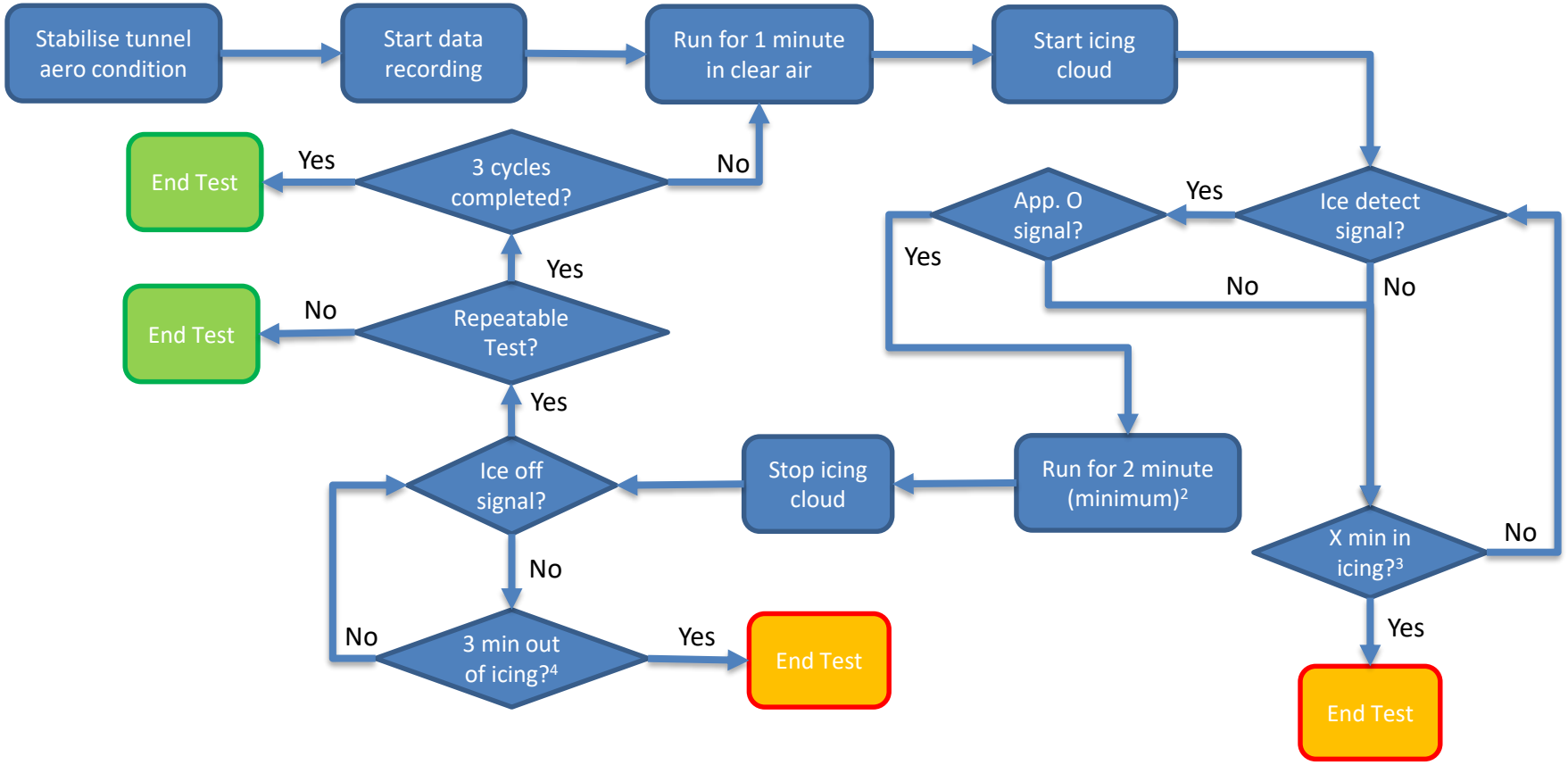
Test Procedures – App C Conditions



Notes:

1. Running in clear air for 1 minute is required to check for false-positives
2. Running for minimum of 2 minutes 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:

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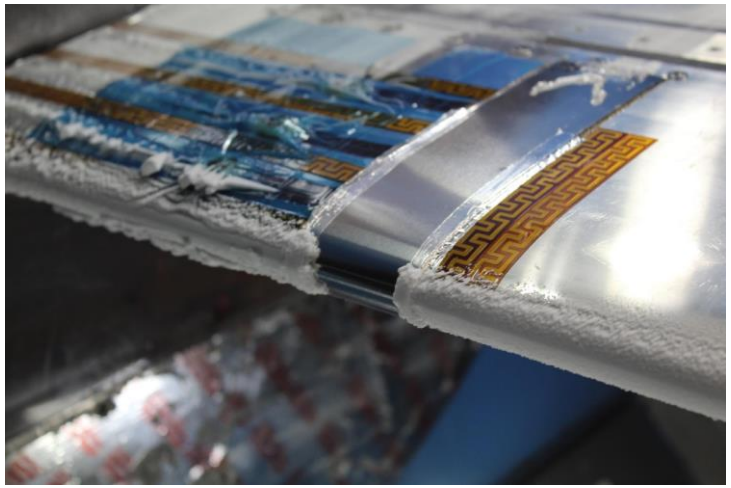
2. Running for minimum of 2 minutes in icing after ice-detect is required to check for false-negatives
3. X is the target calculated detection time + 1 minute
4. Based on AS5498A time to detect exit being a maximum of 3 minutes

Hardware shipped and installed for testing

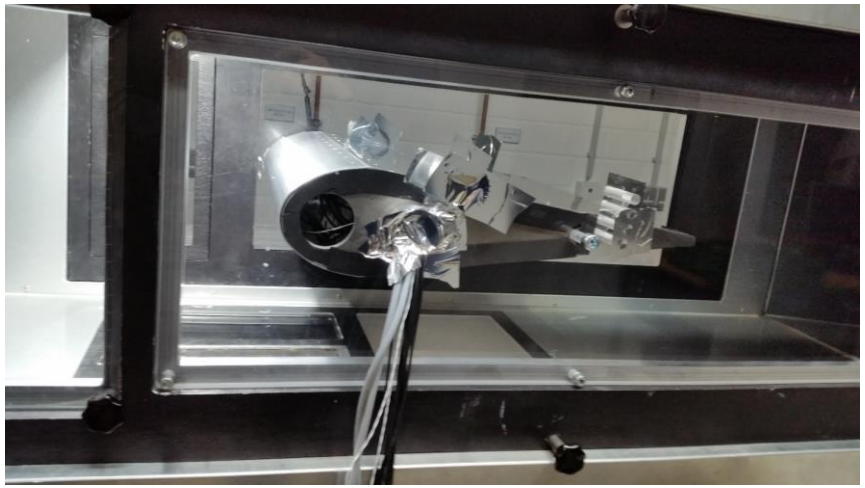
INTA FOD at NRC

Collins-IDS at Collins



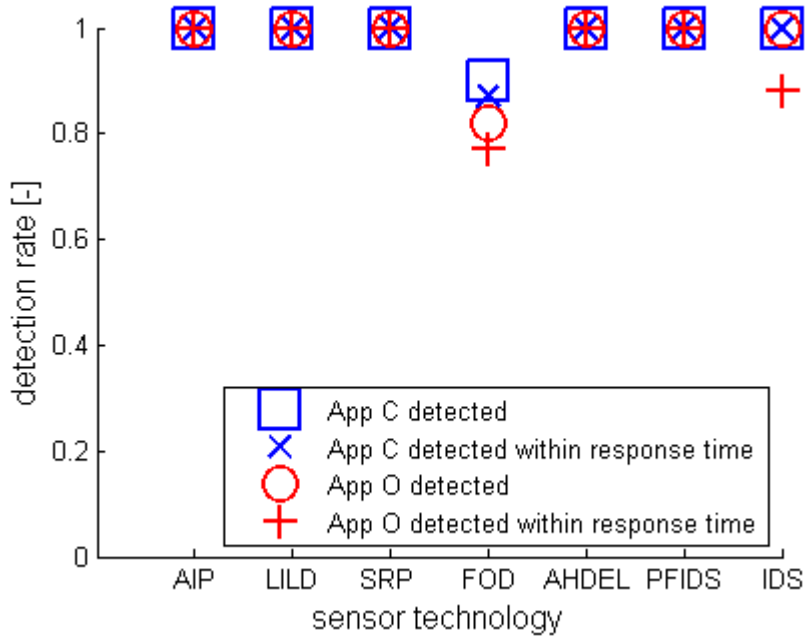
ATX–AIP at NRC

DLR LILD at TUBS



SENS4ICE sensor technologies IWT testing detection rates for App. C and O icing condition test points

- test cases successfully detected related to total number of test cases
- excluding CM2D scientific/reference sensor and AOD that was withdrawn from IWT testing in the context of Covid-19 related delays
- required maximum response time
  - as per EUROCAE inflight icing systems standard ED-103
  - maximum response time depending on icing condition

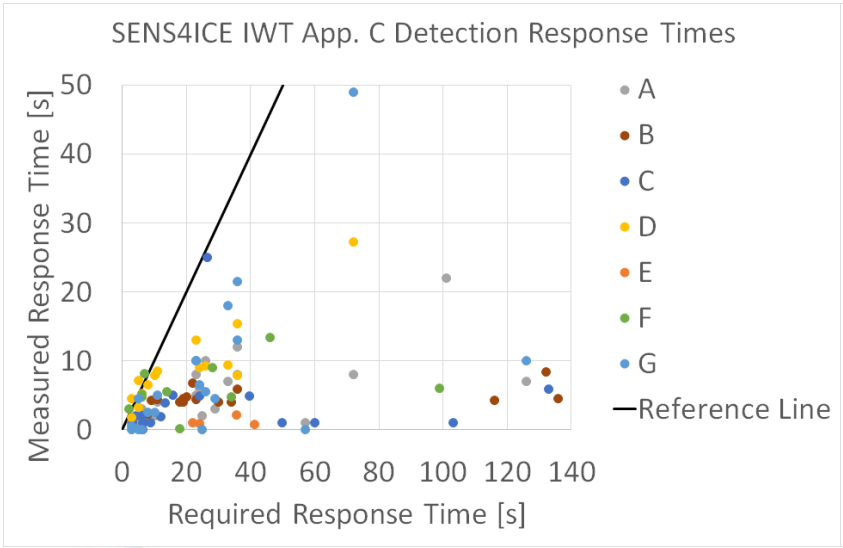


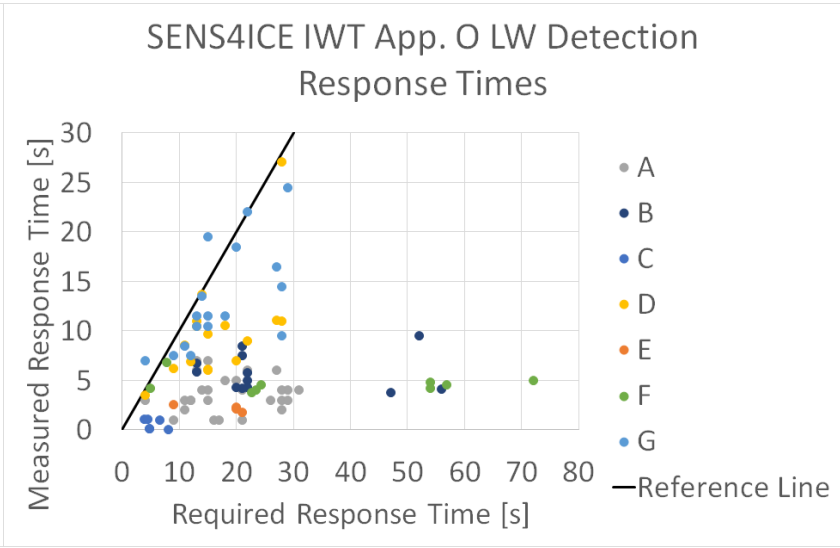
Sensor Name	App. C					
	Test Points Detected [%]	**Test Points detected within Response Time [%]**	**Test Points detected within 1.5X Response Time [%]**	Average MVD error	Average LWC error	Average ACC rate error
ATX – AIP	100%	100%	100%	N/A	N/A	N/A
Collins – IDS	100%	100%	100%	N/A	N/A	N/A
DLR – LILD	96%	100%	100%	N/A	N/A	+147%
DLR – CM2D						
HON – SRP	100%	100%	100%	14%	28%	N/A
INTA - FOD	90%	87%	90%	N/A	75%	66%
ONERA - AHDEL	100%	100%	100%	N/A	N/A	N/A
ZAET - AOD	IWT testing not completed. For details see individual report					
ZAET - PFIDS	100 %	100%	100%	N/A	N/A	+187%

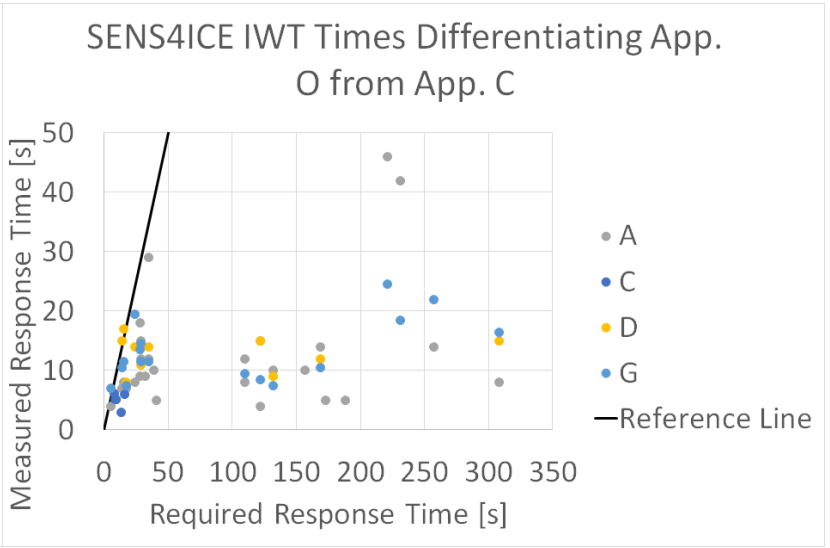
Sensor Name	App. O					
	Test Points Detected [%]	**Test Points detected within Response Time [%]**	**Test Points detected within 1.5X Response Time [%]**	Average MVD error	Average LWC error	Average ACC rate error
ATX – AIP	100%	100%	100%	N/A	N/A	N/A
Collins – IDS	100%	88.24%	94.12%	N/A	N/A	N/A
DLR – LILD	100%	100%	100%	N/A	N/A	+40.5%
DLR – CM2D						
HON – SRP	100%	100%	100%	41%	67%	N/A
INTA - FOD	82%	77%	77%	N/A	36%	48%
ONERA - AHDEL	100%	100%	100%	N/A	N/A	N/A
ZAET - AOD	IWT testing not completed. For details see individual report					
ZAET – PFIDS	100%	100%	100%	N/A	N/A	+133%

SENS4ICE sensor technologies IWT measured sensor response times compared to required response times

- anonymised results
- required maximum response time as per EUROCAE inflight icing systems standard ED-103 (depending on icing condition)
- App. C test points liquid water (LW) detection
- App. O test points liquid water (LW) detection
- differentiating App. C conditions from App. O conditions (for sensors providing differentiation information)







Summary of IWT Test Results

- Outcome of technology evaluation at Gate 2 review

Sensor / Developer	Sensor Type	IWT Facility Used	Outcome of Evaluation based on IWT Results
AIP / AeroTex	Atmospheric	NRC, TUBS	Pass
IDS / Collins	Atmospheric	Collins and NRC	Pass
LILD / DLR	Accretion	TUBS	Pass
SRP / Honeywell	Atmospheric	Collins and NRC	Pass
FOD / INTA	Accretion	NRC	Pass
AHDEL / ONERA	Atmospheric	TUBS	Stop developments with SENS4ICE
AMPERA / ONERA	Atmospheric	N/A	Pass
AOD / Safran	Atmospheric	TUBS	Stop developments with SENS4ICE
PFIDS / Safran	Accretion	TUBS	Pass
CM2D [BCPD] / DLR	Atmospheric	TUBS	Pass
CM2D [Nevzorov] /DLR	Atmospheric	TUBS	Pass

IWT Operators Lessons Learned and Takeaways

- App. O condition characterization at Collins and upgrades at TUBS required an extensive testing campaign.
- 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.
- IWT facilities enhancements for SLD conditions are required
- 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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