Funded by the
European Union

ICE GENESIS

Creating the next generation of 3D simulation means for icing

Type of action: Research and Innovation Action

Call identifier: H2020-MG-2018-SingleStage

Topic: MG-2-5-2018 Innovative technologies for improving aviation safety and certification in icing conditions

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Deliverable D3.6

Definition of numerical capability requirements for snow

EC Grant Agreement number:	824310
Start date of project: 1 January 2019	Duration: 48 months
Lead beneficiary of this deliverable:	AIH
Due date of deliverable: 31/12/2019	Actual submission date: 19/12/2019
	Version #: R2.0

Project funded by the European Commission within the H2020 Programme (2014-2020)		
Type		
R	Document, report excluding the periodic and final reports	X
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
ETHICS	Ethics requirement	
ORDP	Open Research Data Pilot	
Dissemination level		
PU	PUBLIC, fully open, no embargo e.g. web	
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Revision History

V #	Date	Description / Reason of change	Author
0.1	30/04/2019	Draft, first issue for review internaly AIH	AIH
1.0	27/05/2019	First version for distribution within ICE GENESIS (ID3.2)	AIH
1.1	11/10/2019	Review #1	AIH, AI, ON, SAE, TUDA, GE
1.2	31/10/2019	Review #2	AIH, AI, TUDA, POLIMI, SAE, GE, RR
1.3	22/11/2019	Review #3	NRC, TUDA, AIH, AI, GE, AIT
1.4	18/12/2019	ON comments (reviewer) GE comments (reviewer)	AIH, ON, GE
2.0	18/12/2019	Final version	AIH

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1. GLOSSARY

Abbreviation / Acronym	Description/meaning
AA	Airworthiness Authorities
ADS	Air Data System
ATF	Altitude Test Facility
CFD	Computational Fluids Dynamics
EIDS	Electric Impulse De-Icing System
HAIC	High Altitude Ice Crystals
HPC	High Performance Computing
HTC	Heat Transfer Coefficient
HTP	Horizontal Tail Plane
IBM	Immersed Boundary Method
IWC	Ice Water Content
LWC	Liquid Water Content
MMD	Median Mass Diameter
MS	Multi-Step first order calculation
MSPC	Multiple-step higher order predictor-corrector
MVD	Median Volumic Diameter
NACA	National Advisory Committee for Aeronautics
PC	Predictor-corrector
RAT	Ram Air Turbine
SLD	Supercooled Large Droplet
SS	single-step first order
TBD	To Be Defined
TWC	Total Water Content in liquid and solid phases
VTP	Vertical Tail Plane
WEZARD	WEather haZARD
w.r.t	With respect to
C_L	Lift coefficient

2. EXECUTIVE SUMMARY

The intent of the present specification is to give a structure applicable to any tool to be developed to predict ice and snow accretion, even out of the scope of ICE GENESIS. It is based on the specifications initiated in HAIC and STORM projects and complements the deliverable DEL3.4 which provides requirements for liquid icing conditions.

The icing tool would be capable of predicting the droplet and ice particle trajectories and impingements, ice accretion shapes, the resulting aerodynamic characteristics of the iced geometry and the performances of ice protection systems (bleed based, electro-thermal, electro-mechanical or hybrid).

Priorities have then been assigned so as to underline functionalities and validation needed for simulation of falling and blowing snow and mixed phase icing conditions in the framework of ICE GENESIS project.

3. INTRODUCTION

The intent of the present specifications is to give a structure applicable to any tool to be developed to predict ice and snow accretion, even out of the scope of ICE GENESIS. It is based on the specifications initiated in HAIC [6] and STORM [7] projects and complements the deliverable DEL3.4 which provides requirements for liquid icing conditions.

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Section 4 of these specifications provides a basic overview of the user requirements for the code. In order to address the characteristics of the tool in more detail, it has been necessary to make some assumptions about how the icing tool would operate. Section 5 provides a description of detailed characteristics of the tool. Validation requirements for the icing tool are defined in Section 0. The experimental data that are currently available for validation purposes are listed in Annexes A to H.

Finally, annexes I to L provide a description of Appendices C, O, D/P and snow as defined in the regulation.

4. TOP LEVEL USER REQUIREMENTS

This section summarises what capabilities the icing tool would be required to have, without addressing the details about how the code would work.

Req.	Statement	See paragraph
1	The software shall be compatible and comply with industrial simulation environment and platforms	§0
2	The software shall be structured with independent modules that could be interfaced with external modules	§0, 5.2
3	The software shall be delivered with a documented user guide, a theoretical manual, a non-regression/validation database and associated Best Practices	§0
4	The software should encompass arbitrary 2D objects	§4.1
5	The software should encompass arbitrary 3D objects	§4.1
6	The software shall be compliant with FAR/CS-25/27/29 Appendix C conditions	§4.1,
7	The software shall be compliant with FAR/CS-25 Appendix O conditions (SLD)	§4.1
8	The software shall be compliant with FAR/CS-25/27/29 Falling and Blowing Snow conditions	§4.1, 4.2
9	The software shall be able to handle unstructured meshes and/or structured meshes (tetrahedral, prisms, hexaedra, pyramids)	§0

Req.	Statement	See paragraph
10	The software shall compute liquid droplets, ice particles and snowflakes trajectories, heat transfer, phase change and impact	§5.3
11	The software shall be able to compute heat transfer coefficient on smooth / iced and adiabatic / heated surfaces (smooth and rough, laminar/turbulent transition)	§5.2
12	The software shall compute ice accretion on unheated surfaces	§5.4
13	The software shall compute liquid mass transfer between the impacted wall, the impacting droplets / ice particle / snowflake and/or the water/ice layer	§5.4
14	The software should be able to consider active ice protection system (bleed, electro-thermal, electro-mechanical, etc.) & both anti-icing and de-icing mode	§5.4
15	The software should be able to consider passive ice protection system (hydro/ice-phobic coating)	§5.4
16	The software shall handle the time evolution of the ice shape.	§5.4
17	The software shall be validated for a large range of conditions and parameters such as geometry, flight conditions, icing conditions, etc.	§0
18	The software should be able to predict ice shedding	§5.4

Table 1: Synthesis of the requirements

4.1 GENERAL TOP LEVEL USER REQUIREMENTS

The icing tool shall be suitable for the following components:

- Arbitrary 2D objects. For example:
    - 2D single element aerofoils
    - 2D multi-element aerofoils
    - 2D axi-symmetric nacelles
    - Arbitrary 2D non-lifting shapes
    - 2D compressor blades or struts
    - 2D axi-symmetric splitter nose
- Arbitrary 3D objects. For example:
    - Swept, tapered, twisted wings, e.g. wing, winglet, HTP and VTP
    - Wings with deployed high lift systems
    - Any other 3D aerodynamic surfaces, typical of those used on aircraft
    - Non-lifting objects: e.g. fuselage, fairings, protuberances, instruments (such as pitot tubes)
    - Components with internal mass flow: e.g. NACA ducts, pitot intakes, nacelles, flush intakes, scoops, etc.
    - Rotating components: e.g. rotors, Fenestron (shrouded rotor), propellers, RAT, engine fan blades, compressor blades, with one or several stages rotating at different speeds.
    - Any other engine components exposed to the flow: e.g. splitter nose, probes etc.

    - For turbomachinery applications, the software shall be able to handle typical constraints as:
        - Periodicities
        - Rotating boundaries
        - Relative movement of boundaries
        - Multi-domain (e.g. mixing plane)

<u>For those applications, the icing tool shall be suitable for:</u>

- FAR/CS 27/29, FAR/CS 25 Appendix C conditions.
- FAR/CS 27/29, FAR/CS 25 Blowing & Falling snow
    - Able to model snowflake trajectory: Non spherical particles drag and lift, heat exchange and phase change
    - Able to model snowflake impingement: bouncing, sticking, shattering, erosion
    - Able to model snow accretion
    - Able to model saltation
- FAR25/CS25 Appendix O conditions (SLD): Freezing Drizzle and Freezing Rain
    - Able to model large droplet trajectory: deformation and break-up
    - Able to model large droplet impingement: splashing and bouncing
    - Able to model secondary droplet trajectory and re-impingement
- FAR25 Appendix D / CS25 Appendix P conditions and FAR33 Appendix D /CS-E Appendix P conditions (mixed phase and glaciated icing conditions)
    - Able to model ice particle trajectory: Non spherical particles drag and lift, heat exchange and phase change
    - Able to model ice particle impingement: bouncing, shattering, erosion
    - Able to model ice particle accretion
- Ice accretion prediction on unheated surfaces:
    - Able to calculate the ‘general ice shape’
    - Able to model ‘real’ ice accretion characteristics
- Ice removal from heated and unheated surfaces:
    - Ice removal from unheated surfaces due to erosion and sublimation processes (‘negative growth rates’, rather than discrete removal due to shedding)
    - Ice shedding due to aerodynamic forces
    - Ice shedding due to centrifugal forces
    - Ice shedding due to gravitational forces
    - Ice shedding due to impulsive accelerations of the surfaces (e.g. due to EIDS)
    - Ice shedding due to distortion of the surface (e.g. due to pneumatic boots)
    - Ice shedding due to partial or full melting of the ice at the substrate (thermal de-icing)
    - Capable of modelling trajectories of detached blocks of ice
- Modelling anti-icing and de-icing systems:
    - Able to calculate wet/dry surface temperatures
    - Able to model water evaporation.
    - Able to model runback ice
    - Able to model steady-state anti-icing behaviour
    - Able to model cyclic anti-icing behaviour (systems that switch off at the structural temperature limit)

  - Able to model transient de-icing effects on the ice melting, ice shedding and temperatures within the substrate
  - Able to estimate the extent (chordwise and spanwise) of required ice protection and to allow the determination of systems electrical power requirement.
  - Able to easily specify heated and unheated zones and the location of any mechanically ice protected zones
  - Able to take into account surface roughness on water film dynamic and thermal balance
  - Able to characterize water film running back on protected surface (flow rate, shape, velocity and temperature gradient)
- Modelling aerodynamic characteristics due to ice:
  - Able to work with roughness and its effect on surface convective heat transfer coefficient and friction coefficient
  - Able to handle sharp geometry w.r.t. mesh generation, solver accuracy and robustness
  - Able to predict stall due to leading edge separation
  - Able to predict loss in lift coefficient, increase in drag coefficient, and change in pitching moment coefficient

Furthermore, the icing tool shall be:

- Easy to use
- Well documented (user guide) with associated Best Practices
- Delivered with validation report and non-regression report
- Compatible and compliant with industrial simulation environment and platforms (e.g. HPC hardware, size of models, time restitution, Flow solver, …)
- Able to determine easily how sensitive the predicted ice shapes are to small changes in the flight/icing conditions

4.2 SNOW TOP LEVEL USER REQUIREMENTS

This section intends to precise what are the top level priorities in terms of snow icing conditions modelling.

4.2.1 Trajectory models

- Computations shall be at least able to reproduce steady-state situations
- Both Lagrangian and Eulerian models shall be provided
- The tool shall be able to predict snowflake trajectory distribution through a flow path
- The tool shall be able to predict the trajectory of the snowflake after rebound and shattering
- Air/particle thermal interaction shall be taken into account to provide liquid/solid ratios
- If relevant, snowflake evaporation influence on gas properties shall be taken into account.

4.2.2 Wall/Droplet/Snow impingement models

- Computations shall be at least able to reproduce steady-state situations
- The tools shall be able to discriminate “stick-or-bounce” ratios considering :
  - Particles liquid-to-solid ratio
  - Wall temperature

    - Film presence on the wall (and thickness if relevant)
    - Ice presence on the wall

4.2.3 Accretion models

- Computations shall be at least able to reproduce steady-state situations
- The tools shall be able to predict:
    - Wall equilibrium temperature, taking into account evaporative & melting effect
    - Film presence (and thickness if relevant)
    - Water imbibition (slush ice)
    - Ice accretion shape, taking into account erosion

5. TOOL DESIGN DETAILS

Definition of importance categories

Essential	We cannot perform our work without this capability, and there is no way to work around it. Alternatively, the effect on the tool accuracy is such that without this capability, the results are almost useless.
Highly desirable	The absence of this capability would have a significant impact on the speed/efficiency of performing the calculations, although results can still be produced by some other means. Alternatively, there is a significant impact on the accuracy of the code if this capability is not available that would call into question the validity of the results.
Desirable	This capability would improve the speed/efficiency of the calculations and would improve the results.
Nice to have	This capability is useful, but is not too important for the calculations.

Scope of ICE GENESIS

It should not be necessary to use specific tools for SLD, mixed phase & glaciated icing environments or snow, as compared to other icing conditions. Therefore, the present document lists all the requirements of an ideal icing tool. The developments mandatory for ICE GENESIS are underlined through a dedicated column.

Hence, the tables should be read as follow:

- **“Importance” is the importance of the criteria for a complete “ideal” icing tool;**
- **“Development required for ICE GENESIS” states whether the criteria is applicable to ICE GENESIS or not.**

Note that the aim of ICE GENESIS is not to have one complex unified tool but several interoperable modules, each one dedicated to one particular simulation e.g trajectory, HTC, accretion, etc. Hence, some criteria listed here below may be develop on one module but may not concern the others.

5.1 INDUSTRIALIZATION GENERAL REQUIREMENTS

This section details the capabilities needed for the tools to be suitable to industrial constraints.

5.1.1 Generalities

Tool design characteristic/capability		Development required for ICE-GENESIS	Importance				Ref	Notes
			Essential	Important	Desirable	Nice to have		
Documentation	User guide documentation, validation report, non-regression report, best practices (incl. mesh convergence influence)	**X**	X				5.1.1.1	
Structure organization	Independent modules (flow solver, trajectory solver, ice accretion solver) coupled via interfaces	**X**	X				5.1.1.2	

Table 2: INDUSTRIALIZATION GENERAL REQUIREMENTS - Generalities

5.1.2 Mesh compatibility

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Mesh size compatibility	Mesh size limited only by computer hardware.		X				5.1.2.1	Not specific to ICE GENESIS
Mesh type compatibility	Single-block structured meshes		X				5.1.2.2	
	Multi-block structured meshes		X				5.1.2.3	
	Unstructured meshes – tetrahedral		X				5.1.2.4	
	Unstructured meshes – prisms		X				5.1.2.5	
	Unstructured meshes – hexahedra		X				5.1.2.6	
	Unstructured meshes – pyramids		X				5.1.2.7	
	Unstructured meshes – Arbitrary polyhedra			X			5.1.2.8	Includes capability for hybrid structured / unstructured meshes.
	Hanging node compatibility		X				5.1.2.9	Not specific to ICE GENESIS
	Hanging face compatibility		X				5.1.2.10	Not specific to ICE GENESIS

	Cartesian capability			X			5.1.2.11	
	Overlapping mesh capability			X			5.1.2.12	
	Adaptative unstructured meshes	**X**		X			5.1.2.13	
	Immersed boundary method	**X**		X			5.1.2.14	

Table 3: INDUSTRIALIZATION GENERAL REQUIREMENTS – Mesh Compatibilities

5.1.3 Pre and post processing requirements

Tool design characteristic/capability		**Development required for ICE GENESIS**	**Importance**				**Ref**	**Notes**
			Essential	**Highly Desirable**	**Desirable**	**Nice to have**		
Input & Output	Ability to read inputs (meshes, flow solutions) and write outputs in CGNS format	**X**	X				5.1.3.1	Applicable to 3D tools. Need to converge on an icing CGNS like format for mesh, solution and data storage.
Post-processing	Able to visualise the predicted ice surface		X				5.1.3.2	Not specific to ICE GENESIS
	Able to visualise droplets/ice particles trajectories		X				5.1.3.3	
	Able to visualise the surface local catch efficiency (β parameter)		X				5.1.3.4	
	Able to visualise local LWC/IWC concentration (α parameter)		X				5.1.3.5	
	Able to visualise local ice growth rates			X			5.1.3.6	
	Able to visualise wall surface temperature		X				5.1.3.7	
	Able to generate CAD surface/solid from predicted ice		X				5.1.3.8	
	Able to visualise ice debris shape, size at the shedding location		X				5.1.3.9	
	Able to visualise ice debris trajectory, impact location and relative energy		X				5.1.3.10	
	Able to characterise the water film on the skin (speed and thickness)	**X**		X			5.1.3.11	

Table 4: INDUSTRIALIZATION GENERAL REQUIREMENTS – Pre and Post Processing

5.1.4 Efficiency and Performances

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Efficiency and user-friendliness	Easy data pre-processing			X			5.1.4.1	e.g. GUI
	Automatic positioning of droplets/ice particles for the trajectory analysis			X			5.1.4.2	Eulerian approaches for calculating the droplet motion will, by default, satisfy this requirement.
	Automatic monitoring of potential errors and inaccuracies			X			5.1.4.3	Produces warnings/errors when sufficient accuracy is not obtained.
	Automatic control of potential errors and inaccuracies.			X			5.1.4.4	Automatically adjusts trajectory analysis to obtain desired accuracy.
	Fully automatic calculation of water catch on a specified surface.			X			5.1.4.5	No user interaction or checking required.
	Automatic positioning of droplets re-emission injection points			X			5.1.4.6	
Performances 2D	CPU (running) time < 30 minutes	**X**	X				5.1.4.7	These characteristics aim to reflect the need to have a tool that is reasonably practicable to use. Obviously it would have to be for a specific test case and on a specific computer platform (local, 2 to 4 CPU, 32 bits).
	CPU time < 10 minutes	**X**		X			5.1.4.8	
	CPU time < 5 minutes	**X**			X		5.1.4.9	
	CPU time < 1 minute	**X**				X	5.1.4.10	
Performances 3D	CPU time < 1 day (24 hours)	**X**	X				5.1.4.11	These characteristics aim to reflect the need to have a tool that is reasonably practicable to use. Obviously it would have to be for a specific test case and on a specific computer platform (TBD).
	CPU time < 6 hours	**X**		X			5.1.4.12	
	CPU time < 30 minutes				X		5.1.4.13	
	CPU time < 10 minutes					X	5.1.4.14	
Inter-operability	Common format file for each input and output files of the tools shall be defined	**X**	X				5.1.4.15	CGNS format file TBD
Accuracy	Skin Temperature for accretion tools +/- 2°C	**X**	X				5.1.4.16	
	Skin Temperature for Anti-icing tools +/- 5°C	**X**	X				5.1.4.17	+/-2°C would be more appropriate.
	Local concentration +/- 2%	**X**	X				5.1.4.18	
	Collection efficiency coefficient β +/- 2%		X				5.1.4.19	

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Ice thickness +/- 10%	**X**	X				5.1.4.20	ICE GENESIS objective is at least 20%
	Ice mass +/- 10%	**X**	X				5.1.4.21	ICE GENESIS objective is at least 20%
	Ice shape definition +/- 10%	**X**	X				5.1.4.22	Ice shape features: horn angle, ice chordwise extension, …
	LWC/TWC ratio +/- 2%	**X**	X				5.1.4.23	ICE GENESIS objective is at least 20%
	Ice debris mass +/- 10%		X				5.1.4.24	This accuracy is a challenging target but the tools should at least achieve +/-20%
	Ice debris momentum inertia +/- 20%			X			5.1.4.25	
	Ice debris impact probability +/- 10%		X				5.1.4.26	For low fidelity ice debris trajectory tools
	Ice debris trajectory: The numerical ice trajectory should be within the experimental envelope of possible trajectories.		X				5.1.4.27	
	Ice debris kinetic energy +/- 10%			X			5.1.4.28	
Robustness	User inputs checks, error tracking	**X**		X			5.1.4.29	This requirement applies to all developments done in ICE-GENESIS. Minimum mesh quality check would be nice to have

Table 5: INDUSTRIALIZATION GENERAL REQUIREMENTS – Efficiency & Performance

5.2 FLOW SOLVER

5.2.1 Flow solver compatibility

Note that in the scope of ICE GENESIS, the expected flow solver capabilities identified as essential are already available and there is no development required.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Flow solver capability	Inviscid, incompressible solutions (Full potential)		X				5.2.1.1	**Essential for 2D (state-of-the-art)**
	Inviscid, compressible solutions (Euler)		X				5.2.1.2	

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Viscous, compressible steady state solutions (RANS)		X				5.2.1.3	
	Viscous, compressible unsteady solutions (Unsteady RANS, DES)				X		5.2.1.4	**Desirable for URANS** **Nice to have for DES**
	Rotating frame of reference for steady-state computations			X			5.2.1.5	
	Able to model flows with actuator disks		X				5.2.1.6	

Table 6: FLOW SOLVER – Compatibility

5.2.2 External heat transfer coefficient calculation

Note that the external heat transfer coefficient calculation is not a direct aim of ICE GENESIS but improvement might be needed in order to better simulate rotating components.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Physical model for external heat transfer coefficient (HTC) calculation	Calculation of accurate HTCs on iced (rough) surfaces	**X**	X				5.2.2.1	ICE GENESIS will provide new semi-empirical models for the prediction of roughness parameters depending on icing conditions.
	Calculation of accurate HTCs on smooth surfaces, or ability to read in HTCs from CFD		X				5.2.2.2	
	Calculation of HTCs on surfaces with a mixture of iced and smooth regions		X				5.2.2.3	
	Calculation of accurate HTCs on heated wall (heat transport through boundary layer...)		X				5.2.2.4	
	Able to compute natural laminar-turbulent transition over smooth surface (unheated wall)		X				5.2.2.5	
	Able to compute natural laminar-		X				5.2.2.6	Useful for thermal ice protection systems

Tool design characteristic/capability		**Development required for ICE GENESIS**	**Importance**				**Ref**	**Notes**
			Essential	**Highly Desirable**	**Desirable**	**Nice to have**		
	turbulent transition over smooth surface (heated wall)							
	Able to compute laminar-turbulent transition over rough surface		X				5.2.2.7	Including modelling of transition region

Table 7: FLOW SOLVER – Heat Transfer

5.3 TRAJECTORY & IMPINGEMENT TOOLS REQUIREMENTS

5.3.1 General requirements

Tool design characteristic/capability		**Development required for ICE GENESIS**	**Importance**				**Ref**	**Notes**
			Essential	**Highly Desirable**	**Desirable**	**Nice to have**		
Icing environment	App. C	**X**	X				5.3.1.1	
	App.O Freezing Drizzle	**X**	X				5.3.1.2	
	App. O Freezing Rain	**X**		X			5.3.1.3	Lack of experimental validation data in ICE-GENESIS
	App D/P Glaciated and Mixed Phase		X				5.3.1.4	
	Falling and Blowing Snow	**X**	X				5.3.1.5	
Frameworks	Both Eulerian and Lagrangian	**X**	X				5.3.1.6	
Models	Consider Coriolis and centrifugal forces for a rotating frame of reference for steady-state calculations.		X				5.3.1.7	
	Droplet/particle distribution periodicity in rotation or translation for steady-state calculations		X				5.3.1.8	
	Mixing planes for steady state droplets and particles trajectory analysis of different, serial rotating frames		X				5.3.1.9	N/A for H/C
	Able to model crossing of droplet/ice particles trajectories.	**X**		X			5.3.1.10	Both in terms of the trajectory calculation and also the catch efficiency calculation. Available with Lagrangian approach

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Pre/post processing	Able to model spectrum of droplet/ice particles sizes: Manual interaction required.	**X**	X				5.3.1.11	Interim capability where the catch results from mono-dispersed calculations are post-processed, either manually or within a script file, to sum their contribution.
	Able to model spectrum of droplet/ice particles sizes: Fully automatic.	**X**	X				5.3.1.12	User defined spectrum or pre-defined spectrum (eg Langmuir-D+MVD). Fully automatic means that all processing is done within the icing tool.
	Manual Ability to determine the local concentrations, or ‘α’ parameter on planes that are not surfaces.	**X**	X				5.3.1.13	For example, this capability is required for determining the suitable position for sensors. Need for post-processing on basic surface/volume (e.g. annular spheres (desirable)
	Able to model droplet / particle trajectories passing through an actuator disc			X			5.3.1.14	SLD/Snow development should be compatible with an actuator disk model.
	Manual Ability to determine local water catch efficiency along a surface for a given type of particles (diameter, phase…)		X				5.3.1.15	

Table 8: TRAJECTORY & IMPINGEMENT - Generalities

5.3.2 Supercooled Liquid Water conditions models

Small droplets trajectory is already well modelled so no specific additional development is requested in ICE GENESIS.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Physical model for small droplet motion and impingement	Consider aerodynamics forces on the droplet motion		X				5.3.2.1	
	Droplets start at local air velocity		X				5.3.2.2	

Table 9: TRAJECTORY & IMPINGEMENT - Supercooled Liquid Water conditions

5.3.3 Supercooled Large Droplets conditions models

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Physical model for large droplet motion and impingement	Consider gravitational forces on the droplet motion	**X**	X				5.3.3.1	Not specific to ICE-GENESIS
	Increment applied to initial droplet velocity to account for the droplet terminal velocity	**X**	X				5.3.3.2	Not specific to ICE-GENESIS
	Able to model droplet deformation due to high relative velocities.		X				5.3.3.3	
	Able to model droplet break-up due to high relative velocities.		X				5.3.3.4	
	Able to model droplet bounce from impact on the surface (increment to catch only, assuming no re-impingement).	**X**	X				5.3.3.5	
	Able to model droplet splashing from impact on the surface (increment to catch only, assuming no re-impingement).	**X**	X				5.3.3.6	
	Able to model secondary trajectories and subsequent re-impingement of rebounded or splashed droplets.	**X**		X			5.3.3.7	
	Able to compute the droplet change temperature along its trajectory	**X**		X			5.3.3.8	Issue with thermal equilibrium for the large droplets in icing wind tunnel
	Able to take into account wall surface features for large droplet wall impact (roughness, presence of liquid film, temperature for Ice Protection System application…)	**X**	X				5.3.3.9	
	Able to take into account local air flow for large droplet wall impact (crossflow, …)	**X**	X				5.3.3.10	

Table 10: TRAJECTORY & IMPINGEMENT - Supercooled Large Droplets conditions

5.3.4 Ice Crystal and Mixed Phase conditions models

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Physical model for ice particle motion and impingement	Able to model the trajectories of spherical/Non spherical ice particles		X				5.3.4.1	Addressed in the framework of MUSIC-HAIC
	Able to model phase change of ice particle along trajectories		X				5.3.4.2	
	Able to model ice particle or partially melt ice particle bouncing for impact on a dry wall		X				5.3.4.3	
	Able to model ice particle bouncing or partially melt ice particle for impact on a liquid film		X				5.3.4.4	
	Able to model ice particle or partially melt ice particle shattering for impact on a dry wall		X				5.3.4.5	
	Able to model ice particle or partially melt ice particle shattering for impact on a liquid film		X				5.3.4.6	
	Able to model ice particle or partially melt ice particle deposition for impact on a dry wall		X				5.3.4.7	
	Able to model ice particle or partially melt ice particle deposition for impact on a liquid film		X				5.3.4.8	
	Able to model secondary ice particle or partially melt ice particle and subsequent re-impingement		X				5.3.4.9	
	Able to model Erosion of the solid surface by ice particle or partially melt ice particle		X				5.3.4.10	
Outputs	Able to give the local LWC/TWC ratio in the flow		X				5.3.4.11	

Table 11: TRAJECTORY & IMPINGEMENT – Ice Crystals & Mixed Phase icing conditions

5.3.5 Falling and Blowing Snow conditions models

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Physical model for ice particle motion and impingement	Able to handle various particle size distributions as well as various particle shapes	**X**	X				5.3.5.1	
	Able to model the trajectories of snowflakes or partially melt snowflakes	**X**	X				5.3.5.2	
	Able to model thermal equilibrium of snowflakes along trajectories	**X**	X				5.3.5.3	a ~1 °K accuracy is expected in terms of particle temperature.
	Able to model phase change of snowflakes along trajectories	**X**	X				5.3.5.4	An accuracy of ~5% in terms of liquid fraction is expected An accuracy of ~1 % of the total water mass flow is expected in terms of evaporated water
	Able to model snowflakes or partially melt snowflakes bouncing for impact on a dry wall	**X**	X				5.3.5.5	
	Able to model snowflakes or partially melt snowflakes bouncing for impact on a liquid film	**X**	X				5.3.5.6	
	Able to model snowflakes or partially melt snowflakes bouncing for impact on ice/snow accretion	**X**	X				5.3.57	
	Able to model snowflakes or partially melt snowflakes shattering for impact on a dry wall	**X**	X				5.3.5.8	
	Able to model snowflakes or partially melt snowflakes shattering for impact on a liquid film	**X**	X				5.3.5.9	
	Able to model snowflakes or partially melt snowflakes shattering for impact on ice/snow accretion	**X**	X				5.3.5.10	
	Able to model snowflakes or partially melt snowflakes deposition for impact on a dry wall	**X**	X				5.3.5.11	
	Able to model snowflakes or partially melt snowflakes deposition for impact on a liquid film	**X**	X				5.3.5.12	
	Able to model snowflakes or partially melt snowflakes deposition for impact on ice/snow accretion	**X**	X				5.3.5.13	

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Able to model secondary snowflakes or partially melt snowflakes and subsequent re-impingement	**X**	X				5.3.5.14	
	Able to model Erosion of the solid surface by snowflakes or partially melt snowflakes	**X**	X				5.3.5.15	
	Able to model saltation of snowflakes or partially melt snowflakes	**X**	X				5.3.5.16	
Outputs	Able to compute the particle size distribution at a given location in the flow	**X**	X				5.3.5.17	Due to the fact that small particles are the one that are most prone to melting, they play a key role in determining the melt ratio
	Able to compute the local LWC, IWC and LWC/TWC ratio in the flow	**X**	X				5.3.5.18	Useful for evaluation of ice accretion risk A 20% accuracy is expected in terms of LWC, IWC, TWC
	Able to compute the snow accretion rate	**X**	X				5.3.5.19	

Table 12: TRAJECTORY & IMPINGEMENT – Falling & Blowing Snow conditions

5.4 ACCRETION TOOL REQUIREMENTS

In the framework of ICE GENESIS, runback water models and droplet re-emission models will not be developed (previously addressed by other research projects like STORM).

5.4.1 Generic Ice Accretion Features

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Solid and liquid water mass deposition	Able to predict liquid mass transfer between impacting droplets/ice particles/snowflakes and iced/water layer	**X**	X				5.4.1.1	Leading to slush ice deposit
Framework	The model must take into account both the liquid and solid phases.	**X**	X				5.4.1.2	
Runback water flow modelling (general)	Model water flow in terms of mass flow rates	**X**	X				5.4.1.3	Minimum requirement: Current method used within 2D codes Some adaptation could be needed for snow

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Calculation of water film height	**X**		X			5.4.1.4	Potentially useful to model splashing of SLDs, for ice particles (App D/P), and for snowflakes
	Calculation of water film height, taking into account roughness features caused by ice accretion				X		5.4.1.5	
	Calculation of water film break-up into rivulets: Semi-empirical		X				5.4.1.6	This function is needed for any anti-icing ice protection system; not specific to ICE-GENESIS
	Calculation of water film break-up into rivulets: Fully theoretical					X	5.4.1.7	
	Calculation of water film re-emission: geometric rupture		X				5.4.1.8	Not specific to ICE-GENESIS
	Calculation of water film re-emission: aerodynamic peeling			X			5.4.1.9	Specific to engines
Transportation of runback water calculated with allowances for:	Air shear (skin friction)		X				5.4.1.10	Not specific to ICE-GENESIS
	Solid surface friction			X			5.4.1.11	Influence of the roughness, static/dynamic contact angle (hydrophobic or hydrophilic surfaces) Not addressed in ICE-GENESIS
	Pressure forces			X			5.4.1.12	
	Gravitational forces				X		5.4.1.13	
	Centrifugal forces		X				5.4.1.14	Only applicable if the tool has a rotational capability Not specific to ICE-GENESIS
	Coriolis forces		X				5.4.1.15	Only applicable if the tool has a rotational capability Not specific to ICE-GENESIS

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Mass loss due to evaporation and sublimation		X				5.4.1.16	Essential when analyzing anti-icing or modelling ice particles accretion at ambient temperature above freezing Sublimation necessary for ice loss aft of protection (from pre-existing runback ice) Not specific to ICE-GENESIS
Ice growth modeled taking into account :	Kinetic heating/convection		X				5.4.1.17	Basic functions not specific to ICE-GENESIS and already available in numerous icing tools
	Cooling due to evaporation		X				5.4.1.18	
	Cooling due to sublimation		X				5.4.1.19	Basic function not specific to ICE-GENESIS and already available in numerous icing tools
	Correction to evaporation/sublimation heat loss due to relative humidity <100%		X				5.4.1.20	Essential for engine core but not specific to ICE-GENESIS
	Allowances in evaporation/sublimation heat loss due partially wetted surface				X		5.4.1.21	
	Latent heat of freezing		X				5.4.1.22	Basic function not specific to ICE-GENESIS and already available in numerous icing tools
	Sensible heat due impinging droplets/ice particles/snowflakes		X				5.4.1.23	
	Sensible heat from runback water		X				5.4.1.24	
	Heat from kinetic energy of the droplets/ice particles/snowflakes		X				5.4.1.25	
	Heat flow due to conduction		X		X		5.4.1.26	Essential for modelling thermal ice protection systems (addressed later), desirable for modelling substrates with a large thermal mass.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Steady state conduction, from the control volume into the substrate and within the substrate			X			5.4.1.27	No consideration of the thermal mass. Lateral conduction through the substrate affects neighboring ice growth rates.
	Transient conduction, through the ice and within the substrate					X	5.4.1.28	Complete analysis of the conduction characteristics
	Automatic adjustment of spatial discretisation of the mesh used for the ice growth model to control errors			X			5.4.1.29	Not addressed in ICE-GENESIS

Table 13: ACCRETION – Generalities

5.4.2 Specific anti-iced or de-iced features

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
General capabilities (Inputs required from system point of view to confirm the relative importance of these capabilities)	1) Able to perform a steady state calculation of anti-iced surface	**X**	X				5.4.2.1	Constant heat flux or wall temperature at the surface. Option to model steady state conduction within the substrate. Not specific to ICE-GENESIS
	2) Able to perform a transient anti-icing calculation		X				5.4.2.2	Transient effects such as cycling of power at temperature control limits. Transient conduction modeled within the substrate and the ice, but limited to NOT modelling the melting of ice at the surface and shedding. Not specific to ICE-GENESIS
	3) Able to perform a transient de-icing calculation		X				5.4.2.3	Full transient effects modeled. Able to model ice melting at the surface and shedding. Not specific to ICE-GENESIS
Universal requirements for an ice protection analysis model	Analysis capability: Calculates the outcome for a user defined heat flux at the substrate		X				5.4.2.4	Not specific to ICE-GENESIS
	Analysis capability: Calculates the outcome for a user defined internal HTC and temperature		X				5.4.2.5	Not specific to ICE-GENESIS

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Design capability: Calculates what heat input is needed for a certain criteria to be fulfilled.				X		5.4.2.6	The details of this requirement need further clarification. Examples include: - What heat flux distribution is needed to obtain a specified surface temperature - How much heat is needed to obtain a full evaporation of the water within a specified area.
	Able to model ice shapes that form behind protected regions and where heating is insufficient		X				5.4.2.7	Not specific to ICE-GENESIS
	Able to predict liquid mass transfer between impacting droplets/ice particles/snowflakes and iced/water layer	**X**	X				5.4.2.8	Leading to slush ice deposit
	The model must take into account both the liquid and solid phases.	**X**	X				5.4.2.9	
For capability 1 (Steady state calculation)	Include heat flux from surface in heat balance equation		X				5.4.2.10	Not specific to ICE-GENESIS
	Able to model lateral conduction through the substrate		X				5.4.2.11	To prevent unrealistic steps in the surface temperature or runback ice shapes. Slightly more complex because solution of heat balance equations becomes iterative since downstream node affects upstream equation.
For capability 2 (Transient anti-icing analysis)	Able to model heat flux at the surface as a function of time		X				5.4.2.12	Not specific to ICE-GENESIS
	Able to model transient conduction effects through the substrate and the ice		X				5.4.2.13	Anti-icing is achieved during the 'off' periods due to the heat stored in the substrate, therefore modelling of transient conduction is essential.
For capability 3 (Transient de-icing analysis)	Able to model heat flux at the surface as a function of time		X				5.4.2.14	Not specific to ICE-GENESIS

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Able to model transient conduction effects through the substrate and the ice		X				5.4.2.15	Not specific to ICE-GENESIS
	Able to model melting of ice		X				5.4.2.16	Not specific to ICE-GENESIS
Transient effects: short time-scale effects	Modelling of transient conduction effects, rather than a solution of the adiabatic surface heat balance for each time-step		X				5.4.2.17	This capability could enable flight test data to be used with more confidence, or at least investigate the effects of rapidly varying conditions on the shape. Essential for de-icing
	Able to calculate rapidly varying LWC			X			5.4.2.18	Fairly easy to do, no need to re-compute trajectories, etc.
	Able to calculate rapidly varying MVD				X		5.4.2.19	More difficult, need to recalculate trajectories, or re-compute catch from a series of catch data obtained previously for standard droplet diameters
	Able to calculate rapidly varying flight conditions					X	5.4.2.20	Very difficult, need multiple CFD solutions? Solution would be very time consuming.
	Automatic adjustment of time step used for transient derivatives of the ice growth model to control errors.			X			5.4.2.21	

Table 14: ACCRETION – Anti-icing & De-icing

5.4.3 Transient features

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
General capabilities	Able to perform a transient icing calculation	**X**	X				5.4.3.1	ICE GENESIS partners will investigate different techniques to track the ice surface displacement: mesh deformation, re-meshing, IBM.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
Transient calculation methods	Able to perform a single-step first order (SS) calculation		X				5.4.3.2	Transient effects have been categorised into long time-scale and short time-scale effects. Long time-scale effects are things like multi-stepping (interaction between shape, flow and catch) and changes in the icing freestream icing conditions. Single step calculation is already available in 2D/3D.
	Able to perform a single predictor-corrector (PC) calculation	**X**	X				5.4.3.3	Currently considered similar in accuracy?
	Able to perform a multi-step (MS) calculation	**X**	X				5.4.3.4	
	Able to perform a multiple-step predictor-corrector (MSPC) calculation					X	5.4.3.5	Potentially more accurate than MS or PC methods?
For PC, MS and MSPC methods:	Generation of the ice shapes that can be directly processed by the grid generator	**X**	X				5.4.3.6	Interesting format for industrials are : Catia files and ICEM
	Complete automation of PC, MS or MSPC process without user interaction	**X**	X				5.4.3.7	Tracking and processing of the ice surface shall be robust enough to avoid a rework of the generated surface. MSPC is out of the Ice Genesis scope.
	Automatic time-step selection for MS and MSPC method~~s~~ and also intermediate step for PC methods	**X**		X			5.4.3.8	Seen as important by AAs to remove user dependency. At least, best practices to be provided for the definition of the time-step. MSPC is out of the Ice Genesis scope.
	Automatic surface discretization setting for MS and MSPC methods	**X**		X			5.4.3.9	At least, best practices to be provided for the definition of the surface discretization setting.
	Generation of the ice shapes with mass conservation			X			5.4.3.10	The volume of the ice shape shall be consistent with the ice density and the mass balance of the ice accretion calculation.
	Generation of the ice shape taking into account ice bridging			X			5.4.3.11	The surface tracking shall be able to handle hole closure, but also cases with bridging between ice shapes from two components (ex : ice on an engine wall and on a blade leading edge).

Tool design characteristic/capability		**Development required for ICE GENESIS**	**Importance**				**Ref**	**Notes**
			Essential	**Highly Desirable**	**Desirable**	**Nice to have**		
	Automatic time-step calculation based on predicted error for MS and MSPC methods and also intermediate step for PC methods				X		5.4.3.12	
	Able to model changes in the icing conditions	**X**		X			5.4.3.13	Long time-scale changes, so that it can be assumed that accretion from previous time steps has no effect on the new heat balance.
	Modelling of ice sublimation rates: Ignoring where the original substrate is.		X				5.4.3.14	Not specific to ICE-GENESIS
	Modelling of ice sublimation rates: Stopping ice sublimation when it reaches the original substrate.		X				5.4.3.15	Not specific to ICE-GENESIS
	Melting of ice for subsequent warm temperature calculation steps					X	5.4.3.16	

Table 15: ACCRETION – Transient

5.4.4 Ice shedding modelling requirements

Tool design characteristic/capability		**Development required for ICE GENESIS**	**Importance**				**Ref**	**Notes**
			Essential	**Highly Desirable**	**Desirable**	**Nice to have**		
Shedding is predicted based on:	Empirical method for modelling shedding based on size of melt zone	**X**	X				5.4.4.1	
	Adhesive (ice-snow/substrate) strength	**X**		X			5.4.4.2	Able to characterise the change in ice/snow adhesive strength with ice/snow-substrate temperature and/or freezing fraction
	Cohesive (ice/ice or snow/snow) strength			X			5.4.4.3	Able to characterise the change in ice/snow cohesive strength with ice/snow-substrate temperature and/or freezing fraction
	Aerodynamic forces on the ice/snow	**X**		X			5.4.4.4	
	Gravitational forces on the ice/snow				X		5.4.4.5	To predict self-shedding.
	Inertial forces due to accelerations					X	5.4.4.6	E.g. due to mechanical forces or EIDS type systems

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Forces due to surface distortion					X	5.4.4.7	E.g. due to pneumatic boots
	Centrifugal forces		X				5.4.4.8	Applicable only if a tool with a rotational capability is needed.
Shedding is predicted for:	Metallic surfaces (aluminium, titanium, steel)	**X**	X				5.4.4.9	
	Organic composite materials	**X**		X			5.4.4.10	
	Ice-phobic/ hydrophobic coatings			X			5.4.4.11	To predict shedding from passive IPS.
Boundary conditions	Able to model heat sources representative of hot air de-icer		X				5.4.4.12	
	Able to model heat sources representative of electrical heating elements	**X**	X				5.4.4.13	
Outputs	Able to predict shed and no-shed events	**X**	X				5.4.4.14	
	Updated accreted ice/snow shape after the shedding event	**X**			X		5.4.4.15	The output must be readable by meshing software, or allow generating automatically a flow solver mesh.
	Able to predict size, shape and speed of ejection of ice/snow debris	**X**		X			5.4.4.16	Size/mass is essential.

Table 16: ACCRETION – Ice Shedding

5.5 ICE DEBRIS TRAJECTORY MODELLING

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
General capabilities	1) Simulation using tabulated aerodynamics coefficient		X				5.5.1	State-of-the art approach Not specific to ICE-GENESIS
	2) High fidelity simulation (Chimera, Immersed boundaries)					X	5.5.2	
Universal requirements	Able to model trajectory for complex ice shapes			X			5.5.3	Examples of debris shapes: curved flat plate, horn.

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Able to calculate trajectory for an uniform flow field		X				5.5.4	Less time-consuming approach, taking into account only initial debris velocity. Not specific to ICE-GENESIS
	Able to calculate trajectory for a non-uniform flow field		X				5.5.5	Not specific to ICE-GENESIS
	Able to import an aerodynamic flow field from an external CFD solver		X				5.5.6	Not specific to ICE-GENESIS
	Able to model different ice density		X				5.5.7	Ice density depends on ice accretion conditions Not specific to ICE-GENESIS
	Able to model ice debris roughness					X	5.5.8	Influence on the modelling of the turbulent boundary layer
Physical model for debris motion	Able to model drag, lift forces		X				5.5.9	2D simulation Not specific to ICE-GENESIS
	Able to model side forces		X				5.5.10	3D simulation Not specific to ICE-GENESIS
	Able to model pitching movement			X			5.5.11	4 degrees of freedom simulation
	Able to model rolling and yawing movements			X			5.5.12	6 degrees of freedom simulation
	Able to model gravitational forces		X				5.5.13	Not specific to ICE-GENESIS
	Able to model fragmentation under aerodynamic forces				X		5.5.14	
	Able to model fragmentation at impact					X	5.5.15	Ideally, modelling of the trajectory of the produced debris
	Able to model bouncing of the debris					X	5.5.16	Ideally, modelling of the trajectory of the produced debris
Initial conditions	Ice debris initial velocity up to 10m/s		X				5.5.17	Low velocity for ice release Not specific to ICE-GENESIS
	Ice debris initial velocity up to 300 m/s		X				5.5.18	Maximum value at fan blade tip, but shedding will occur for lower speed. Not specific to ICE-GENESIS
Initial parameters for statistical approach (Monte-Carlo)	Shedding location		X				5.5.19	Influence of the shedding location for a given component on impact location Not specific to ICE-GENESIS
	Debris shape			X			5.5.20	Influence of the initial shape on impact location (assuming no fragmentation)

Tool design characteristic/capability		Development required for ICE GENESIS	Importance				Ref	Notes
			Essential	Highly Desirable	Desirable	Nice to have		
	Debris yaw, pitch, roll angles		X				5.5.21	Influence of the initial orientation on impact location Not specific to ICE-GENESIS
	Aircraft flow field					X	5.5.22	
For capability 1 (low fidelity tools)	Steady aerodynamic coefficients for simple shapes		X				5.5.23	Example of simple shape: flat plate Not specific to ICE-GENESIS
	Steady aerodynamic coefficients for complex shape			X			5.5.24	
For capability 2 (high fidelity)	Calculation of steady aerodynamic coefficients for complex shapes		X				5.5.25	Not specific to ICE-GENESIS
	Calculation of dynamic derivative aerodynamic coefficients for complex shapes		X				5.5.26	Not specific to ICE-GENESIS
	Automatic/adaptative unstructured mesh of the debris shape					X	5.5.27	Adaptative unstructured mesh will be developed for the Immersed Boundaries method
Outputs	Able to give the impact location for one trajectory		X				5.5.28	Not specific to ICE-GENESIS
	Able to produce probability map for the impact location			X			5.5.29	Low fidelity tools (Monte-Carlo approach)
	Able to export the history of aerodynamic forces				X		5.5.30	The export should be used by an external F.E.M solver to compute ice debris fragmentation
	Able to compute kinetic energy of the debris at impact		X				5.5.31	Not specific to ICE-GENESIS

Table 17: ACCRETION – Ice Debris Trajectory

6. TOOL VALIDATION REQUIREMENTS

This section is intended to define a range of conditions and parameters that should be addressed by the code validation evidence. For each item where data for validation already exists, there is a reference to existing experimental data defined in Annex A, B, C, D, E, F, G and H, which is considered to be the best available data at this time. Hence, Annex A, B, C, D, E, F, G and H will help identify what data for validation is required and should evolve with time as more experimental data becomes available.

The importance categories should reflect the necessity to apply to the tool to that particular component, flight condition or icing condition, or how valuable any supporting validation evidence is considered to be to improve the overall confidence in the tool.

Definition of importance categories

Essential These flight/icing regimes are part of the conventional conditions considered for aircraft design/certification work and without this validation evidence the code cannot be used for aircraft certification purposes.

Highly desirable These flight/icing regimes are frequently considered during normal aircraft design/certification work and without this validation evidence the results from the code, if it is used, would be highly questionable.

Desirable These flight/icing regimes may be considered during aircraft design/certification work and therefore there is a desire to validate the code for these conditions.

Nice to have These flight/icing regimes would only occasionally be considered during aircraft design/certification work and therefore there is a only a weak requirement to validate the code for these conditions.

6.1 GEOMETRY

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
Type	2D, unswept, single element, generic aerofoil	**X**	X				6.1.1	NASA/NRC experiments & Validation test case 1	C1-C7, C10-C25,
	2D, unswept, multi-element element, generic aerofoil		X				6.1.2		C8-C9
	3D, unswept aerofoil (tip effects only)		X				6.1.3	i.e. effects of reduced loading towards tip only	
	3D variable swept airfoil		X				6.1.4		
	3D, swept generic wing (sweep<15°)		X				6.1.5		C16
	3D, swept generic wing (sweep=15-30°)		X				6.1.6		
	3D, swept generic wing (sweep=30-45°)					X	6.1.7		
	3D, swept generic wing (sweep>45°)					X	6.1.8	No anticipated need to consider wings >45° sweep?	
	3D non-lifting items: Fuselages and fuselage fairings/protuberances		X				6.1.9		C16-C20
	3D non-lifting items: NACA ducts		X				6.1.10		

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
	3D non-lifting items: Pitot tubes				X		6.1.11		
	3D non-lifting items: Air intake, Scoops	**X**	X				6.1.12		
	3D rotating components: Spinners (e.g. RAT, propeller)			X			6.1.13		
	3D rotating components: Rotor blades			X			6.1.14		
	3D rotating components: Propeller blades			X			6.1.15		
	3D rotating components: Fan blades					X	6.1.16		
	3D rotating components: RAT blades					X	6.1.17		
	3D rotating components: Engine compressor blades					X	6.1.18		
Size	0.05m < Chord < 0.2m (e.g. engine application, propeller)	**X**	X				6.1.19		
	Chord < 0.5m (e.g. suitable for propeller/ RAT, rotor blades, horizontal stabilizer)	**X**	X				6.1.20		C1, C2, C11
	0.5m < Chord ≤ 1.0m	**X**	X				6.1.21		C3-C10, C12-C15, C21, C23-C25
	1.0m < Chord ≤ 10m		X				6.1.22		C16, C22
	Chord > 10m					X	6.1.23		

Table 18: VALIDATION – Geometry

6.2 FLIGHT CONDITIONS

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
Altitude	Sea level < Altitudes ≤ 2,000ft	**X**	X				6.2.1	Altitude considered being a weak influence on supercooled droplets icing, if everything else is fixed. However, it should be studied for App D/P.	C1-C11, C14, C15, C17-C26-C32
	2,000ft < Altitudes ≤ 10,000ft	**X**	X				6.2.2		C12, C13, C16
	10,000ft < Altitudes ≤ 22,000ft				X		6.2.3		
	22,000ft ≤ Altitude ≤ 60,000ft					X	6.2.4		
	Local $C_L \leq 0.8$	**X**	X				6.2.5	These C_L categories are somewhat	C1-C7, C10, C11, C13-C25, C27-C32

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
Incidence (configurations without high lift systems)	Local $C_L > 0.8$					X	6.2.6	arbitrary but should recognise that our normal requirement is to analyse ice accretion at quite low incidences (e.g. hold, descent), rather than near stall.	C12 (estimated)
Incidence (configurations with high lift systems)	Local $C_L < 1.6$		X				6.2.7		C9
	Local $C_L > 1.6$			X			6.2.8		C8 (estimated)
Mach number	$M \le 0.4$	**X**	X				6.2.9		C1-C12, C14-C32
	$0.4 < M \le 0.5$		X				6.2.10		C13
	$0.5 < M \le 0.6$		X				6.2.11		
	$0.6 < M \le 0.8$		X				6.2.12		

Table 19: VALIDATION – Flight Conditions

6.3 ICING CONDITIONS

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
Top level validation requirements	Appendix C maximum continuous envelope definition for SAT, LWC and MVD	**X**	X				6.3.1	Although Appendix C is not the scope of ICE GENESIS, it is important to have validated tools for supercooled droplets for assessment of mixed phase capability	A1-A30 C1, C5-C9, C12, C13, C16, C17, C19, C21, C23-C26, 30-C32
	Appendix C intermittent maximum envelope definition for SAT, LWC and MVD	**X**	X				6.3.2		C3, C4, C10, C11, C14, C15, C27-C29
	Appendix O envelope for SLD	**X**	X				6.3.3		B1-B114 D1-D71
	Appendix D/P envelope for ice particles and mixed phase		X				6.3.4		E1-E23
	Snow	**X**	X				6.3.5		F1
Static air temperature	SAT < -30°C	**X**				X	6.3.6	This breakdown could be used to better identify what validation data is available, via the references to the Appendix.	
	-30°C < SAT ≤ -20°C	**X**	X				6.3.7		
	-20°C < SAT ≤ -15°C	**X**	X				6.3.8		C3-C6, C23
	-15°C < SAT ≤ -10°C	**X**	X				6.3.9		C7, C16, C21, C32
	-10°C < SAT ≤ -5°C	**X**	X				6.3.10		C10-C16, C22, C24, C25, C28-C31
	-5°C < SAT ≤ 0°C	**X**	X				6.3.11		C1, C2, C8, C9, C17-C20, C27
	0°C < SAT ≤ +5°C	**X**	X				6.3.12		
	5°C < SAT < 30°C					X	6.3.13		
Total air temperature	-30°C < TAT ≤ -20°C	**X**	X				6.3.14	This breakdown could be used to better identify what validation data is available, via the references to the Appendix.	
	-20°C < TAT ≤ -15°C	**X**	X				6.3.15		
	-15°C < TAT ≤ -10°C	**X**	X				6.3.16		C3-C6, C16, C33

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
	-10°C < TAT ≤ -5°C	X	X				6.3.17		C7, C10, C12, C16, C21, C23, C25, C29, C32
	-5°C < TAT ≤ -2°C	X	X				6.3.18		C11, C14-C16, C22, C24-C25, C27-C28, C30-C31
	-2°C < TAT ≤ +2°C	X	X				6.3.19		C1, C2 , C8, C9, C17-C20
	+2°C < TAT ≤ +5°C	X	X				6.3.20		C13
	+5°C < TAT ≤ +10°C	X				X	6.3.21		
	+10°C < TAT < +20°C	X				X	6.3.22		
	+20°C < TAT < +38°C					X	6.3.23		
LWC	0 < LWC ≤ 0.3 g/m^3	X	X				6.3.24	Appendix C , Appendix O	
	0.3 < LWC ≤ 0.8 g/m^3	X	X				6.3.25		C1, C2, C5-C10, C12, C13-C21, C23-C26, C30-C32
	0.8 < LWC ≤ 1.5 g/m^3	X	X				6.3.26		C3, C4, C11, C22, C27-C29
	1.5 < LWC ≤ 2.75 g/m^3	X	X				6.3.27		
TWC Ice crystals	0.1 < TWC < 6 g/m^3 (engines)					X	6.3.28	Appendix D/P taking into account installation factor	E1-23
	4 < TWC < 20 g/m^3 (probes)					X	6.3.29		
TWC Snow	0 < TWC ≤ 1 g/m^3	X	X				6.3.30		F1
	1 < TWC ≤ 3 g/m^3	X	X				6.3.31		
MVD	15µm < MVD ≤ 50µm	X	X				6.3.32	App. C	C1, C3-C17, C19, C21, C23-C32
	Frizzing Drizzle MVD ≤ 40µm	X	X				6.3.33		
	Frizzing Drizzle MVD > 40µm	X	X				6.3.34		
	Frizzing Rain MVD ≤ 40µm			X			6.3.35		
	Frizzing Rain MVD > 40µm			X			6.3.36		
MMD Ice Crystals	50µm < MMD < 900µm					X	6.3.37	Appendix D/P Based on HAIC FT, 300µm <MMD<900µm	
MMD Falling Snow	2000µm < MMD < 3000µm	X	X				6.3.38	Based on AIH FT	
MMD Blowing Snow	50µm < MMD < 150µm	X		X			6.3.39	Based on EPFL MASC measurementT	
Particle shapes	Spheres	X	X				6.3.40		
	Quasi-spheres	X	X				6.3.41	Using sphericity parameters	
	Needles	X	X				6.3.42		
	Plates	X	X				6.3.43		
	Graupel	X	X				6.3.44		
	Agregates	X	X				6.3.45		

Validation requirements	Required for ICE GENESIS	Importance				Ref	Notes	Available data
		Essential	Highly Desirable	Desirable	Nice to have			
Data from natural icing conditions	**X**	X				6.3.46	Advantage is that it is real icing conditions and any geometry can be tested. Disadvantages are that conditions are not steady and ice shapes are difficult to measure.	C16,
Data from artificial icing conditions	**X**	X				6.3.47	Advantage is that conditions are steady and ice shapes can be accurately recorded. Disadvantages are that there may be restrictions on the size of geometry and uncertainties about how representative conditions are to real icing.	C1-C15, C17-C32

Table 20: VALIDATION – Icing Conditions

6.4 OTHER VALIDATION REQUIREMENTS

Validation requirements		Required for ICE GENESIS	Importance				Ref	Notes	Available data
			Essential	Highly Desirable	Desirable	Nice to have			
Steady state anti-icing	Prediction of surface temperatures and ice shapes, if applicable (i.e. runback ice)	**X**	X				6.4.1		
Transient anti-icing	Prediction of surface temperature histories and ice shapes, if applicable		X				6.4.2		
De-icing	Prediction of surface temperature and ice formation histories, including occurrences of ice shedding		X				6.4.3		
	Prediction of inter-cycle ice thickness, ice shape and location		X				6.4.4		
	Prediction of spanwise extent of unheated (IPS off) icing on rotating components		X				6.4.5		
Ice sublimation			X				6.4.6		
Ice thicknesses < 3”		**X**	X				6.4.7		C1-C15, C17-C32 (need to check if these are <3”)
Ice thicknesses > 3”		**X**			X		6.4.8		C16
Snow saltation		**X**	X				6.4.9		

Validation requirements	Required for ICE GENESIS	Importance				Ref	Notes	Available data
		Essential	Highly Desirable	Desirable	Nice to have			
Catch efficiencies	**X**		X			6.4.10	The predicted catch efficiencies should be also validated in addition to the final predicted ice shape. This will help the validation process, since catch efficiencies directly affect the ice prediction and ice protection analysis results and would also enable alternative droplet trajectory calculation methods to be assessed more effectively than only comparing the predicted ice shapes.	A1-A31 B1-B114

Table 21: VALIDATION – Other

7. CONCLUSION

These specifications are the result of a consensus among WP3 partners for what is needed for falling and blowing snow & mixed phase models and tools development and validation, based on available data. During models and tools development and TRL review process, other needs might emerge to model adequately the consequences of falling and blowing snow & mixed phase conditions. Finally, the detailed definition of test cases geometry and matrix through WP8 should allow filling in the gaps in terms of validation.

The scope of these specifications could then be completed and extended to identify the gaps for a state-of-the-art icing tool in other projects.

8. REFERENCES

[1] EASA CS25 Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes
[2] EASA CS27 Certification Specifications and Acceptable Means of Compliance for Small Rotorcraft
[3] EASA CS29 Certification Specifications and Acceptable Means of Compliance for Large Rotorcraft
[4] EASA CS-E Certification Specifications and Acceptable Means of Compliance for Engines
[5] FAA AC29-2C Advisory Circular – Certification of Transport Category Rotorcraft
[6] Deliverable D62.1 – HAIC Model, Tool & Validation Specification, FP7 HAIC, 2013
[7] Deliverable D1.2 - Report on generic requirements of industrial needs for icing tools, FP7 STORM, 2014
[8] W.Strapp et al, An Assessment of Cloud Total Water Content and Particle Size from Flight Test Campaign Measurements in High Ice Water Content, Mixed Phase/Ice Crystal Icing Conditions: Primary In-Situ Measurements, FAA report, DOT/FAA/TC-18/1, in publication process.

9. ANNEX A – WATER CATCH VALIDATION DATA AVAILABLE FOR APPENDIX C

Flight and icing condition data values should be checked against the original source before being used for validation purposes. This table is intended as a summary of the available data for validation, rather than a comprehensive and accurate source of data.

Ref.	Short description	Type of icing (natural/ artificial)	Model description	Facility	TAS (m/s)	M	α (deg)	Pressure altitude (nearest 100 ft)	SAT (°C)	TAT (°C)	LWC (g/m³)	VMD (μm)	Data available	Ice shape type	Comments about data quality
A.1	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	11.5	Impingement distribution		
A.2	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	21	Impingement distribution		
A.3	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	92	Impingement distribution		
A.4	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	8.0	2000	8	11	-	11.5	Impingement distribution		
A.5	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	8.0	2000	8	11	-	21	Impingement distribution		
A.6	1997 IRT Test	artificial	MS(1)-317 36 Inches chord	IRT	78.68	0.23	8.0	2000	8	11	-	94	Impingement distribution		
A.7	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	1.5	2000	8	11	-	11.5	Impingement distribution		
A.8	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	1.5	2000	8	11	-	21	Impingement distribution		
A.9	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	1.5	2000	8	11	-	92	Impingement distribution		

A.10	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	6.0	2000	8	11	-	11.5	Impingement distribution		
A.11	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	6.0	2000	8	11	-	21	Impingement distribution		
A.12	1997 IRT Test	artificial	GLC305 36 Inches chord	IRT	78.68	0.23	6.0	2000	8	11	-	92	Impingement distribution		
A.13	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	11	Impingement distribution		
A.14	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	21	Impingement distribution		
A.15	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	0	2000	8	11	-	94	Impingement distribution		
A.16	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	8	2000	8	11	-	11	Impingement distribution		
A.17	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	8	2000	8	11	-	21	Impingement distribution		
A.18	1997 IRT Test	artificial	NLF(1)-0414 36 Inches chord	IRT	78.68	0.23	8	2000	8	11	-	94	Impingement distribution		
A.19	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	0	2000	0	11	-	11	Impingement distribution		
A.20	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	0	2000	0	11	-	21	Impingement distribution		
A.21	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	0	2000	0	11	-	94	Impingement distribution		

A.22	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	4	2000	0	11	-	11	Impingement distribution		
A.23	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	4	2000	0	11	-	21	Impingement distribution		
A.24	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	4	2000	0	11	-	94	Impingement distribution		
A.25	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	8	2000	0	11	-	11	Impingement distribution		
A.26	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	8	2000	0	11	-	21	Impingement distribution		
A.27	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 0 deg flap defl.	IRT	78.68	0.23	8	2000	0	94	-	94	Impingement distribution		
A.28	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 15 deg flap defl.	IRT	78.68	0.23	0	2000	0	11	-	11	Impingement distribution (main + flap)		
A.29	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 15 deg flap defl.	IRT	78.68	0.23	0	2000	0	11	-	21	Impingement distribution (main + flap)		
A.30	1997 IRT Test	artificial	NLF(1)-0414 48 Inches chord 15 deg flap defl.	IRT	78.68	0.23	8	2000	0	94	-	94	Impingement distribution (main + flap)		

10. ANNEX B – WATER CATCH VALIDATION DATA AVAILABLE FOR APPENDIX O

Flight and icing condition data values should be checked against the original source before being used for validation purposes. This table is intended as a summary of the available data for validation, rather than a comprehensive and accurate source of data.

Ref.	Short description	Type of icing (natural/ artificial)	Model description	Facility	TAS (mph)	M	α (deg)	Pressure altitude (psi)	SAT (°K)	TAT (°K)	LWC (g/m³)	VMD (μm)	Data available	Ice shape type	Comments about data quality
B.1	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		0	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.2	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.3	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		0	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.4	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		6	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.5	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		6	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.6	NASA SLD database	artificial	NACA 64A008 Finite Swept Tail	IRT	176		6	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.7	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	176		0	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.8	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.9	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		0	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.10	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	176		0	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.11	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		0	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.12	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		0	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.13	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		4	14,0	279,15		0,2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.14	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		4	14,0	279,15		0,2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.15	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		4	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.16	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		4	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.17	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	175		4	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.18	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	176		8	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.19	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	176		8	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.20	NASA SLD database	artificial	NACA 65(2)-415 Airfoil	IRT	176		8	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.21	NASA SLD database	artificial	GLC-305 Airfoil	IRT	176		1,5	14,0	279,15		0,2	11,5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.22	NASA SLD database	artificial	GLC-305 Airfoil	IRT	175		1.5	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.23	NASA SLD database	artificial	GLC-305 Airfoil	IRT	175		1.5	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.24	NASA SLD database	artificial	GLC-305 Airfoil	IRT	176		1.5	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.25	NASA SLD database	artificial	GLC-305 Airfoil	IRT	175		1.5	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.26	NASA SLD database	artificial	GLC-305 Airfoil	IRT	175		1.5	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.27	NASA SLD database	artificial	GLC-305 Airfoil	IRT	176		6	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.28	NASA SLD database	artificial	GLC-305 Airfoil	IRT	176		6	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.29	NASA SLD database	artificial	GLC-305 Airfoil	IRT	176		6	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.30	NASA SLD database	artificial	Full-scale Business Jet Tail Section	IRT	176		1	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.31	NASA SLD database	artificial	Full-scale Business Jet Tail Section	IRT	176		1	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.32	NASA SLD database	artificial	Full-scale Business Jet Tail Section	IRT	176		1	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.33	NASA SLD database	artificial	Full-scale Business Jet Tail Section	IRT	176		6	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.34	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		0	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.35	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.36	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		0	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.37	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		4	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.38	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		4	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.39	NASA SLD database	artificial	Commercial Jet Transport Tail Section	IRT	176		4	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.40	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		0	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.41	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.42	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	175		0	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.43	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		0	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.44	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	175		0	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.45	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	175		0	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.46	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		8	14.0	279.15		0.2	11.5	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.47	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		8	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.48	NASA SLD database	artificial	MS(1)-317 Airfoil	IRT	176		8	14.0	279.15		0.2	92	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.49	NASA SLD database	artificial	NACA 23012 Airfoil	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.50	NASA SLD database	artificial	NACA 23012 Airfoil	IRT	175		2,5	14,0	279,15		0,2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.51	NASA SLD database	artificial	NACA 23012 Airfoil	IRT	175		2,5	14,0	279,15		0,2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.52	NASA SLD database	artificial	NACA 23012 Airfoil	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.53	NASA SLD database	artificial	NACA 23012 Airfoil	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.54	NASA SLD database	artificial	NACA 23012 & 5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.55	NASA SLD database	artificial	NACA 23012 & 5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.56	NASA SLD database	artificial	NACA 23012 & 5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.57	NASA SLD database	artificial	NACA 23012 & 5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.58	NASA SLD database	artificial	NACA 23012 & 5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.59	NASA SLD database	artificial	NACA 23012 & 10-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.60	NASA SLD database	artificial	NACA 23012 & 10-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.61	NASA SLD database	artificial	NACA 23012 & 10-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.62	NASA SLD database	artificial	NACA 23012 & 10-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.63	NASA SLD database	artificial	NACA 23012 & 10-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.64	NASA SLD database	artificial	NACA 23012 & 15-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.65	NASA SLD database	artificial	NACA 23012 & 15-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.66	NASA SLD database	artificial	NACA 23012 & 15-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.67	NASA SLD database	artificial	NACA 23012 & 15-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.68	NASA SLD database	artificial	NACA 23012 & 15-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.69	NASA SLD database	artificial	NACA 23012 & 22.5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.70	NASA SLD database	artificial	NACA 23012 & 22.5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.71	NASA SLD database	artificial	NACA 23012 & 22.5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.72	NASA SLD database	artificial	NACA 23012 & 22.5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.73	NASA SLD database	artificial	NACA 23012 & 22.5-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.74	NASA SLD database	artificial	NACA 23012 & 45-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	20	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.75	NASA SLD database	artificial	NACA 23012 & 45-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	52	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.76	NASA SLD database	artificial	NACA 23012 & 45-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	111	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.77	NASA SLD database	artificial	NACA 23012 & 45-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	154	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.78	NASA SLD database	artificial	NACA 23012 & 45-min Glaze Ice Shape	IRT	175		2.5	14.0	279.15		0.2	236	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.79	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.80	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.81	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		0	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.82	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		0	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.83	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		0	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.84	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		4	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.85	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		4	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.86	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		4	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.87	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		4	14.0	279.15		0.2	137	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.88	NASA SLD database	artificial	Twin Otter Tail Section	IRT	175		4	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.89	NASA SLD database	artificial	Twin Otter & 22.5-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.90	NASA SLD database	artificial	Twin Otter & 22.5-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.91	NASA SLD database	artificial	Twin Otter & 22.5-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.92	NASA SLD database	artificial	Twin Otter & 22.5-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.93	NASA SLD database	artificial	Twin Otter & 45-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.94	NASA SLD database	artificial	Twin Otter & 45-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.95	NASA SLD database	artificial	Twin Otter & 45-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	79	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.96	NASA SLD database	artificial	Twin Otter & 45-min Glaze Ice Shape	IRT	175		0	14.0	279.15		0.2	168	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.97	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.98	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.99	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		0	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.100	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		8	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.101	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		8	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.102	NASA SLD database	artificial	36" NLF(1)-414 Airfoil	IRT	176		8	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.103	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.104	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.105	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		0	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

B.106	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		4	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.107	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		4	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.108	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		4	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.109	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		8	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.110	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		8	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.111	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap	IRT	175		8	14.0	279.15		0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.112	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap Deflected	IRT	175		0	14.0	279.15		0.2	11	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.113	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap Deflected	IRT	175		0	14.0	279.15		0.2	21	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available
B.114	NASA SLD database	artificial	48" NLF(1)-414 Airfoil with Flap Deflected	IRT	175		0	14.0			0.2	94	Impingement distribution	-	2 droplet distributions available: 10 bin and 27 bin LEWICE results available

11. ANNEX C - ICE ACCRETION VALIDATION DATA AVAILABLE FOR SUPERCOOLED DROPLETS

Flight and icing condition data values should be checked against the original source before being used for validation purposes. This table is intended as a summary of the available data for validation, rather than a comprehensive and accurate source of data.

Ref.	Short description	Type of icing (natural/ artificial)	Model description	Facility	TAS (m/s)	M	α (deg)	Pressure altitude (nearest 100 ft)	SAT (°C)	TAT (°C)	LWC (g/m³)	VMD (μm)	Data available	Ice shape type	Comments about data quality
C.1	NATO-RTO C4	Artificial	450mm chord NACA0012	ACT Artington IWT	77.2	0.234	0.0	500	-2.65	+0.32	0.32	18.0	Iced profile	Glaze	Humidity probe serviceability during trial cannot be confirmed. No repeat runs performed so tunnel variability unknown.
C.2	NATO-RTO C5	Artificial	450mm chord NACA0012	ACT Artington IWT	77.2	0.234	0.0	400	-2.45	+0.52	0.39	100.0	Iced profile	Rime	As above
C.3	NATO-RTO C6	Artificial	914mm chord GLC-305 aerofoil	NASA Glenn IRT	69.87	0.217	0.0	Sea level (nominal)	-15.72	-13.29	1.16	50.00	Iced profile	Glaze	Uncertainties in ice shape-tracing method. Repeatability and non-uniformity of cloud produce shapes that vary by 2-3% based on evaluation of 11 ice shape features.
C.4	NATO-RTO C7	Artificial	914mm chord GLC-305 aerofoil	NASA Glenn IRT	69.87	0.217	0.0	Sea level (nominal)	-15.72	-13.29	1.16	50.0	Iced profile	Glaze	As above
C.5	NATO-RTO C8	Artificial	914mm chord NLF0414 aerofoil	NASA Glenn IRT	92.54	0.288	0.0	Sea level (nominal)	-15.55	-11.29	0.33	20.0	Iced profile	Rime	As above
C.6	NATO-RTO C9	Artificial	914mm chord NLF0414 aerofoil	NASA Glenn IRT	92.54	0.288	0.0	Sea level (nominal)	-15.55	-11.29	0.33	20.0	Iced profile	Rime	As above
C.7	NATO-RTO C10	Artificial	914mm chord NLF0414 aerofoil	NASA Glenn IRT	67.06	0.206	3.5	Sea level (nominal)	-10.41	-8.17	0.44	20.0	Iced profile	Glaze	As above
C.8	NATO-RTO C11	Artificial	McDonnell-Douglas Multi-element aerofoil, 914mm undeployed chord	NASA Glenn IRT	88.4	0.269	8.0	Sea level (nominal)	-4.95	-1.06	0.6	20.0	Iced profile	Glaze	As above

C.9	NATO-RTO C12	Artificial	McDonnell-Douglas Multi-element aerofoil, 914mm undeployed chord	NASA Glenn IRT	88.4	0.269	4.0	Sea level (nominal)	-4.95	-1.06	0.6	20.0	Iced profile	Glaze	As above
C.10	NATO-RTO C13	Artificial	553mm chord NACA0012	NASA Glenn IRT	67.0	0.206	0.0	1200	-8.75	-6.52	0.65	40.0	Iced profile	Glaze	An accuracy of +/- 10-12 % in LWC and MVD, 1% in Airspeed.
C.11	NATO-RTO C14	Artificial	267mm chord NACA0012	NASA Glenn IRT	57.0	0.174	0.0	900	-5.55	-3.93	1.04	27.73	Iced profile	Glaze	An accuracy of +/- 10-12 % in LWC and MVD, 1% in Airspeed.
C.12	NATO-RTO C15	Artificial	600mm chord Super Puma section	CEPr - R2 ATF	81.3	0.250	10.0	6600	-9.95	-6.66	0.6	20.0	Iced profile	Glaze	Test performed in 1980 without in-situ icing condition measurements.
C.13	NATO-RTO C16	Artificial	600mm chord Super Puma section	CEPr - R2 ATF	163.0	0.500	0.0	6600	-9.95	+3.27	0.6	20.0	Iced profile	Glaze	Test performed in 1980 without in-situ icing condition measurements.
C.14	NATO-RTO C17	Artificial	910mm chord NACA0012	Boeing IWT	67.0	0.205	3.0	100	-7.15	-4.92	1.0	24.8	Iced profile	Glaze	No humidity control - related effects/within tunnel calibration affecting accuracy.
C.15	NATO-RTO C18	Artificial	910mm chord NACA0012	Boeing IWT	67.0	0.205	3.0	100	-7.15	-4.92	1.0	38.8	Iced profile	Glaze	No humidity control - related effects/within tunnel calibration affecting accuracy
C.16	NATO-RTO O1	Natural	Jetstream 41 development aircraft (G-GCJL), 1.5m chord	Flight trials based at Reykjavik, Feb-Jun 1992	Variable, approx 70 m/s	0.214	3.7	Variable, 6000-7600ft	Variable -7.00 – 14.15	Variable -4.56 – -11.71	Variable up to 1.0	Variable, 15-19	Iced profile	Glaze	Conditions varied with time. Delay from end of test to recording of the ice shape.
C.17	NATO-RTO O5	Artificial	63.5mm diameter cylinder	ACT Artington IWT	77.2	0.234	0.0	400	-2.95	+0.02	0.44	18.0	Iced profile	Glaze	Humidity probe serviceability during trial cannot be confirmed. No repeat runs performed so tunnel variability unknown.
C.18	NATO-RTO O6	Artificial	63.5mm diameter cylinder	ACT Artington IWT	77.2	0.234	0.0	400	-2.55	+0.42	0.37	100.0	Iced profile	Glaze	As above

C.19	NATO-RTO O7	Artificial	114.5mm diameter cylinder	ACT Artington IWT	77.2	0.234	0.0	500	-3.05	-0.08	0.38	18.0	Iced profile	Glaze	As above
C.20	NATO-RTO O8	Artificial	114.5mm diameter cylinder	ACT Artington IWT	77.2	0.234	0.0	500	-3.05	-0.08	0.41	100.0	Iced profile	Rime	As above
C.21	NATO-RTO O9	Artificial	553mm chord NACA0012 aerofoil	NASA Glenn IRT	102.8	0.317	3.5	Sea level (nominal)	-11.15	-5.89	0.6	15.0	Iced profile	Glaze	Uncertainties in ice shape-tracing method. Repeatability and non-uniformity of cloud produce shapes that vary by 2-3% based on evaluation of 11 ice shape features.
C.22	NATO-RTO O10	Artificial	1.745m chord NACA23014 (mod)	NASA Glenn IRT	87.20	0.266	0.00	Sea level (nominal)	-6.25	-2.47	0.82	160.00	Iced profile	Rime	Same as above
C.23	NATO-RTO O11	Artificial	914mm chord Large Transport Horizontal Stabilizer	NASA Glenn IRT	128.60	0.399	0.00	Sea level (nominal)	-15.20	-6.97	0.34	21.00	Iced profile	Rime	Same as above
C.24	NATO-RTO O12	Artificial	914mm chord NLF0414 Aerofoil	NASA Glenn IRT	67.06	0.204	2.00	Sea level (nominal)	-5.35	-3.11	0.54	20.00	Iced profile	Glaze	Same as above
C.25	NATO-RTO O13	Artificial	914mm chord NLF0414 Aerofoil	NASA Glenn IRT	67.10	0.205	2.00	Sea level (nominal)	-5.35	-3.11	0.54	20.00	Iced profile	Glaze	Same as above
C.26	LEWICE2.0 Validation report – Run 404	Artificial	533.4mm chord NACA0012	NASA Glenn IRT	104.7	0.326	3.5	Sea level	-16.66 average	-11.21 average	0.55	20.0	Iced profile	Rime	
C.27	NASA – Run 421	Artificial	533.4 mm chord NACA 0012	NASA Glenn IRT	67	0.205	3.50	Sea level	-4.5	-2.24	1	20.0	Iced profile	Glaze	
C.28	BOEING – BRAIT Run 1017	Artificial	914.4 mm chord NACA 0012	Boeing IWT	67	0.204	3.00	111 ft	-7.1	-4.89	1	24.8	Iced profile	Glaze	

C.29	NASA – Run 423	Artificial	533.4 mm chord NACA 0012	NASA Glenn IRT	67	0.206	3.50	Sea level	-7.8	-5.55	1	20.0	Iced profile	Glaze	
C.30	NASA – Run 402	Artificial	533.4 mm chord NACA 0012	NASA Glenn IRT	103	0.316	3.50	Sea level	-9.1	-3.83	0.550	20.0	Iced profile	Glaze	
C.31	NASA – Run 206	Artificial	533.4 mm chord NACA 0012	NASA Glenn IRT	103	0.315	3.50	Sea level	-7.5	-2.23	0.340	20.0	Iced profile	Glaze	
C.32	NASA – Run 403	Artificial	533.4 mm chord NACA 0012	NASA Glenn IRT	103	0.317	3.50	Sea level	-10.8	-5.53	0.550	20.0	Iced profile	Glaze	

12. ANNEX D - ICE ACCRETION VALIDATION DATA AVAILABLE FOR SUPERCOOLED LARGE DROPLETS (SLD)

Flight and icing condition data values should be checked against the original source before being used for validation purposes. This table is intended as a summary of the available data for validation, rather than a comprehensive and accurate source of data.

Ref.	**Short description**	**Ref**	**Type of icing (natural/ artificial)**	**Model description**	**Facility**	**TAS (mph or m/s)**	**M**	**α (deg)**	**Alt (m)**	**SAT (°K or °C)**	**TAT (°C)**	**LWC (g/m^3)**	**VMD (µm)**	**Data available**	**Ice shape type**	**Comments about data quality**
D.1	NASA SLD database	IG1058136	artificial	NLF0414	IRT	83,4		5.0		267.79		1.2	118.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.2	NASA SLD database	IG1058236	artificial	NLF0414	IRT	83.4		5.0		267.79		1.2	118.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.3	NASA SLD database	IG1058436	artificial	NLF0414	IRT	135.5		1.0		266.31		0.8	118.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available

D.4	NASA SLD database	IG1058536	artificial	NLF0414	IRT	135.5		1.0		266.31		0.8	118.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.5	NASA SLD database	AF1116136	artificial	NACA0012	IRT	96.0		0.0		263.38		1.4	205.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.6	NASA SLD database	AF1116236	artificial	NACA0012	IRT	87.0		0.0		263.54		1.4	205.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.7	NASA SLD database	AF1116536	artificial	NACA0012	IRT	103.0		0.0		253.22		1.3	205.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.8	NASA SLD database	AF1116636	artificial	NACA0012	IRT	95.0		0.0		253.27		1.4	205.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.9	NASA SLD database	AF1116736	artificial	NACA0012	IRT	87.0		0.0		253.32		1.4	205.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.10	NASA SLD database	AE1114036	artificial	NACA0012	IRT	100.0		0.0		247.05		1.0	120.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.11	NASA SLD database	AE1114136	artificial	NACA0012	IRT	100.0		0.0		247.05		1.0	100.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.12	NASA SLD database	AE1114236	artificial	NACA0012	IRT	100.0		0.0		247.05		0.8	70.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available

D.13	NASA SLD database	CG1015536	artificial	NACA4415MOD	IRT	108.6		0.0		252.72		1.4	160.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.14	NASA SLD database	CG1021336	artificial	NACA4415MOD	IRT	169.5		0.0		268.31		0.8	160.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.15	NASA SLD database	CG1021436	artificial	NACA4415MOD	IRT	169.5		0.0		268.31		1.4	160.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.16	NASA SLD database	CG1021736	artificial	NACA4415MOD	IRT	108.6		0.0		269.39		1.4	160.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.17	NASA SLD database	CG058236	artificial	NACA4415MOD	IRT	180,0		3,0		266,73		0,3	133,0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.18	NASA SLD database	CG058436	artificial	NACA4415MOD	IRT	180,0		3,0		266,73		0,5	120,0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.19	NASA SLD database	CG058836	artificial	NACA4415MOD	IRT	180.0		-1.0		266.73		0.3	133.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.20	NASA SLD database	CG059328	artificial	NACA4415MOD	IRT	180.0		3.0		266.73		0.3	133.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.21	NASA SLD database	AF1196136	artificial	NACA0012	IRT	150.0		0.0		249.66		0.6	100.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available

D.22	NASA SLD database	AF1196236	artificial	NACA0012	IRT	150.0		0.0		249.66		0.6	100.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.23	NASA SLD database	AF1197436	artificial	NACA0012	IRT	150.0		0.0		256.32		0.4	54.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.24	NASA SLD database	AF1161036	artificial	NACA0012	IRT	99.5		0.0		251.32		0.9	70.0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.25	NASA SLD database	AF1186936	artificial	NACA0012	IRT	199.9		0.0		252.20		0,4	160,0	Iced profile		2 droplet distributions available: 10 bin and 27 bin LEWICE results available
D.26	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.3	40	Iced profile		Mono-modal distribution
D.27	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.6	40	Iced profile		Mono-modal distribution
D.28	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.3	40	Iced profile		Bi-modal distribution
D.29	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.3	180	Iced profile		Bi-modal distribution
D.30	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.3	104	Iced profile		Bi-modal distribution

D.31	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.6	104	Iced profile		Bi-modal distribution
D.32	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-10		0.3	104	Iced profile		Bi-modal distribution
D.33	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	0	0	-10		0.3	104	Iced profile		Bi-modal distribution
D.34	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	6	0	-10		0.3	104	Iced profile		Bi-modal distribution
D.35	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-10		0.3	104	Iced profile		Bi-modal distribution
D.36	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-10		0.2	104	Iced profile		Bi-modal distribution
D.37	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-10		0.4	104	Iced profile		Bi-modal distribution
D.38	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-25		0.3	40	Iced profile		Mono-modal distribution
D.39	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-25		0.3	40	Iced profile		Bi-modal distribution
D.40	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-25		0.3	104	Iced profile		Bi-modal distribution

D.41	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-25		0.3	180	Iced profile		Bi-modal distribution
D.42	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.65	2	6000	-25		0.3	104	Iced profile		Bi-modal distribution
D.43	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-10		0.3	104	Iced profile		Bi-modal distribution
D.44	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-25		0.22	215	Iced profile		Mono-modal distribution
D.45	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.2	2	0	-10		0.22	215	Iced profile		Mono-modal distribution
D.46	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-25		0.21	250	Iced profile		Mono-modal distribution
D.47	2D EXTICE SLD database		artificial	NACA0012	DGA S1		0.5	2	4000	-10		0.21	250	Iced profile		Mono-modal distribution
D.48	3D EXTICE SLD database		artificial	DASSAV wing tip / clean	CIRA	60	0.19	-2	0	-25	-23.2	0.12	39.7	Iced profile		Bi-modal distribution Uncertainty on LWC
D.49	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.24	41	Iced profile		Bi-modal distribution Uncertainty on LWC
D.50	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.17	35	Iced profile		Mono-modal distribution Uncertainty on LWC

D.51	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.25	52.2	Iced profile		Bi-modal distribution
D.52	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.4	77.4	Iced profile		Bi-modal distribution Uncertainty on LWC
D.53	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.54	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	2	0	-25	-23.2	0.65	165.33	Iced profile		Bi-modal distribution Uncertainty on LWC
D.55	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.65	165.33	Iced profile		Bi-modal distribution Uncertainty on LWC
D.56	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.183	-2	0	-5	-3.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.57	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.185	-2	0	-10	-8.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.58	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.183	-2	0	-5	-3.2	0.4	77.4	Iced profile		Bi-modal distribution Uncertainty on LWC
D.59	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.183	-2	0	-5	-3.2	0.65	165.33	Iced profile		Bi-modal distribution Uncertainty on LWC
D.60	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.19	-2	0	-25	-23.2	0.12	39.7	Iced profile		Bi-modal distribution Uncertainty on LWC

D.61	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.183	-2	0	-5	-3.2	0.51	20	Iced profile		Mono-modal distribution Uncertainty on LWC
D.62	3D EXTICE SLD database		artificial	DASSAV wing tip/ clean	CIRA	60	0.183	-2	0	-5	-3.2	0.29	26	Iced profile		Bi-modal distribution Uncertainty on LWC
D.63	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.19	3.5	0	-25	-23.2	0.24	41	Iced profile		Bi-modal distribution Uncertainty on LWC
D.64	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.19	3.5	0	-25	-23.2	0.17	35	Iced profile		Mono-modal distribution Uncertainty on LWC
D.65	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.19	3.5	0	-25	-23.2	0.4	77.4	Iced profile		Bi-modal distribution Uncertainty on LWC
D.66	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.183	3.5	0	-5	-3.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.67	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.19	3.5	0	-25	-23.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.68	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.19	3.5	0	-25	-23.2	0.65	165.33	Iced profile		Bi-modal distribution Uncertainty on LWC
D.69	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended	CIRA	60	0.185	3.5	0	-10	-8.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC
D.70	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended, flap extended 20°	CIRA	60	0.185	4	0	-10	-8.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC

D.71	3D EXTICE SLD database		artificial	DASSAV wing tip/ slat extended, flap extended 20°	CIRA	60	0.185	8	0	-10	-8.2	0.33	142.6	Iced profile		Bi-modal distribution Uncertainty on LWC

13. ANNEX E – ICE ACCRETION VALIDATION DATA AVAILABLE FOR GLACIATED ICING CONDITIONS

Flight and icing condition data values should be checked against the original source before being used for validation purposes. This table is intended as a summary of the available data for validation, rather than a comprehensive and accurate source of data.

Test cases E.1 to E.19 are issued from the paper SAE 2011-38-0018 and AIAA 2012-3035.

Test cases E.20 to E.23 are issued from the paper K. Al-Khalil & E. Irani, “Mixed Phase Icing Simulation and testing at Cox Icing Wind Tunnel”, AIAA 2003-0903

Ref.	**Short description**	**Type of icing (natural/ artificial)**	**Model description**	**Facility**	**TAS (m/s)**	**M**	**α (deg)**	**Pressure altitude (kPa)**	**SAT (°C)**	**TAT (°C)**	**IWC (g/m^3)**	**LWC (g/m^3)**	**Data available**	**Ice shape type**	**Comments about data quality**
E.1	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		93		14.6	8	2	Iced profile		
E.2	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		93		14.6	8	0	Iced profile		
E.3	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		93		11.9	4-12	0	Iced profile		
E.4	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		93		5.8	5-14	0	Iced profile		
E.5	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.21		93		5.6	9	0	Iced profile		

E.6	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.21		93		5.3	14	0	Iced profile		
E.7	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		93		6.2	20	0	Iced profile		
E.8	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.3		93		15.2	2-14	0	Iced profile		
E.9	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.3		93		6.8	10	0. 0.5. 1	Iced profile		
E.10	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.29		93		7.6	10	3. 2. 1	Iced profile		
E.11	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		45		11.3	0	1	Iced profile		
E.12	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		45		12.5	0	1	Iced profile		
E.13	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		45		13.8	5	0	Iced profile		
E.14	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.2		45		14.6	5	1	Iced profile		
E.15	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.21		45		12.3	5	0	Iced profile		

E.16	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.21		45		11.9	5	2	Iced profile		
E.17	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.21		45		13.4	5	2	Iced profile		
E.18	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.3		45		12.9	5	0	Iced profile		
E.19	2010 NASA/NRC experiment	artificial	2D airfoil (chord: 220mm)	NRC		0.3		56		14.8	5	1.5	Iced profile		
E.20	2002 Cox Experiment	artificial	NACA0012 (chord: 0,914m)	Cox		0.166	0	101.325	-11		0.7	0.3	Iced profile		
E.21	2002 Cox Experiment	artificial	NACA0012 (chord: 0,914m)	Cox		0.166	0	101.325	-11		0.3	0.7	Iced profile		
E.22	2002 Cox Experiment	artificial	NACA0012 (chord: 0,914m)	Cox		0.165	0	101.325	-6		0	0.7	Iced profile		
E.23	2002 Cox Experiment	artificial	NACA0012 (chord: 0,914m)	Cox		0.166	0	101.325	-6		0.7	0.7	Iced profile		

14. ANNEX F - ICE ACCRETION VALIDATION DATA AVAILABLE FOR SNOW CONDITIONS

Test case F.1 is issued from the Phd Thesis A.Vigano, “*Modélisation numérique et expérimentale des phénomènes de givrage par accrétion de neige collante*”

Ref.	Short description	Type of icing (natural/ artificial)	Model description	Facility	TAS (m/s)	M	α (deg)	Pressure altitude (kPa)	SAT (°C)	TAT (°C)	MVD (μm)	MMD (μm)	TWC (g/m³)	IWC (g/m³)	LWC (g/m³)	Data available	Ice shape type	Comments about data quality

F.1	2012 CSTB Experiment	artificial	Cylinder (diam: 50, 200, 315mm)	CSTB	10	na	na	101.325	-9 - -3	na	290	na	1	na	0.3 – 0.8	Iced profile		

15. ANNEX G – AERODYNAMIC PERFORMANCE PREDICTION VALIDATION DATA AVAILABLE

Ref.	**Test Case**	**Model Description**	**Facility**	**TAS (m/s)**	**Mach no.**	**Re No. (10^6)**	**α (deg)**	**Pressure Altitude (nearest 100ft)**	**SAT (°C)**	**LWC (g/m^3)**	**MVD (µm)**	**Data available**	**Ice shape type**	**Comments about results**
G.1	GARTEUR AG32 - Case A	NACA65A413 single-element aerofoil with roughness applied to leading edge of aerofoil back to 3% upper and lower surface	Ohio State University 6x22 inch Transonic Wind Tunnel		0.4 / 0.23	3.0 / 2.0	-4 to +19	na	Na	na	na	CL, Cd, Cm & pressure distribution at α = 2°	Surface roughness only	40% decrease in maximum lift due to roughness. Increase in drag due to roughness of about 33%. Moment coefficient about the quarter point of aerofoil shows reduction in nose down pitching moment compared to clean model
G.2	GARTEUR AG32 - Case B	NACA0012 section with artificial ice shape based on real ice shape	Ohio State University subsonic Wind Tunnel	58.1	0.12	1.4	-8 to +8	Sea level	-7.8	2.1	20	CL, Cd, Cm & pressure distributions at α = 4° & 6°	Glaze	
G.3	GARTEUR AG32 - Case C	Model 5-6, typical outer wing section of a transport aircraft. Artificial ice shape/roughness added to leading edge, based on a predicted shape	DNW-LST	101.2	0.2	3.0	-6, to +16	FL 150	-14.7	1.96	20	CL, Cd, Cm & pressure distributions, boundary layer measurement α = 6°	Glaze	40% decrease in max lift due to ice shape. Residual ice also gives reduction in max lift of 10 to 15%. Significant increase in aerofoil drag due to presence of ice. Strong increase in boundary layer thickness at given angle of attack, even for residual ice case.
G.4	GARTEUR AG32 - Case D	Model 5-6, typical outer wing section of a transport aircraft with extended flap. Artificial ice shape/roughness added to leading edge,	DNW-LST	101.2	0.2	3.0	-6 to +16	FL 150	-14.7	1.96	20	CL, Cd, Cm & pressure distributions, boundary layer measurement at α = 6°	Glaze	As above

		based on a predicted shape												
G.5	GARTEUR AG32 - Case E	SA13112 helicopter rotor blade aerofoil with two artificial ice shapes added to leading edge	CEAT S10		0.2/0.3/0.4	1.8/2.6 / 3.5	-16 to +19, -17 to +20, -16 to +20	Sea level	-6	0.26	24	CL, Cd & Cm	Beak ice	
G.6	GARTEUR AG32 - Case F	NACA 0012 aerofoil with two artificial, rotor blade specific ice accretions	ONERA S3-Chalais wind tunnel		0.3 to 0.8	1.3 to 2.75	-5, +16	Sea level	-9.2, -6	0.8 (0.6)	10 (28)	CL, Cd & Cm	Glaze and beak ice	Drag corrected to suppress 3d effects - testing of code sensitivity for ice-shape extent and Mach number effect

16. ANNEX H – ICE PROTECTION SYSTEM PERFORMANCE PREDICTION VALIDATION DATA AVAILABLE

Ref.	Test Case	Model Description	Facility	TAS (m/s)	Mach no.	Re No. (10^6)	α (deg)	Pressure Altitude (nearest 100ft)	SAT (°C)	LWC (g/m^3)	VMD (µm)	Data available	Ice shape type	Comments about results
H.1	N/A													

17. ANNEX I - APPENDIX C ICING CONDITIONS

17.1 DESCRIPTION OF ICING CONDITIONS

Icing classically occurs when an aircraft crosses clouds in which **supercooled droplets** are suspended. A supercooled droplet is a small drop of liquid water with an ambient air temperature below the freezing point. This is an unstable state for water, and any energy input will make the water turn to its stable phase: ice. Therefore, when the droplets impinge on the aircraft surfaces, they freeze, leading to ice accretion.

Appendix C Supercooled conditions can be encountered either in flight or on ground (freezing fog). Appendix C Supercooled droplets can be encountered either in cumuliform or stratiform clouds.

Figure 1: CS25/27/29 Appendix C Typical Clouds

Two standard clouds are considered by Appendix C regulation:

- Maximum Continuous Cloud
- Maximum Intermittent Cloud

These two standard clouds aim to cover supercooled icing conditions encountered in atmosphere.

17.2 ATMOSPHERIC ICING ENVELOPES DEFINITION

Appendix C envelope, defined as a function of altitude, temperature and Liquid Water Content, covers only supercooled droplet with diameters up to 50µm. It is based on a database from extensive 1950s flight tests, and had been statistically defined to 99th percentile of data set.

Icing conditions for both maximum continuous and maximum intermittent clouds are defined by two charts giving atmospheric conditions (altitude vs. Temperature) and icing conditions (liquid water content vs. size of particles function of air temperatures).

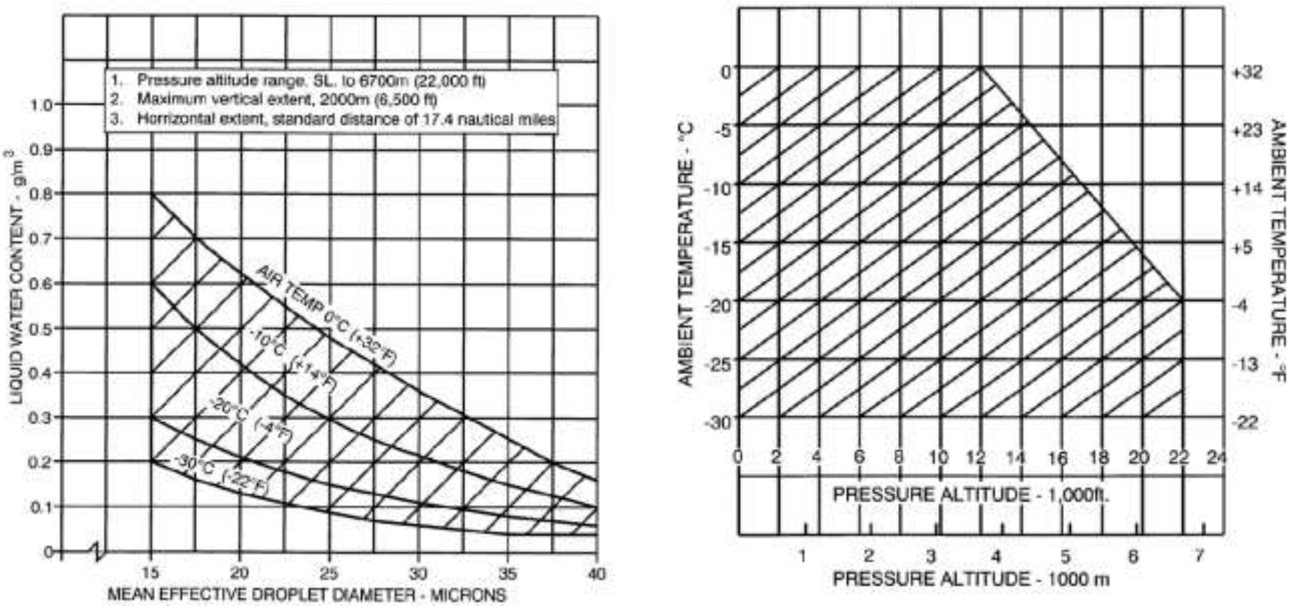

Figure 2: CS25/27/29 Appendix C Maximum Continuous Icing conditions

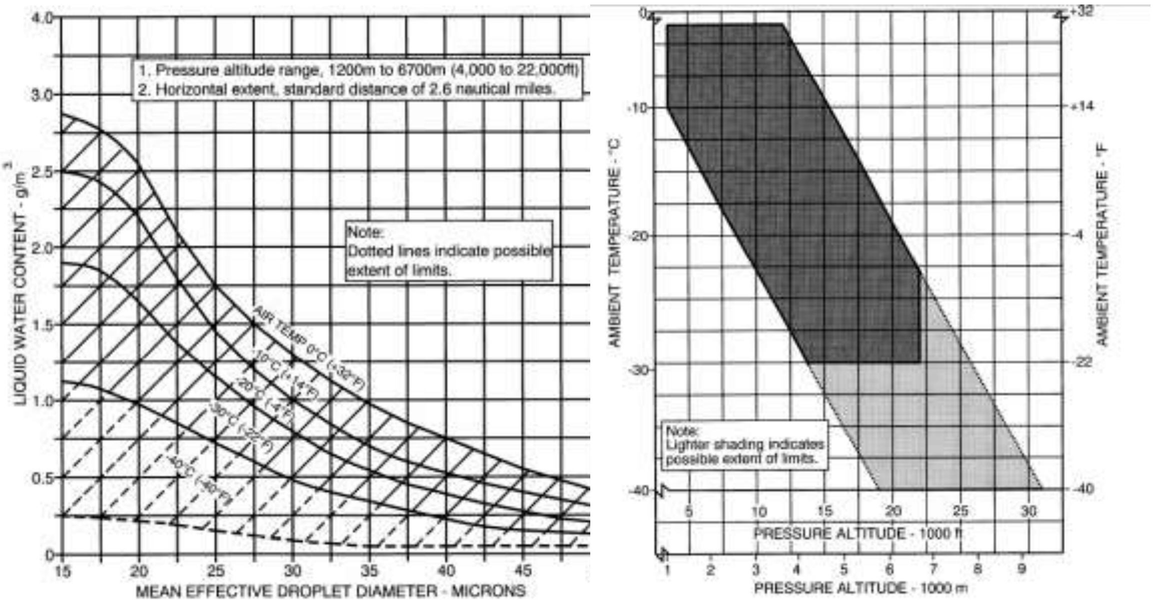

Figure 3: CS25/27/29 Appendix C Maximum Intermittent Icing conditions

Exposure time is an important parameter to take into account when characterizing the icing conditions. This exposure time is function of the size of the standard cloud.

- Maximum Continuous standard Cloud:
  - Maximum Vertical extent = 6500ft,
  - Horizontal extent = 17.4 Nm
- Maximum Intermittent Cloud: Horizontal extent = 2.6 Nm

Liquid water content for different sizes of cloud than the standard one can be calculated using the f factor given in the following charts.

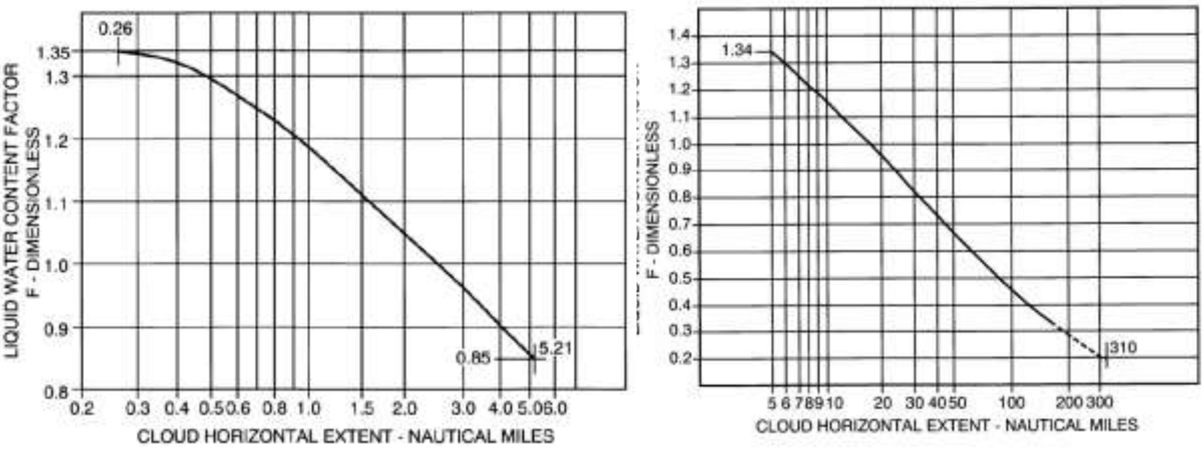

Figure 4: CS25/27/29 Appendix C f factor

Unity on previous charts corresponds to the horizontal extent of standard clouds.

17.3 MICROPHYSICAL PROPERTIES OF PARTICLES

Appendix C supercooled droplets are spherical particles, with same density as water. Appendix C envelope covers only supercooled droplet with diameters up to 50µm.

Droplet size refers to particles 'Median Volumetric Diameter' (MVD), which is the diameter above/below which 50% of the mass water content of the cloud is contained (Strict term is MVD_{50} but rarely used).

In stratiform clouds (maximum continuous icing conditions), MVD are usually lower (15 to 20 µm) than in cumuliform clouds (maximum intermittent icing conditions) with values around 25µm.

Classical value for aircraft certification is 20µm, with a Langmuir-D distribution, representative of existing distributions, measured during flight tests campaigns.

18. ANNEX J - APPENDIX O ICING CONDITIONS

Supercooled Large Droplets (SLD) have been incriminated as main contributors in noteworthy accidents including Roselawn. SLD icing involves much larger droplet than icing envelope covered by the Appendix C.

18.1 DESCRIPTION OF ICING CONDITIONS

Supercooled Large Droplets develop as falling snow encounters a layer of warm air deep enough for the snow to completely melt and become rain/drizzle. As the drops continue to fall, they pass through a thin layer of cold air just above the surface and cools to a temperature below freezing. When the supercooled drops strike the frozen ground (power lines, or tree branches), they instantly freeze, forming a thin film of ice, hence freezing rain.

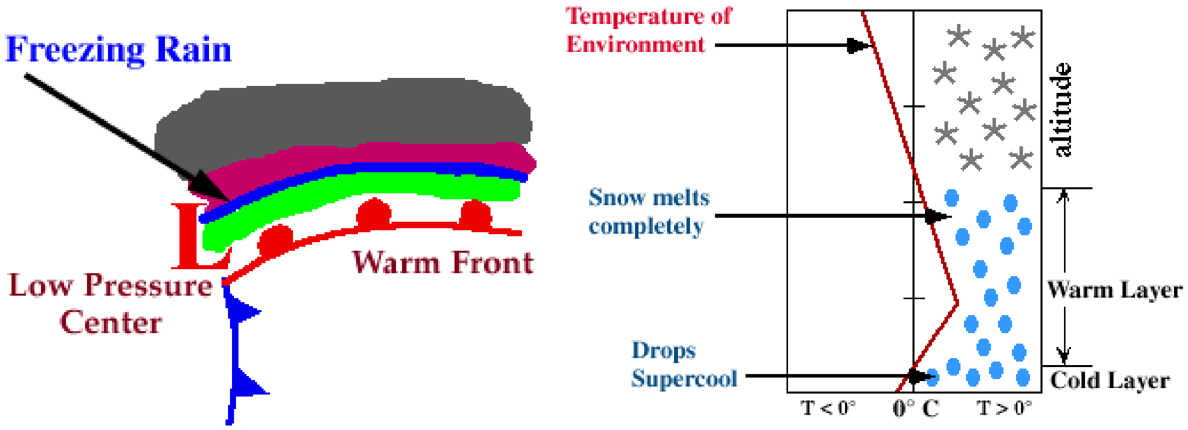

Figure 5: Supercooled Large Droplets formation processus

Drop becomes supercooled when crossing the thin layer of cold air close to the ground and freezes upon impact with cold surfaces. Freezing rain and freezing drizzle are most commonly found in a narrow band on the cold side of a warm front, where surface temperatures are at or just below freezing.

18.2 ATMOSPHERIC ICING ENVELOPES DEFINITION

In 2004, the ARAC (Aviation Rulemaking Advisory Committee) formed the Ice Protection Harmonization Working Group (IPHWG) to address possible needs for certification regarding supercooled large droplet (SLD), mixed phase and glaciated icing conditions. The IPHWG concentrated mainly on airframe icing issues and asked the Engine Harmonization Working Group (EHWG) to address issues related to propulsion systems.

The work performed as part of these ARAC groups led to the issuing by FAA of the NPRM10-10 (Notice for Proposed Rule Making) on June 2010 and the issuing by EASA of the NPA 2011-03 CS25 and NPA 2011-04 CS-E in March 2011.

The proposed rule defines a new icing envelope for SLD (CS25 Appendix O) and mixed phase and glaciated icing conditions (CS25 Appendix P). These new regulations to cover freezing drizzle and freezing rain icing conditions have been applicable since 2015.

Two envelopes are considered: *freezing drizzle* for particles in the range of 40-400 µm and *freezing rain* for particles beyond 400µm.

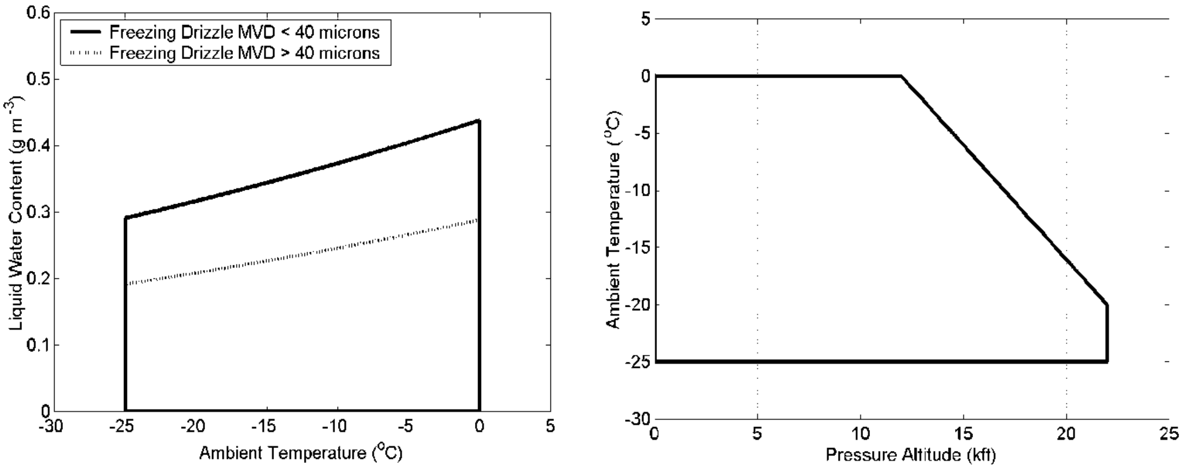

Figure 6: CS25 Appendix O Freezing Drizzle Icing Conditions

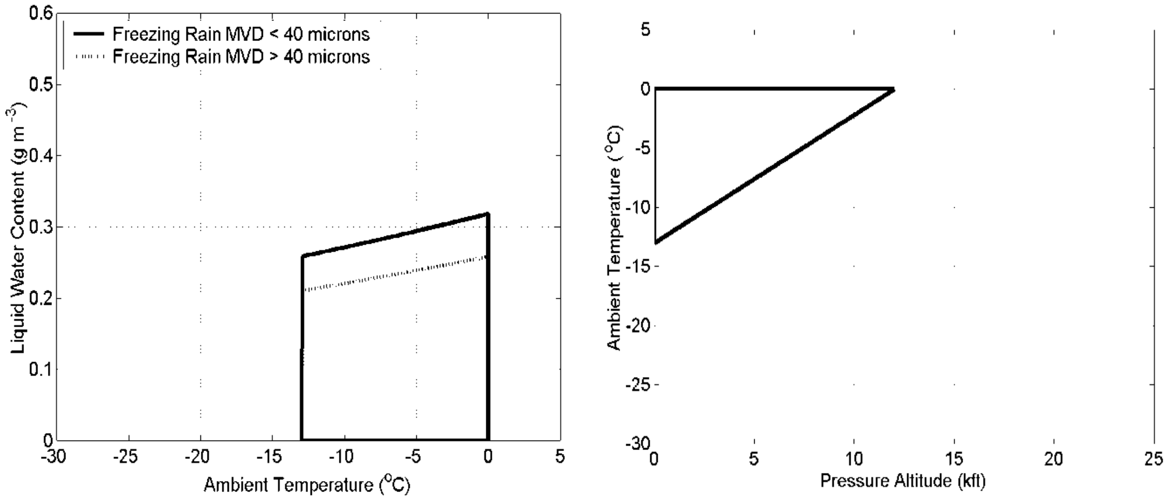

Figure 7: CS25 Appendix O Freezing Rain Icing Conditions

The standard cloud to consider for each condition is:

- Freezing Drizzle standard Cloud:
  - Maximum Vertical extent = 12 000 ft,
  - Horizontal extent = 17.4 Nm.
- Freezing Rain standard Cloud
  - Maximum Vertical extent = 7 000 ft,
  - Horizontal extent = 17.4 Nm.

18.3 MICROPHYSICAL PROPERTIES OF PARTICLES

CS25 Appendix O supercooled droplets are spherical particles, with same density as water.

Two different sizes of particles and associated distribution are considered, for each type of condition part of appendix O of CS25.

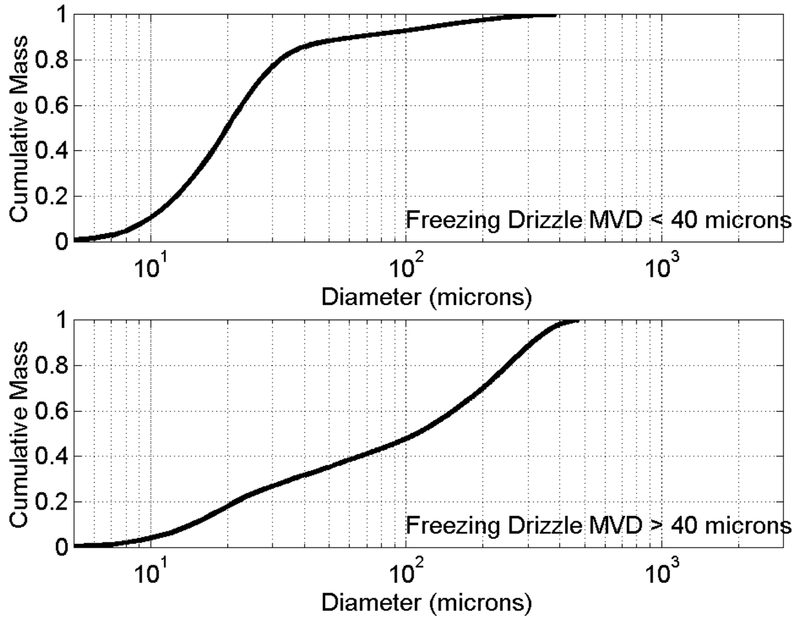

Figure 8: CS25 Appendix O – Freezing Drizzle Particles Distribution

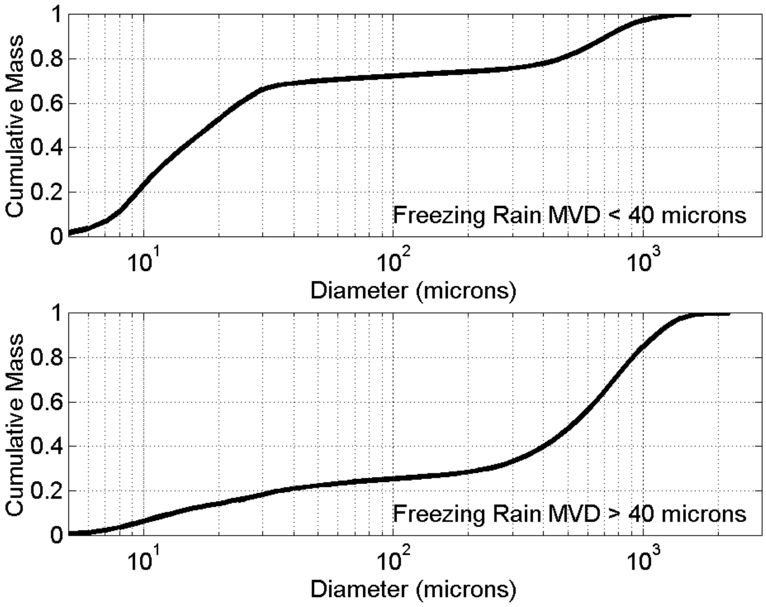

Figure 9: CS25 Appendix O – Freezing Rain Particles Distribution

19. ANNEX K - APPENDIX D/P ICING CONDITIONS

19.1 DESCRIPTION OF ICING CONDITIONS

Information gathered since the 1990's on over 100 weather related engine powerloss events has also permitted the Scientific and Regulatory community to conclude that aircraft flying through areas of high Ice Water Content (IWC) are subject to a specific type of weather induced incidents.

High water content is often found in deep convective clouds present in the warm tropical regions around the globe. These clouds can contain deep updraft cores that transport low-level air high into the atmosphere, during which water vapour is continually condensed as the temperature drops. In doing so, these updraft cores may produce localized regions where very high concentration of ice particles, or ice crystals, can be encountered. Such conditions are called glaciated icing conditions.

These ice particles can also be found simultaneously with supercooled droplet. Such conditions are called mixed phase icing conditions.

Ice particles are mainly encountered in high levels of atmosphere (above the freezing level estimated at approximately 20000ft for a standard atmosphere).

This means that ice particles are present in:

- high altitude clouds (cirrus, cirrostratus, cirrocumulus),
- aircraft contrails (condensation trails – artificial cirrus clouds) ,
- deep convective complexes (anvils of thunderstorms, tropical storms…)

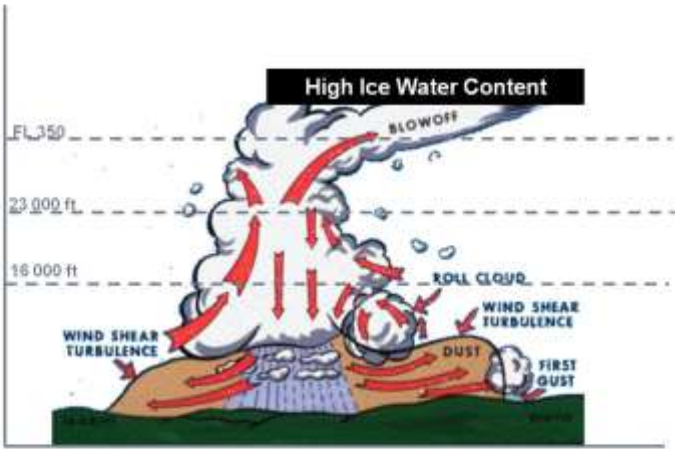

Figure 10: Scheme of a convective cloud and associated high IWC area

Mixed-phase clouds tend towards being either all liquid or all ice and there is substantial regional variability in relative fractions of liquid, mixed and glaciated phase. Moreover, the liquid fraction tends to increase with warmer temperatures.

19.2 ATMOSPHERIC ICING ENVELOPES DEFINITION

NPRM10-10 and NPA 2011-03 CS25 & NPA 2011-04 CS-E propose, among other things, new icing envelopes to cover mixed phase and glaciated icing conditions. This is the CS25 future Appendix P. These new regulations to cover mixed phase and glaciated icing conditions have been applicable since 2015.

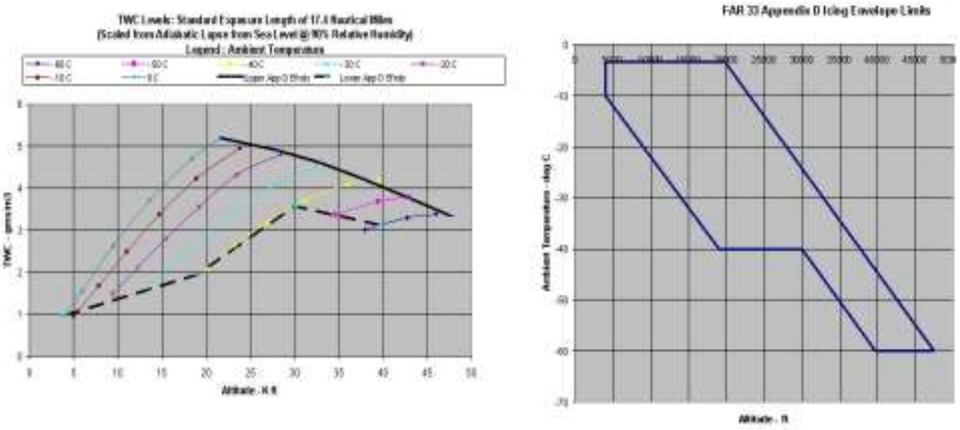

Figure 11: CS25 appendix P mixed phase and glaciated icing envelope

If TWC values are given in the above chart for a standard exposure length of 17.4Nm, other sizes of clouds can be considered, by using the f factor provided on following graph.

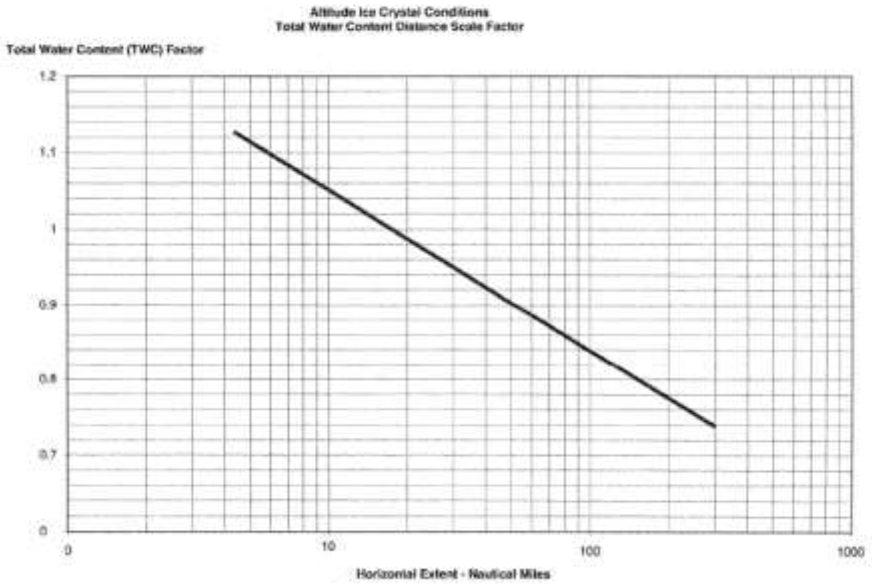

Figure 12: CS25 appendix P f factor

The LWC to consider for liquid part of mixed phase conditions is provided in next table.

Table 1 – Supercooled Liquid Portion of TWC

Temperature range – deg C	Horizontal cloud length	LWC – g/m^3
0 to -20	≤92.6 km (50 nautical miles)	≤1.0
0 to -20	Indefinite	≤0.5
< -20		0

Table 1 : CS25 appendix P supercooled liquid portion of TWC

19.3 MICROPHYSICAL PROPERTIES OF PARTICLES

Ice crystals are various macroscopic crystalline formations, with a basic hexagonal symmetry, which depends on the conditions of temperature and vapor pressure.

Their creation is induced by the formation of a crystalline structure on microscopic nuclei or by the freezing of very small supercooled droplets. Ice particles may be in the form of individual ice crystals, aggregates of crystals such as snowflakes, or crystals that have collided with supercooled water droplets to form bigger and spherical particles such as graupel and hail. Ice particles can span a very large size range, from microns to centimeters.

Future regulation considers that ice crystals median mass dimension (MMD) range is 50-200µm (equivalent spherical size) based upon measurements near convective storm cores.

19.4 APPENDIX D/P ASSESSMENT IN THE FRAMEWORK OF HAIC/HIWC [8]

An international effort to collect in-situ cloud data to assess the Appendix D/P was initiated in 2004, when the Engine Harmonization Working Group (EHWG) recognized that the primary issue related to flight in mixed-phase/glaciated conditions at the time was jet engine power-loss due to suspected ice crystal icing, which has since been shown to occur in high mass concentrations of ice crystals, and without the requirement for supercoooled LWC in the atmosphere. The EHWG efforts have also led to improved understanding that air data probe failures also occur in such conditions. The EHWG established a Technical Plan recommending among other things improvement of cloud measurement instrumentation, and a flight campaign to make in-situ measurements up to current cruise altitudes and in the types of clouds that caused engine power-loss events. The High Ice Water Content (HIWC) study was started in North America in 2006, initially concentrating on instrument development and the outfitting of a flight campaign aircraft. In 2012, the European High Altitude Ice Crystal (HAIC) project joined efforts with HIWC to perform the first HAIC-HIWC flight campaign in 2014 in Darwin, Australia using the French Falcon-20 cloud research aircraft. A second HAIC-HIWC flight campaign was conducted in May 2015 in Cayenne, French Guiana to collect additional data, where the Falcon-20 was joined by a Canadian Convair-580 aircraft, also equipped for cloud in-situ measurements. A third campaign, the NASA/FAA HIWC-RADAR campaign, was conducted by HIWC in August 2015 out of Fort Lauderdale, Florida with a NASA DC-8 aircraft. The dataset resulting from the three flight campaigns was from 45 flight missions with 472 runs in approximately 115 clouds, providing about 29,600 Nm of in-cloud data in deep convection over four temperature intervals: -10, -30, -40, and -50 ± 5 C.

Active convective cells were directly sampled in more benign systems, and from a safe distance in more vigorous systems. In all, about 92% of the in-cloud data were collected in such tropical MCS, including 6 flights in tropical storms.

Cloud TWC was dominated by ice crystals. At -10 C, the spatial fraction of mixed-phase zones with LWC > 0.1 gm-3 was only about 5%, with LWC never exceeding about 0.25 gm-3. The width of such zones was usually less than a few nautical miles. The spatial fraction decreased with decreasing temperature as expected. There were no mixed-phase zones colder than -35 C. These observations are well below the guideline maximum LWC exposures provided in Appendix P (e.g. 0 to -20 C range, LWC ≤ 1.0 gm-3 for a cloud length of ≤ 50 Nm). However, it is important to note that the flight campaign clouds, representative of engine-event clouds, had tops typically colder than -60 C with high ice concentrations that could mix to lower altitudes and grow at the expense of the liquid content of any imbedded updraft. Shallower clouds may well contain more significant mixed-phase regions.

TWC values were averaged over 13 distance scales from 0.5 Nm to 100 Nm, including the 17.4 Nm reference distance scale of Appendix D. The maximum TWCs at the 0.5 and 50 Nm scales were 4.1 gm-3 and 2.4 gm^{-3} respectively. For comparison to Appendix P, the data were also analyzed to provide TWC99 values for all distance scales with at least 100 data points. TWC99 at the 17.4 Nm reference distance (TWC99(17.4)) was found to increase with temperature, from 1.81 gm-3 at -50 C to 2.69 gm-3 at -10 C. The ratios of observed TWC99(17.4) to Appendix D values were fairly constant with temperature, varying from about 0.49 to 0.61 (average 0.56), providing some support for the adiabatic TWC calculations that are the basis for the Appendix P envelope. Appendix P TWCs are based on simple adiabatic calculations for deep lift, scaled by a factor of 0.65 to match the TWC99(17.4) values of an industry dataset collected in the 1950s. If the same approach had been taken using the new flight test dataset, the calculated scale factor would have been about 0.36 rather than 0.65. TWC99 values were found to decrease with increasing distance scale in a manner similar to the Appendix P distance factor. However, below the 4.5 Nm minimum Appendix P distance scale, the extrapolated Appendix D/P distance factor overestimated the observed TWC99 values by as much as 25% at 0.5 Nm.

The characteristic size of particles provided in Appendix P was based on best estimates available at the time, but instrumentation was not optimum for this purpose and possibly subject to bias. For the new flight test dataset, a much larger body of PSD data were collected, using modern instrumentation and processing techniques commonly used and accepted in the atmospheric research community. MMD was found to increase with temperature from about 320 µm at -50 C to 690 µm at -10 C. Although higher than those specified in Appendix P, MMDs are still relatively low, particularly in the -30 to -50 C range, as they were expected to be at the outset of the flight campaigns.

The retasking process has begun with a letter sent from the FAA to AIA to request the retasking of the EIWG in preparation for the ARAC to discuss the reanalysis of the 14 CFR Part 33 Appendix D environmental envelope for ice crystals.

20. ANNEX L – FALLING AND BLOWING SNOW CONDITIONS

Snowflakes, also called snow crystals, are aggregates of many single ice crystals. In nature, ice crystals often form in mixed-phase clouds, where nucleated ice crystals grow via water vapour deposition at the expense of evaporating supercooled liquid water droplets once the environment becomes sub-saturated with respect to water. This so called Bergeron-Findeisen effect corresponds to a net transport of water vapour from the liquid to the ice phase; in this phase transition, water vapour transforms directly into solid. The shape of the ice crystals depends on the temperature and humidity of the clouds, with a large variety of resulting crystal shapes. The “Snow Crystal Morphology Diagram” from Furukawa and Wettäufer (2007) classifies the shapes into (1) plates and dendrites (from 0 to -3 °C), (2) needles, columns and prisms (from -3 to -10 °C), (3) solid, thin, and sectored plates and dendrites (from -10 to -22 °C), and finally solid plates and columns (below -22 °C), according to cloud temperature and water vapour content. In addition to crystal growth from pure water vapour deposition, aggregation and riming growth modes generate highly irregular shaped larger ice crystals.

Finally, snowflake aggregation mostly appears at air temperatures near 0°C and is predominantly affected by the air temperature and the shape of the aggregating ice crystals. Columns and needles aggregate into rather small flakes, while aggregates of dendritic crystals tend to become large. Snowflake diameters are mainly between 2 and 5 mm, ranging up to 15 mm. Snowflake density varies, ranging from 0.005 to 0.2 g cm-3, being inversely proportional to snowflake diameter, i.e. the larger the flakes, the lower the density. This constant of proportionality between snowflake diameter and the density of the snowflake is almost four times larger for wet than for dry snowflakes.

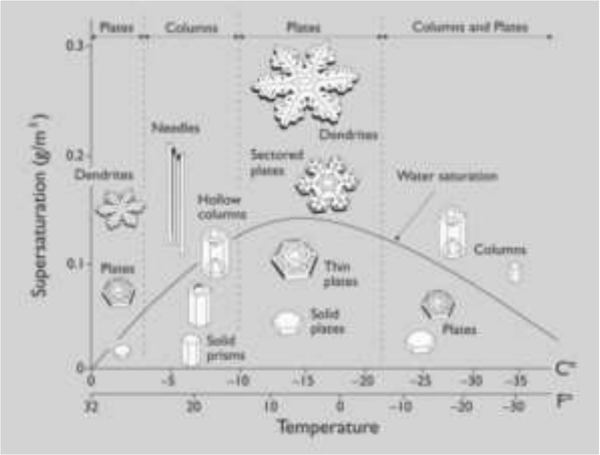

Figure 13: Snow Crystal Morphology Diagram

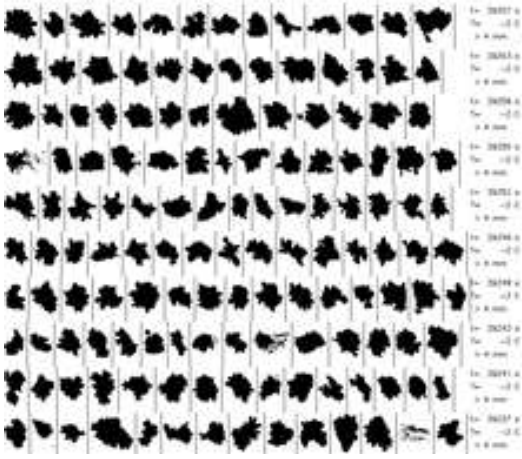

Figure 14: Representative snowflakes with sizes around 2 to 3 mm, obtained in flight test at -3°C (Source: Airbus Helicopters)

The available regulations (CS25/29) and guidance material (AC, AMC) provide recommendations for the types of snow conditions to be tested, if tests are required. However the conditions are less detailed than for other icing conditions especially with regards to Particle Size Distribution (PSD), density or wet/dry snowflake characteristics.

Additional information are provided in the following ICE GENESIS deliverables:

- ID5.1 / CNRS / M06 / Preliminary characterization of snow microphysical properties
- ID5.5 / CNRS / M18 / First update of the characterization of snow microphysical properties
- ID5.7 / CNRS / M24 / Second update of the characterization of snow microphysical properties
- D5.8 / CNRS / M36 / Synthesis & Characterization of snow microphysical properties