Research Needs for Appendix O Supercooled Large Drop Icing with MVD Greater Than 40mm to Support Airframe Ice Accretion Certification – A Gap Analysis

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Abstract

Compliance with the icing requirements specified in CS 25.1420 / 14 CFR 25.1420 and Appendix O present a significant challenge for innovative Part 25 transport category airplanes aiming for climate neutrality or net-zero greenhouse gas emissions by 2050. The lack of validated engineering tools for the Appendix O envelope necessitates the use of comparative analysis or certification exceptions, which rely on conventional aircraft history and are therefore not applicable to novel designs. These challenges apply broadly to large turbojet transport, turboprop transports, business and regional jets, and smaller propeller-driven aircraft alike. Tool limitations, coupled with the complexity of current regulatory requirements, extend certification barriers to all Part 25 aircraft—regardless of size, design features, mission type, or certification authority. While progress has been made in simulating portions of Appendix O—particularly freezing drizzle with a median volumetric diameter (MVD) less than 40 µm—supercooled large droplet (SLD) distributions with MVDs greater than 40 µm remain insufficiently addressed and are believed to produce critical ice shapes that pose safety risks for unrestricted operations under Appendix O. This paper outlines key research gaps in Appendix O icing, with particular focus on freezing rain with MVDs greater than 40 µm, viewed through the lens of transport category airplane certification. Emphasis is placed on airframe ice accretion. Given the scope and complexity of addressing these gaps, MICG has developed an alternative, pragmatic approach to enable the safe certification of innovative aircraft designs in the near term, while SLD ice prediction technology continues to evolve. [1]

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Introduction

There have been a limited number of new certified large transport aircraft and engine types over the last few years with marginal environmental improvements [2]. Meaningful progress toward global aviation sustainability goals requires significant innovation and development of novel technologies and aircraft configurations. Development of a means to ensure safe flight in or around the atmospheric icing conditions represented by Appendix O is a key challenge that must be addressed if certification and deployment of these sustainable aircraft designs is to become a reality.

There are currently three paths to show compliance, each of which pose significant, if not insurmountable challenges in their current form: Comparative Analysis (EASA only), exception (FAA/TCCA/ANAC only), and direct compliance (both EASA and FAA). Existing exceptions and Comparative Analysis methods are based on assumptions of similarity to the existing fleet. The 60,000 pound MTOW criterion in 14 CFR25.21(g)(1)(i) was based on surveys of airplanes within the existing fleet [3] and therefore cannot be assumed to apply to novel configurations. As stated in FAA–2010–0636; Amendment Nos. 25–140 and 33–34:

> *…the applicability of § 25.1420 is limited based on airplane weight due to the positive service histories of certified airplanes.*
>
> *If future designs for larger airplanes contain novel or unusual design features that affect this successful in-service history, and those design features make the airplane more susceptible to the effects of flight in SLD icing conditions, the FAA can issue special conditions to provide adequate safety standards.*

Similarly, the use of Comparative Analysis requires the use of a reference fleet with no fewer than two million flights without accidents or serious incidents in SLD icing conditions (AMC 25.1420(f)(3)(3.4)). Identifying a reference fleet of this size can be a significant challenge for manufacturers of smaller fleets, even when they have an impeccable safety record. Thus, direct compliance is considered the only path for certifying novel airplane configurations such as the NASA Transonic Truss-Braced Wing, Airbus Wing of Tomorrow, Blended Wing-Bodies, etc.

Direct compliance requires the identification of critical ice accretions for each flight phase contained in Subpart B (Appendix O Part II (a)). Whether certifying for a portion of Appendix O or for the entirety, specific ice shapes and their effects must be considered. This remains true, even for aircraft that only intend to operate in Appendix C as the "Detect-and-Exit" path via CS 25.1420(a)(1)/14 CFR 25.1420 requires demonstration of an ability to safely exit icing conditions after an unintentional encounter with Appendix O icing conditions. Therefore, unless an aircraft is restricted from flight in <u>*all*</u> icing conditions, an assessment of Appendix O ice shapes and the associated effects must be completed.

Many gaps exist that prevent direct compliance for flight in Appendix O icing conditions for Part 25 aircraft. The following sections aim to detail these gaps from the perspective of certification of transport category airplanes with a particular focus on Freezing Rain with MVD greater than 40 µm. This sub-envelope of Appendix O is of interest due to current analytical predictions of ice shape accretions on both protected and unprotected surfaces. The shapes, as predicted, would be expected to cause large aerodynamic separation that would require significant increases in operating speeds compared to the existing in-service fleet, to the point where these faster speeds would themselves lead to a reduction in safety.

In addition to the technical gaps associated with ice shape prediction, this paper also aims to address the gaps associated with the encounter scenarios required to be considered when certificating for Appendix O icing, particularly the challenges with combining various types of icing conditions and the time in holding requirements.

While further research is necessary to enable direct compliance in a manner consistent with today's certification in Appendix C icing conditions, explicitly addressing each gap outlined herein is expected to be a significant undertaking. Therefore, to facilitate certification of innovative and transformative aircraft designs, it is crucial to consider alternate means of addressing safety concerns related to flight in and around SLD icing conditions. The MICG has developed a proposal focused on providing a practical and pragmatic approach to these safety concerns, allowing for continued innovation while research and technology development progress [1].

Gap #1: Computational Ice Prediction Tools Remain Unvalidated for Use in Appendix O

Computational tools and icing wind tunnels are the primary means for predicting Appendix C ice shapes early in a development program and have resulted in robust means for configuration design well in advance of flight testing. However, these tools and tunnels have not been validated for the full range of Appendix O icing conditions. This leaves manufacturers unable to assess with the necessary confidence the effects of Appendix O ice and develop novel configurations to ensure safety. Only after the investment has been made to build and fly can the product behavior be assessed in flight testing. This heightened risk of failure at the end of a development program prohibits the large investments necessary to introduce groundbreaking technology.

It is worth noting that improvements to predictive and experimental capabilities are needed for both protected and unprotected surfaces icing. Ridges of ice resulting from the use of an ice protection/de-icing system can cause large aerodynamic separation over critical surfaces, as was determined to be the probable cause behind the American Eagle flight 4184 crash in Roselawn, Indiana in 1994 [4]. Unprotected surfaces ice, in addition to ice ridges aft of protected surfaces, has been attributed to substantial performance penalties as was seen in the NASA Twin Otter flight tests in 1997-1998 [5]. Furthermore, current state-of-the-art simulations have also shown that rough ice accretions can develop on a large portion of unprotected surfaces [6] [7], such as those shown in Figure 1. One major concern with respect to these results is the prediction of ice forming on areas of the wing that are not possible to protect via traditional anti- or de-icing systems (e.g. the trailing portion of a high light device with minimal structure, or the main wing element behind deployed surfaces where fuel leakage zones are commonplace), either as a result of direct impingement, via runback behind a heated system, or a combination of the two. A contaminated main element is less able to withstand adverse pressure gradients that otherwise would minimize the downstream effects of a contaminated deployed device, causing large regions of aerodynamic separation at a significantly lower angle of attack. These types of deployed leading edges (e.g., slats) are common on large transport category airplanes and provide a significant portion of the airplane’s maximum lift and handling qualities capabilities.

Prediction of runback ice behind heated surfaces is another significant challenge that highlights the existence of numerous research gaps in today’s state-of-the-art computational tools, stemming from the complex interplay of the physical phenomena involved. Although somewhat common to challenges faced in simulating runback in the traditional Appendix C environment, the significance is likely to be heightened considerably in large drop conditions. Gaps include:

- Runback water film dynamics: The presence of a thin liquid water film on heated surfaces, which can vary in thickness and flow characteristics (film vs. rivulets) introduces critical modeling challenges that are not adequately addressed in current research. Specifically, there is a gap in understanding how the dynamic interaction between the water film and impinging SLD affects the overall ice accretion process. The flow of water can be influenced by shear stress, surface tension, and gravity, leading to irregular ice shapes such as "horns" or "ridges" that can form far downstream of the leading edge [8] [9]. Current models do not sufficiently capture these interactions, resulting in uncertainties in predicting the thickness and behavior of the film, which significantly alters heat and mass transfer processes.

- Freezing dynamics: The freezing process of runback water in SLD conditions can be erratic. Unlike rime ice, which freezes immediately, glaze ice – common in SLD – involves partial freezing and runback. The exact point of freezing and the resulting ice shape are highly sensitive to surface temperature, airflow, and water film thickness. This is further complicated by the unsteady and spatially varying nature of runback.
- Heat transfer modeling: Ice accretion, particularly in glaze or mixed icing conditions, leads to substantial surface roughness, which dramatically enhances convective heat transfer; however, accurately modeling this enhancement remains a major challenge for numerical codes as traditional roughness models may not adequately capture the complex relationship between ice roughness features and local heat convection [10] [11].
- Conjugate heat transfer: For heated surfaces, simulating the heat transfer from the internal heating system through the aircraft structure to the outer surface, and its interaction with the impinging water and ice, necessitating coupled thermal analysis (conjugate heat transfer) is computationally intensive and is often simplified in current codes, leading to inaccuracies in predicting heat transfer and the resulting ice accretion.
- Temperature gradient and phase change: melting, freezing, and evaporation occurring on the heated surface and within the runback water film require more precise modeling techniques. There is a need for improved methodologies that can accurately resolve these transient phenomena and their interactions, particularly in relation to the sensitivity of freezing rates to heat transfer coefficients.
- Physics coupling: Icing simulations typically involve coupling multiple modules: flow field calculation, droplet trajectory, thermal balance, and ice growth (both in terms of runback and direct impingement on existing runback). The accurate and robust coupling of these modules, especially in the unsteady and highly non-linear SLD runback regime, remains inadequately validated.

The absence of SLD physics in numerical runback prediction tools, along with the use of conservative assumptions in the computation of convective heat transfer coefficients, may contribute to an increase in runback water loading and freeze-out rates. Additionally, the lack of ice erosion and shedding models introduces further conservatism [12], the extent of which is not fully understood due to limited data available for validation. These missing physics could potentially lead to larger runback ice heights than what might be expected under different conditions and existing validation efforts often reveal significant disparities between predicted and experimental ice shapes, with the predicted shapes typically being larger and more conservative than experiment [13].

If the protected and un-protected ice accretions predicted by today's state of the art computational tools are representative of reality, the associated aerodynamic effect would be expected to be so severe as to cause accidents or incidents in the fleet; however, there are no known accidents or incidents of large Part 25 aircraft due to loss of control in flight in SLD icing conditions [14]. Although there are no known, quantified, in-flight observations of large drop ice accretions on large transport aircraft that could be used for validation of the analytical tools, there exists a disconnect between the predicted accretions and the safety record of the in-service, large transport fleet. Possible explanations for this disconnect include:

A. The current state-of-the-art tools may be providing overly conservative results, potentially due to not properly modeling the physics associated with large drop icing, or potentially some full-scale effects such as ice shape erosion or shedding, especially at warm temperatures.
B. Certain design features of large transport category airplanes (e.g. spoiler-driven lateral controls, thermal ice protection systems, etc.) are able to successfully mitigate the effects of SLD ice accretions.
C. The margins provided via a robust certification to the existing Appendix C regulations are sufficient to cover the effects of SLD.

The need for further development and improvement of the engineering certification tools was identified by the Ice Protection Harmonization Working Group (IPHWG) in 2005 [14]. An assessment of Appendix O engineering tool capabilities was made by the IPHWG in 2009 (Figure 2). In the accompanying recommendation letters for Task 2, the IPHWG urged the continuing development and validation of engineering tools for SLD icing, noting the immaturity of the analytical and test techniques available to address compliance demonstrations [14]. The IPHWG assessment was subsequently published in AC 25-28 in 2014 with no change to the assessed capabilities. While there was significant effort and valuable testing immediately following the roadmap development, similar questions regarding droplet breakup, splashing, re-impingement, etc. identified in 2004 [15] were still unaddressed in 2013 [16]. As such, many of the gaps identified by the IPHWG that were to be addressed by the SLD Technology Roadmap have not been closed, including the ability to reproduce SLD conditions in icing facilities to accurately produce ice shapes, develop validation data, and address the ice prediction codes.

Initiatives such as ICE GENESIS, SENS4ICE, and JOICE have made great strides in progressing the knowledge of icing physics, simulation, prediction, and detection of Freezing Drizzle icing conditions. Over €24 million have been dedicated to Appendix O research from these efforts alone [17] [18] [19], with additional projects such as PrISM and Horizon Europe 2026 emerging to continue research in Appendix O icing. However, most of these projects did not include research into Freezing Rain with MVD greater than 40μm, so less progress has been made in this area. A 2019 survey of the state-of-the-art by the ICE GENESIS effort identified similar gaps that continue to require additional research, especially for the larger droplet sizes [20]. As such, over ten years after Appendix O was codified and twenty years after the IPHWG Task 2 Report was released, no airplanes have shown direct compliance to the rule and the IPHWG's concerns regarding inadequate analytical and test techniques for Appendix O icing remain just as valid today as when they were originally published.

Whilst acknowledging the IPHWG assessment, the information published in the preamble to Appendix O to Part 25 relayed a firm stance that the regulatory agencies believed there was sufficient compliance methods and engineering tools to comply with the rule [21]. While the option of using existing tools in a conservative way, along with engineering judgement, was acknowledged as necessary due to the lack of mature tools for Freezing Rain before Appendix O was codified, it was clear that the expectation was for the tools to improve to the point of enabling less conservative approaches [14]. Current guidance material (AC 25-28 Appendix E) acknowledges the technological challenges associated with analytical and experimental prediction of Appendix O ice shapes. It has been proposed that engineering judgement combined with flight tests provide a sufficient and viable means of compliance. It is also acknowledged that flight testing may be the primary means of certification for Freezing Rain. The MICG unanimously agrees that this compliance strategy is unrealistic and infeasible due to the following key factors:

1. To ensure that the performance and handling qualities of the airplane are safe and certifiable following flight in Appendix O conditions, the aerodynamic effects of airframe icing contamination need to be known early in the design process. This early knowledge allows for the effects to be mitigated through appropriate configuration design choices.

2. The use of engineering judgement early in the design phase without explicit agreement and approval by the certifying agencies does not provide the necessary confidence that the aerodynamic effects of Appendix O ice accretions are understood and properly accounted for.

Although evaluation of in-flight ice accretions was historically performed as a relatively straight-forward validation exercise towards the end of a development program, the quantitative requirements introduced by 14 CFR Part 25 Amendment 121/CS-25 Amendment 3 have driven in-flight icing effects to become a primary design requirement that directly affect nearly every aspect of configuration development including operating speeds, wing and high lift system sizing and primary structure, crew alerting system architecture, primary flight control law architecture, air data systems, and safety hazard assessments. As such, the use of flight test as the sole means of assessing the aerodynamic effects is prohibitive. Development of a large commercial transport aircraft typically costs billions of dollars, euros, and pounds, and takes upwards of six to ten years to complete. Proceeding with such a level of investment without knowledge of how the aircraft will behave in the presence of SLD contamination is a significant economic and safety risk that can either discourage a new program from the onset or lead to significant conservatism that not only impacts emissions, weight, fuel burn, and other key configuration decisions, but also can have a contradictory effect on safety by significantly increasing operating speeds.

When discussing the validation of Appendix O computational tools and tunnels, the question of accuracy can be interpreted in different ways. For the purposes of aerodynamic design and configuration development, the accuracy of the aerodynamic effect of the ice shape on the performance and handling qualities of the airplane is of primary concern. As such, exact 3D features may not be required for modelling. Rather, their effects should be understood, and an engineering standard should be used to sufficiently capture the aerodynamic effects – i.e., an ice shape that provides similar or appropriately conservative airplane-level aerodynamic degradations.

For example, most computational tools used for Appendix C certification do not predict the formation of individual “feathers” or “scallops” (also called “lobster tails”) of ice that can be seen in natural icing conditions. Instead, computational tools typically capture important features such as impingement limits, bulk mass, ice height, and general shape with reasonable match to icing wind tunnel testing. Combined with the acknowledgement that Appendix C was intended to include 99% of icing conditions (AC 25-28 Sect. 8.6.2.2), it has been accepted that the ice shapes predicted from these methods are sufficiently representative and can be used for certification for flight in Appendix C icing conditions. Predicting the impingement limits, bulk mass, ice height, and general shape in a similar manner should also be the goal for tools that can be used for Certification to App O for both protected and unprotected surfaces.

Very little to no research has been found that characterizes the effect of Appendix O ice accretions on ice protection systems or on/behind deployable surfaces such as slats. Flight campaigns have been conducted to evaluate airplane performance changes in the presence of Appendix O icing, such as those flown during the SENS4ICE campaigns, but only one known flight campaign attempted to characterize the ice shape and size in flight: The NASA Twin Otter testing from the 1998-2005 timeframe. This endeavor may be the only set of experimental data collected to date where ice shapes resulting from de-icing boots can be compared from both flight and icing tunnel testing; however, such comparisons have not been completed at the time of this writing [5]. Additionally, no research has been found for deployed surfaces, heated surfaces, or on aircraft of the size and speed representative of large transports. Given that single-aisle and widebody aircraft account for 82% of the global fleet as of 2023, with projected growth to nearly 90% in 2043 [22], it is of the utmost importance that future research be tailored to address the systems, scale, and flight conditions common to these configurations if meaningful progress towards aviation sustainability is to be achieved.

While continued research is still needed to understand how to accurately simulate the full range of Appendix O icing conditions, existing state-of-the-art codes such as those from research entities (e.g., NASA, CIRA, ONERA, etc.) or proprietary entities can be used to compare with flight test observations, if available. There have been anecdotes confirming the relatively larger impingement of Appendix O to Appendix C, but little has been published to help in improving the numerical simulations. Although the Twin Otter does not represent the size and speed of large transport aircraft, developing comparisons of numerical simulations with the NASA Twin Otter flight and IRT results should be conducted as it would be a valuable initial datapoint from which to gain a better understanding of the relative accuracy of the codes.

Due to the lack of validation data, it is difficult to determine the accuracy of state-of-the-art Appendix O icing simulation codes, especially for Freezing Rain. While there are some indications that flight tests have qualitatively matched well with predictions for smaller transport airplanes, no corresponding evidence has been found for large transports. As such, similar research addressing configurations representative of large transport aircraft should also be prioritized as size and speed may be a critical component for accurate modeling of large droplet icing physics.

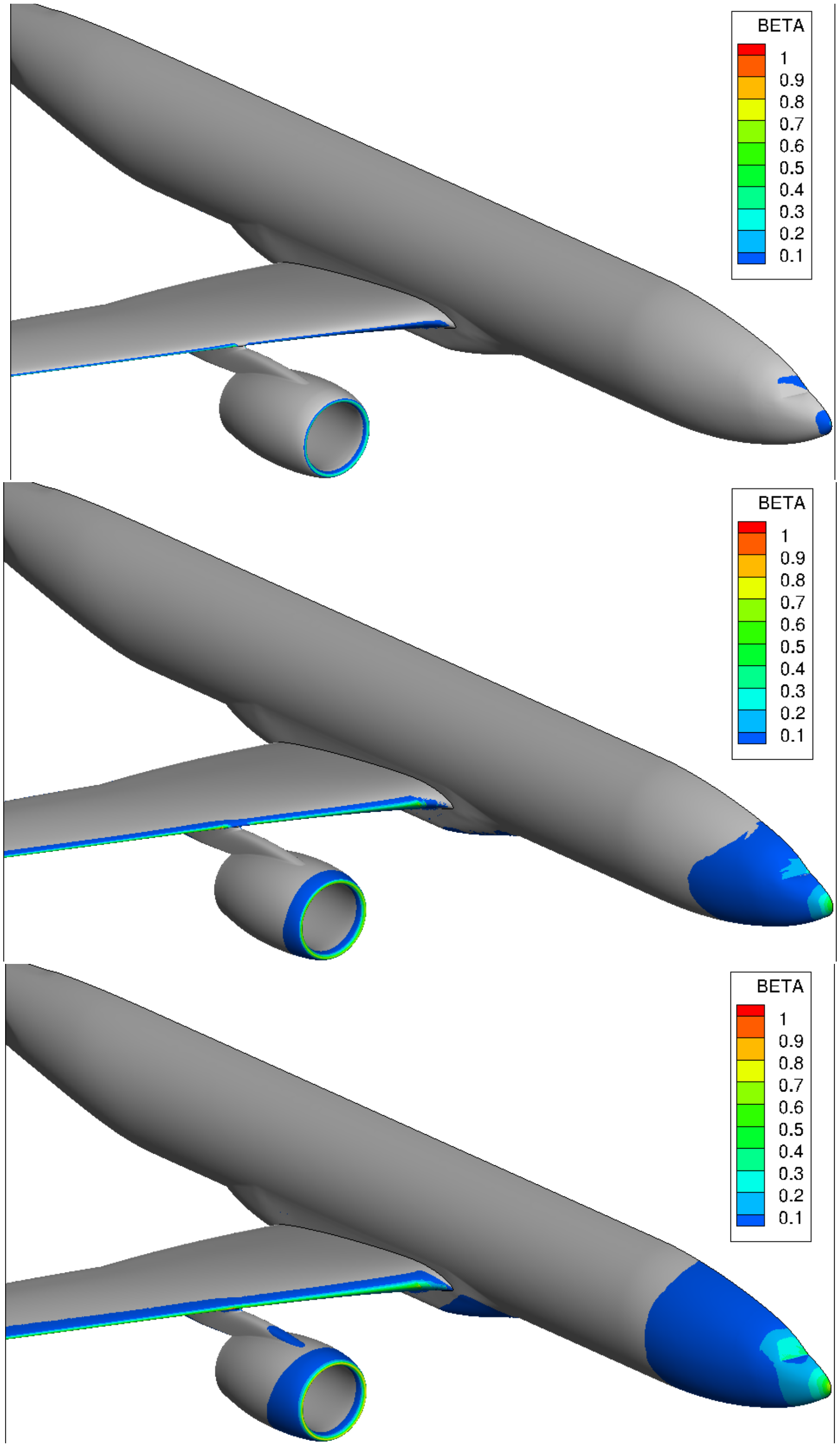

Figure 1 LEWICE3D Collection Efficiency Simulation of Appendix C (Top), FZDZ > 40μm (Middle), and FZRA > 40μm (Bottom) [6]

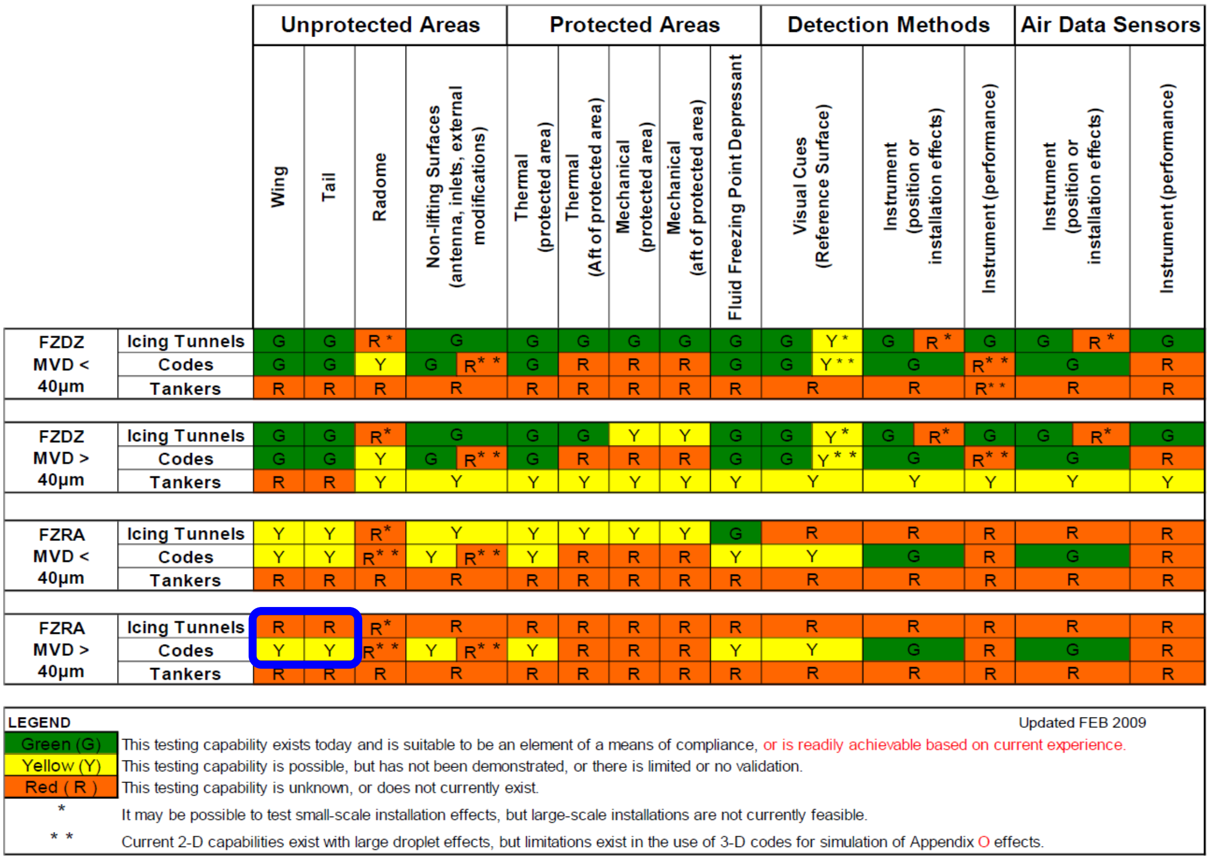

Table E-1. Assessment of Appendix O Engineering Tool Capabilities

		Unprotected Areas				Protected Areas					Detection Methods			Air Data Sensors	
		Wing	Tail	Radome	Non-lifting Surfaces (antenna, inlets, external modifications)	Thermal (protected area)	Thermal (Aft of protected area)	Mechanical (protected area)	Mechanical (aft of protected area)	Fluid Freezing Point Depressant	Visual Cues (Reference Surface)	Instrument (position or installation effects)	Instrument (performance)	Instrument (position or installation effects)	Instrument (performance)
FZDZ MVD < 40µm	Icing Tunnels	G	G	R *	G	G	G	G	G	G	G Y *	G R *	G	G R *	G
	Codes	G	G	Y	G R* *	G	R	R	R	G	G Y * *	G	R* *	G	R
	Tankers	R	R	R	R	R	R	R	R	R	R	R	R* *	R	R
FZDZ MVD > 40µm	Icing Tunnels	G	G	R*	G	G	G	Y	Y	G	G Y *	G R*	G	G R*	G
	Codes	G	G	Y	G R* *	G	R	R	R	G	G Y * *	G	R* *	G	R
	Tankers	R	R	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FZRA MVD < 40µm	Icing Tunnels	Y	Y	R*	Y	Y	Y	Y	Y	G	R	R	R	R	R
	Codes	Y	Y	R* *	Y R* *	Y	R	R	R	Y	Y	G	R	G	R
	Tankers	R	R	R	R	R	R	R	R	R	R	R	R	R	R
FZRA MVD > 40µm	Icing Tunnels	R	R	R*	R	R	R	R	R	R	R	R	R	R	R
	Codes	Y	Y	R* *	Y R* *	Y	R	R	R	Y	Y	G	R	G	R
	Tankers	R	R	R	R	R	R	R	R	R	R	R	R	R	R

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Green (G)	This testing capability exists today and is suitable to be an element of a means of compliance, or is readily achievable based on current experience.
Yellow (Y)	This testing capability is possible, but has not been demonstrated, or there is limited or no validation.
Red (R)	This testing capability is unknown, or does not currently exist.
*	It may be possible to test small-scale installation effects, but large-scale installations are not currently feasible.
* *	Current 2-D capabilities exist with large droplet effects, but limitations exist in the use of 3-D codes for simulation of Appendix O effects.

Figure 2 Assessment of Appendix O Engineering Tool Capabilities (IPHWG Task 2, AC 25-28)

Gap # 2: Experimental Facilities Remain Unvalidated for Simulating Appendix O

Icing wind tunnels are an important aspect of airplane configuration development and certification, and continued improvements to these tunnels are of the utmost importance. Not only are icing tunnels needed for compliance demonstrations, but computational tools that also aid configuration design early in a program prior to certification rely heavily on validation data typically obtained from icing wind tunnel testing. As such, three of the four key areas identified in the IPHWG's SLD Engineering Tools Development Project Plan depended heavily on the use of experimental facilities to simulate SLD conditions, develop scaling methodologies, and develop instrumentation to measure SLD [14]. The use of icing wind tunnels had been recognized as a need for demonstrating compliance to the Appendix O icing rules via experimental and computational means [14], and this need is unchanged twenty years later as many of the gaps remain unaddressed, including the ability to reproduce SLD conditions in icing facilities to accurately produce ice shapes, develop validation data, and further develop the ice prediction codes.

Simulating both the Freezing Drizzle and Freezing Rain conditions described by Appendix O within icing tunnels has proven to be a challenging task. The challenge is high enough such that icing wind tunnel standards for Appendix O have not been developed due to the lack of understanding of the conditions themselves [23]. Of six wind tunnels that aimed to improve their Freezing Drizzle generation capabilities as part of the ICE GENESIS project, only one (CIRA-IWT) was able to make progress [24]. One result from previous icing tunnel testing is depicted in Figure 3, where Freezing Drizzle ice was accreted on a deployed slat and compared to analytical predictions. Results indicated that rough, thin ice accreted on the entire slat chord. (Not included in the report is mentioned of contamination that may or may not have accreted on the main wing element behind the slat. The aerodynamic implications of main wing element contamination were discussed in the previous section.) While a leading-edge device fully covered in ice is not likely to cause as severe an aerodynamic effect as ice on the main wing element, it is still anticipated that such accretions would cause a significant airplane-level effect on performance and handling qualities.

Without accompanying flight test data or icing tunnel validation, it is difficult to ascertain whether the experimental results are representative of Appendix O icing conditions. However, it is well-known that icing tunnels struggle to model physics associated with large drop icing at high speeds, typically due to practical limitations of the facilities such as model size, air speed, and atmospheric and droplet properties. In experiments conducted by various facilities, challenges associated with modeling large drop icing conditions include:

1. the trajectories of the particles can be seen to be heavily influenced by gravity and will impinge at an angle relative to the oncoming flow [25]
2. the thermal inertia of the droplets is so high that they can be upwards of 10degC warmer than the ambient temperature [25] [26]
3. the droplet velocity decreases significantly with diameter relative to the freestream [25] [26] [27]

To mitigate the issues of droplet trajectory, droplet temperature, and gravitational settling for Freezing Drizzle only, it has been theorized that a tunnel with a contraction length of 175m (~575ft) would be required [26] – an unrealistic task from a practical standpoint. The requirements for Freezing Rain would drive the contraction length to be even larger.

In addition to particle behavior within an icing tunnel, the droplet distribution and Liquid Water Content (LWCs) are also challenging to attain. Three tunnels with test sections large enough to accommodate some transport category airplane testing – Rail Tec Arsenal's (RTA) Climactic Wind Tunnel in Vienna, Austria; Centro Italiano Ricerche Aerospaziali Icing Wind Tunnel (CIRA-IWT) in Capua, Italy; and NASA Icing Research Tunnel (IRT) in Cleveland, Ohio in the USA – were surveyed for available data [28]. Available tunnel comparisons are shown in Figure 4 and Figure 5. These data are presented as "snapshots" because apart from IRT, the icing tunnels have not been fully assessed, and calibration work is ongoing. As such, data cannot be summarized for the same speed and in the case of the LWC comparisons, similar MVDs. However, these show the relative capabilities of these tunnels for simulating Appendix O icing. It is worth noting that the uncertainties in icing tunnel capabilities remain unquantified and should be understood before conclusions about the readiness of such tunnels are made.

The droplet distributions among all three facilities agreed reasonably well with Appendix O Freezing Drizzle, especially considering the flight test scatter from which it was developed, as shown in Figure 4. CIRA had not completed the tunnel calibrations for Freezing Rain, and no data was available from RTA for Freezing Rain with MVD less than 40μm. Two separate MVDs were required to cover the range of distributions for Freezing Rain with MVD less than 40μm within the IRT. The bimodal distribution of Freezing Rain drop sizes is challenging to obtain.

Though the tunnels' capabilities for Freezing Drizzle with MVD less than 40μm agreed reasonably well with flight test scatter, it can also be seen that Appendix C with a Langmuir D drop size distribution for 25μm MVD also fits within the flight test scatter up to approximately 80% of the cumulative mass (shown in Figure 6). As Appendix C overlaps with the smallest drop sizes within Appendix O, it is not surprising that the tunnels can reasonably attain the smaller drop sizes but deviate at the larger drop sizes. This overlap between Appendix C icing and Appendix O icing for drop sizes less than 40μm was also recognized when Appendix O was originally developed [29]; however, the concern for a lack of distinction between Appendix C and Appendix O was not clearly addressed and it was left to the manufacturers to determine the means to distinguish when the airplane was outside of the certified envelope [21]. Furthermore, there was acknowledgement that no clear mass distribution boundary could be defined [21].

Though the LWC capabilities summarized in Figure 5 were not determined at the same MVDs, speeds, and temperatures due to the availability of tunnel calibration information, it is useful for understanding the range of current state-of-the-art capabilities and the sensitivities to speed and pressure (in the case of CIRA-IWT). Depending on the specific MVD, tunnel speed, and temperature, the LWC attained for drop distributions with MVD greater than 40μm could be within a few percent of the regulatory requirement up to four times greater than the upper bound. Although valuable efforts are in-work to reduce the LWC at the IRT, no single icing tunnel facility has demonstrated the capability of modeling the entire Appendix O icing atmosphere.

Matching the droplet distribution and LWC with the Appendix C regulatory requirements is not always necessary provided appropriate scaling (also known as similitude) can be used. A 2008 examination of the application of scaling parameters used for Appendix C conditions to those for Appendix O [30] showed that for MVDs up to 190µm up to a speed of 200kts, similar methodology can lead to matching of unprotected ice shapes with what is expected in flight; however, various constraints limited the validation of the approach, including ensuring the stagnation freezing fraction was greater than 0.3 and total temperature should be below -2degC. As discussed previously, both warm and cold conditions are of interest with regards to unprotected ice shapes, and the scaling methodology did not address protected (usually heated) surfaces ice shapes. Furthermore, large LWCs can artificially thicken the water film and affect the interaction of the impinging/splashing droplets, thereby affecting the resulting water and ice mass [31]. Therefore, it is critical to initially match required LWC because the Appendix O tunnel condition scaling methods are still in their infancy. Additional research is needed to address these questions and develop a set of calibration standards for Appendix O icing within tunnels.

With regards to instrumentation, probes to measure droplet size, trajectory, and velocity in the test section have become more readily available, with various improvements still in work [25] [27]. However, droplet temperature has not been measured directly, and simulation-based estimates indicate significant deviation from the ambient temperature [25]. Additional work is needed to verify that droplets impinging on the model are truly supercooled.

While fundamental icing physics research in Freezing Rain for droplets larger than 40µm MVD should remain a high priority for icing wind tunnels, there is also a need for icing tunnels that can be used for airplane configuration and design. The tunnel test section size, achievable airspeed associated with its size, and ability to accommodate different ice protection architectures are important factors. Achieving adequate air speed is critical for matching droplet splashing effects [30]. Reasonable requirements for these factors may be extracted from existing icing tunnels used for Appendix C icing certification as a starting point. For example, RTA-IWT, CIRA-IWT, and the NASA IRT may be capable of accommodating large models, though further research may be required to determine if a minimum test section size (to accommodate the necessarily large model size) is needed to capture the real-world impingement extents. Lastly, tunnel capability in accommodating different ice protection architectures such as pneumatic air, electro-thermal, inflatable boots, etc. are necessary to address protected surfaces testing. All tunnels mentioned in this paper currently have this capability.

Other identified gaps for icing tunnels include a lack of understanding real-time cloud uniformity to ensure adequate uniformity across the test section, developing validation databases for computational models to address droplet physics behaviors such as mass loss [31], the inability to generate an ice shape resulting from a combination of Appendix C and O conditions as required by the regulations, and a currently un-quantified level of tunnel-to-tunnel variability due to not having a single facility that can model the entire range of Appendix O conditions.

With regards to accuracy needs for icing tunnels: While ARP5905A provides calibration, acceptance criteria, and procedures for icing wind tunnels, it is unknown how achievable such targets can or should be for transport category aircraft testing for Appendix O icing conditions, especially where even larger models would be required for certification to adequately capture the impingement extents. The standard itself states it does not provide recommended practices for creating Supercooled Large Drop (SLD) or ice crystal conditions, since information on these conditions is not sufficiently mature for a recommended practice document at the time of publication [23]. It also does not provide guidance on appropriate margins or acceptable uncertainty to consider around the regulatory requirements. For example: there is significant variability in the cumulative mass spectra collected from the in-situ flight testing for each sub-envelope in Appendix O (Figure 4) [29]. While the average of these datasets has been codified within Appendix O, the source data's large variability, combined with the difficulties in simultaneously fully supercooling the drops whilst achieving the regulatory droplet distribution and LWC, suggest that additional consideration should be given to relaxed distribution requirements (that still fall within the data scatter) in favor of improvements in the other parameters of interest.

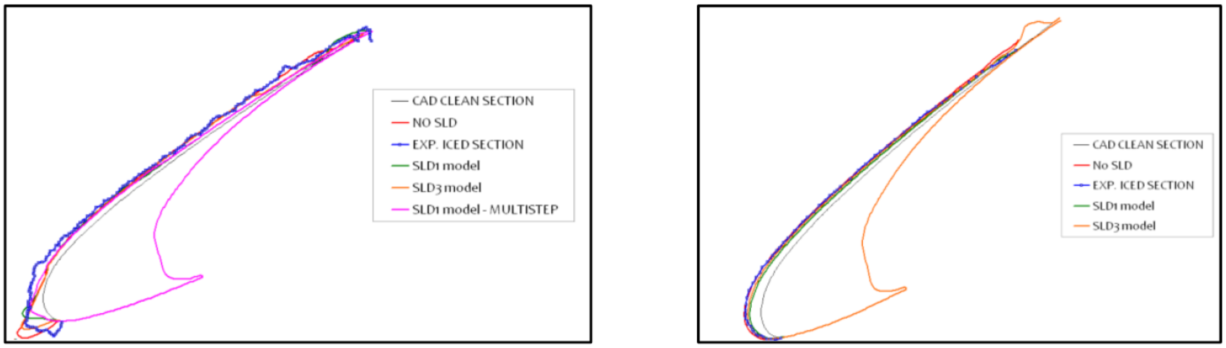

Figure 3 Experimental vs CIRA 3D Simulation Ice Accretion [20]

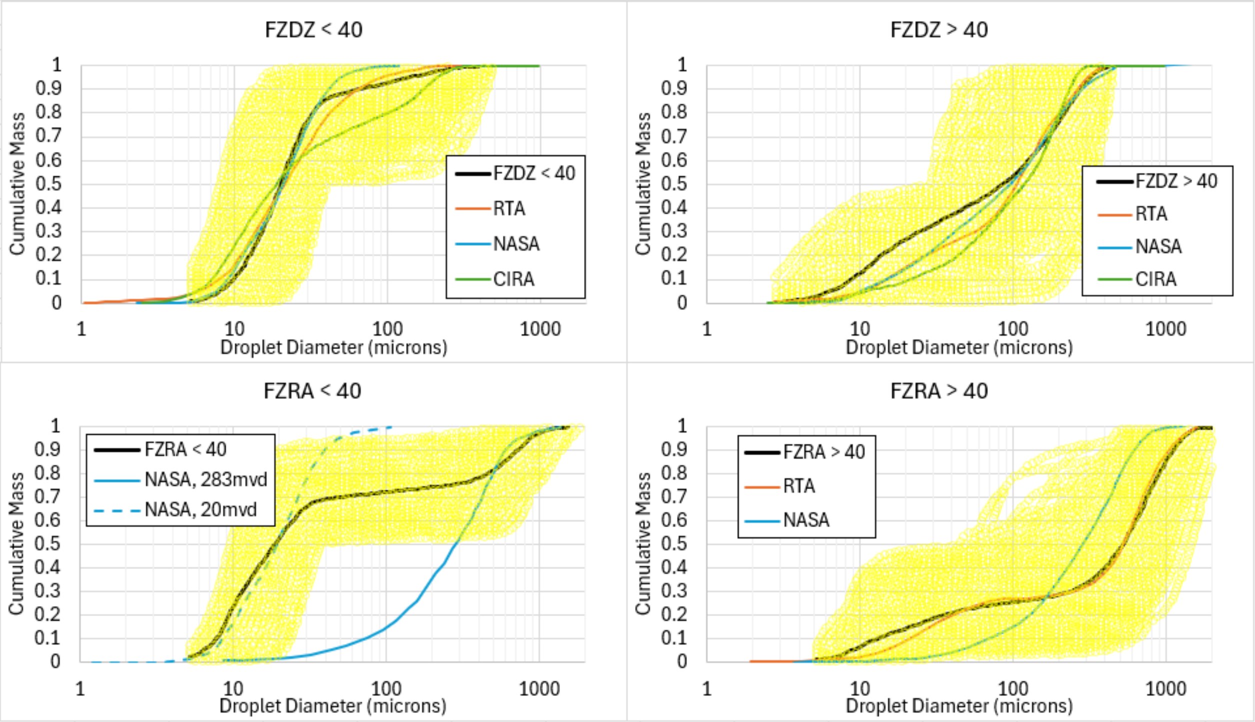

Figure 4 Snapshot of Achievable Drop Size Distributions Amont RTA, CIRA-IWT, and IRT, Compared to the Average Cumulative Mass Spectra from Appendix O (Black) Developed from Flight Test Points (Yellow) [29]

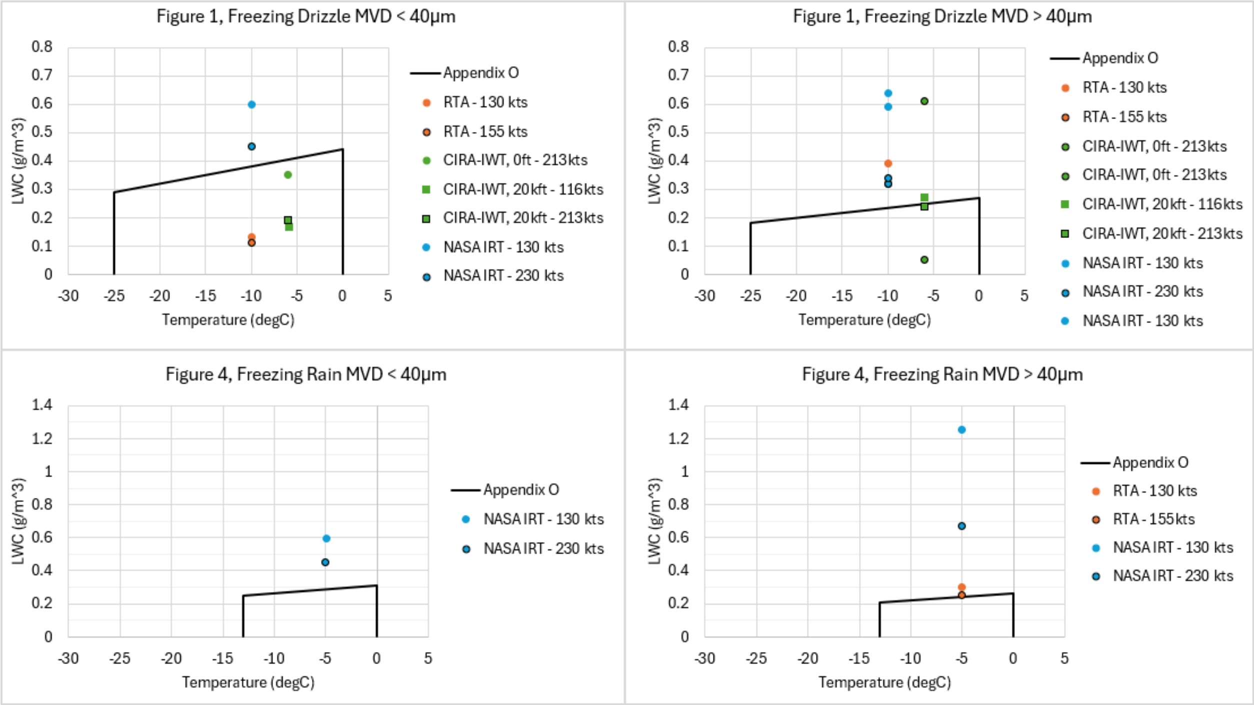

Figure 5 Snapshot of Achievable LWCs Among RTA, CIRA-IWT, and IRT

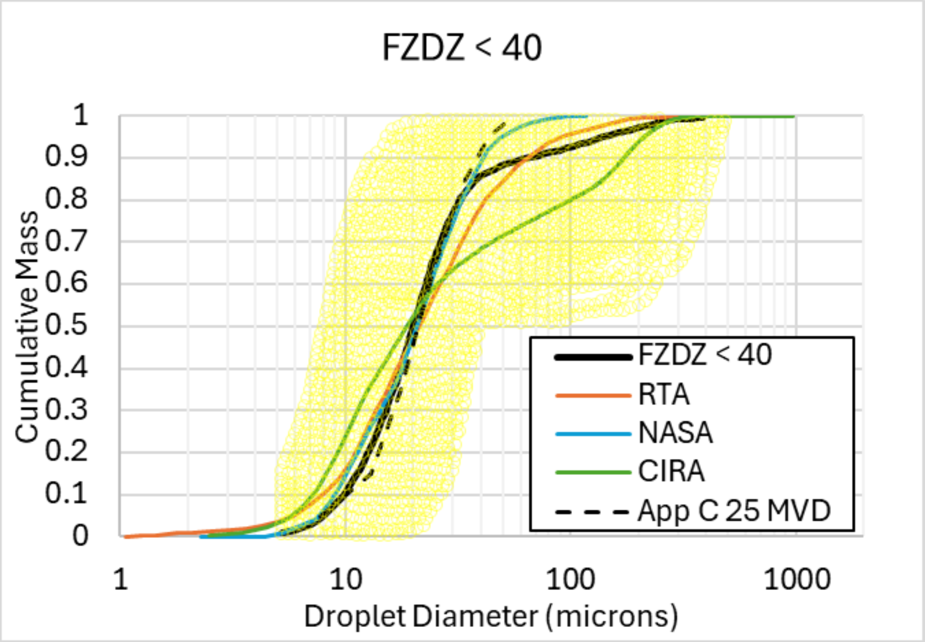

Figure 6 A Comparison of Appendix C Drop Sizes (using a Langmuir D Distribution at 25µm MVD) with Appendix O Freezing Drizzle Less than 40µm

Gap # 3: Encounter Scenario Complexity and Severity

In addition to the technical challenges associated with analytically or experimentally predicting in-flight Appendix O ice accretions, an additional challenge exists with respect to the complexity and severity of the Appendix O requirements themselves. Unlike the relatively straightforward scenarios for airframe ice accretions specified in Appendix C Part 2, the airframe ice accretions specified in Appendix O Part 2 require combinations of various types of ice from both Appendix C and Appendix O using specific operational assumptions. For example, below is a comparison of the scenarios required to develop a landing ice shape for Appendix C (Part 2(a)(6)) and Appendix O (Part 2(b)(4), assuming certification to 25.1420(a)(2) – operating safely in a portion of Appendix O), with minimal changes to the wording for readability:

Appendix C Landing Ice (Part 2(a)(6)) consists of the combination of:

1. Holding ice (Part 2(a)(4)) – Critical ice accreted during the holding flight phase specified by the applicant,
2. Approach ice (Part 2(a)(5) – Critical ice accreted following exit from the holding phase and transition to the most critical approach configuration specified by the applicant,
3. Landing ice (Part 2(a)(6) – Critical ice accreted following exit from the approach phase and transition to the most critical landing configuration specified by the applicant.

Appendix O Landing Ice (Part 2(b)(4), assuming certification to 25.1420(a)(2) – operating safely in a portion of Appendix O) consists of the combination of (in order of description):

1. Approach ice (Part 2(c)(5)(i)) – Critical ice accreted during a descent from 7,000 ft (in the case of Freezing Rain),
2. Approach ice (Part 2(c)(5)(i)) – Critical ice accreted during a descent from 2,000 ft above the landing surface in the cruise configuration.
3. Approach ice (Part 2(c)(5)(i)) – Critical ice accreted during a transition to the approach configuration.
4. Approach ice (Part 2(c)(5)(i)) – Critical ice accreted from flying for 15 minutes at 2,000 ft above the landing surface,
5. Landing ice (Part 2(b)(4)(i)) – Ice accreted during a descent from 2,000 ft above the landing surface to a height of 200 ft above the landing surface with a transition to the landing configuration,
6. Pre-detection ice (Part 2(b)(5)) – The ice based on the more critical of the Appendix C pre-existing ice or ice from Appendix O Part 1 in which the airplane is approved to operate prior to encountering the conditions requiring an exit, plus the ice accumulated during the detection time,
7. Pre-detection ice (Part 2(b)(5)) – The above plus two minutes,
8. Landing ice (Part 2(b)(4)(i)(B)) – Ice accreted during an exit maneuver, beginning with a minimum climb gradient required by CS25.119/14CFR 25.119, from a height of 200 ft above the landing surface through one cloud in the critical icing conditions defined in Appendix O Part 1,

9. Landing ice (Part 2(b)(4)(i)(B)) – The above plus one cloud in the continuous maximum icing conditions defined in Appendix C

Similar examples can be shown for other ice accretions and flight phases.

Not only are the Appendix O airframe icing scenarios more prescriptive than that of Appendix C for the same phase of flight, the operational behavior of the airplane is also prescribed. As most current engineering computational tools assume static flight conditions, the ability to accurately model continuously changing or dynamic maneuvers has not been demonstrated or validated. Additionally, there are no validation data showing the accurate computational prediction of Appendix C ice accreting on top of Appendix O ice (or vice-versa), especially with regards to boundary criteria for roughness within CFD, so it is unclear how an applicant would generate such an ice shape without significant engineering judgment, excessive conservatism, and certification risk. Future research is needed to define an appropriately representative engineering standard that can be practically applied using current state-of-the-art technology.

It is also important to note that the current implementation of the “Detect-and-exit” (D&E) compliance path provided by CS 25.1420(a)(1)/14 CFR 25.1420(a)(1) and CS 25.14020(a)(2)/14 CFR 25.1420(a)(2) poses several issues:

- 25.1420(a)(1)(ii) requires exiting *all* icing conditions if Appendix O icing is encountered. The true impact on the air transport system and safety of such a limitation is unknown, but considering that single aisle, widebody, and freighter airplanes alone accounted for over 90% of the global fleet in 2023 [22], regular mass diversions around busy airports (where there currently is none due to Appendix O icing) is a significant concern. This would not only impact the global air traffic network but may also lead to diversions where significant ice accretions remain on critical areas for longer than is necessary; instead, the safest procedure may be to land as soon as possible. Additionally, the human factors implications of having to divert during an already elevated workload situation should be assessed.
- Instituting D&E on a new large transport airplane would be a disadvantage relative to older designs as it would introduce additional restrictions not currently implemented or necessary. This not only leads to a perceived lowering of safety standards on the new aircraft but also discourages airlines from improving the sustainability of their fleet.
- The overlap between Appendix C and O for drop sizes less than 40μm is a challenge for detection. This lack of distinction was recognized when Appendix O was originally developed [29], but was not clearly addressed. Rather, it was left to the manufacturers to determine a reasonable method of discrimination. This decision has the ramification of increased conservatism in ice detection design, potentially resulting in unnecessary diversions and significant operational inefficiencies – counterproductive to both safety and sustainability.

There has been recent acknowledgement that the critical holding condition for Appendix O certification is not rational and does not provide an appropriate level of severity, as it is uncommon in the ATC environment today to hold for 45 minutes, let alone in icing, especially in Appendix O conditions. An important consideration in this regard is the level of difficulty associated with developing the Appendix O icing envelope. As documented in DOT/FAA/AR-09/10 [29], of the 48,301

30sec in-flight datapoints captured, 5% were used to develop Appendix O. Thirty second intervals were chosen because it represented a short averaging scale and would improve the statistical significance of the results. From these datapoints, different averaging intervals of 30sec, 60sec, 120sec, and 300sec averages that corresponded to 3, 6, 12, and 30km, respectively, normalized to 0degC, were used in conjunction with extreme value analysis to compute the 99% Liquid Water Content (LWC) values leading to the final Appendix O envelopes.

While there is general confidence that the Appendix O environment has been reasonably characterized, several challenges arise when attempting to develop means of compliance for transport category airplanes:

- Compliance to Appendix O requires the consideration of 45min of holding in conditions (per Appendix O Part II(b)(2)(iii)) that were generated based on datapoints not exceeding 5min (300sec). While there have been observations that Freezing Rain conditions can have a relatively long lifecycle due to typically being driven by synoptic features like large-scale fronts [32], such cloud sizes and durations have not been measured and compared with the characteristics of Appendix O. It is worth recalling the relative difficulty in finding Appendix O icing – of the 48,301 30sec in-flight datapoints, 2,444 observations were usable. Of those observations, 640 datapoints were used to develop the portion of Appendix O for drop sizes larger than 40μm. This represents approximately 1.3% of the total number of 30sec in-flight datapoints attained over all the flight test campaigns. It has therefore been inferred that the 45min holding time was not based on the meteorological data, but solely due to a desire for commonality with Appendix C guidance.
- In-situ measurements for drop diameter distributions varied significantly. While it was reasonable to use the average of these datasets, the use of the average distribution obviously does not necessarily correlate to any of the flight conditions observed in flight. This provides context regarding accuracy needs and what a reasonable representation of the resulting ice accretions should look like.

Further research into the development of a more rational encounter scenario should be conducted and could include statistical evaluation of both atmospheric data and real-world operations to create a framework that provides a practical and quantifiable means of addressing the safety concern [1].

Gap # 4: Flight Testing, Whether via Natural Icing or Icing Tanker, is Impractical

Finding natural SLD conditions that are sustained and are similar enough to the critical portions of Appendix O is significantly more challenging than Appendix C conditions. During the flight test campaigns that specifically targeted SLD conditions in support of Appendix O development, around 400 hours (48,301 30sec in-flight observations) of in-flight icing conditions were obtained, yet only 5% of the in-flight observations were deemed useable for the development of Appendix O [29]. As it was necessary to employ an extreme value analysis to produce the final Appendix O envelope, critical Appendix O icing conditions would be even more difficult to find for the sustained time required by the regulations for the purposes of certification flight testing.

It is worth noting that a major reason behind the relatively low number of in-flight observations that led to the development of Appendix O (5% of in-flight observations) was due to presence of ice crystals [29]. As ice crystals can significantly skew the drop size distribution, great care was taken to identify and remove the effects when developing Appendix O. It has also been seen in research that approximately 40 percent of icing condition events consist of coexisting liquid water drops and ice crystals [33]. These results indicate that ice crystals occur commonly in liquid water icing conditions, reaffirming the difficulty in finding Appendix O icing conditions, let alone critical conditions without ice crystals for extended periods of time.

Though criteria were developed for filtering ice crystals during the development of Appendix O [29], a standard has not been formalized for allowable ice crystal concentrations during certification or research flight testing. As ice crystals can erode ice accretions [34], it is important to understand the balance of acceptable ice crystals in the environment that will minimally impact critical ice accretions without undue difficulty in finding critical icing conditions. Existing guidance simply directs applicants to take care to account for these ice crystals and use the proper equipment [35].

There is little to no known publicly available research from using tankers to simulate SLD icing conditions for transport category aircraft despite the large amount of usage immediately following the crash of American Eagle Flight 4184. Most testing appeared to be proprietary in nature and focused on pass/fail criteria for flight in SLD rather than dedicated research into the ice accretion characteristics. Some attempts have been made or there were some inadvertent SLD conditions produced during such testing; however, the difficulties in producing the conditions necessary (similar to the difficulties for icing wind tunnels), the difficulties in gleaning useful validation information such as ice shape size, shape, and roughness, and the expense of an entire flight test campaign make tanker testing difficult to justify. Icing tanker testing was acknowledged as possibly producing larger ice build-ups and different ice shapes than those observed in natural icing conditions of Appendix C icing [29]. Additionally, the US Air Force KC-135 Icing Tanker (now retired, with no known replacement) was only able to simulate a portion of the freezing drizzle envelope [4]. Considering these factors, the usefulness of tanker testing would therefore be limited to qualitative assessments for a subset of the Appendix O environment at best.

Gap # 5: Detection and Discrimination

Although advancements have been made towards the ability to discriminate between Appendix C and Freezing Drizzle icing conditions, further work is necessary before these technologies can be deployed on commercial aircraft. Challenges that remain include:

1. Freezing Rain: Flight test campaigns as part of the SENS4ICE project were able to evaluate various conditions detectors and increase the Technology Readiness Level (TRL) of such products; however, tests were not conducted in Freezing Rain [36], which were out of scope for the SENS4ICE project entirely [37].
2. Implementation and integration into airplane configurations: While detection and discrimination technology typically refer to the detectors themselves, the ability to reliably integrate and deploy this technology is an important factor to consider. As previously detailed in Gap # 2: Experimental Facilities Remain Unvalidated for Simulating Appendix O, a single flight may encounter icing conditions that can fall into either the Appendix C or Appendix O envelopes. These conditions may also fall within the known scatter of drop size distributions, not attain the critical LWCs, or present any combination of these factors. Additionally, as there is significant overlap between Appendix C and Appendix O drop sizes for FZDZ < 40μm as shown in Figure 6, it is challenging to determine how to discriminate between C and O clouds when the droplet sizes are similar or equal. This complexity creates significant challenges in accurately determining the in-flight atmospheric conditions, underscoring the need for comprehensive solutions that address both detection capabilities and the practical integration of these technologies into operational environments.
3. Droplet physics: The behavior of the detector or discriminator in the presence of an airplane is unknown. As such, further research is necessary to understand how the local flow can affect droplet behavior, especially if droplet breakup could lead to an artificially low concentrations of Appendix O drops impinging on the aircraft surface.
4. Calibration: Due to the difficulties of icing wind tunnels to reproduce Appendix O Freezing Rain conditions, there is corresponding difficulty in developing improved detectors and calibrating those that are being developed. Furthermore, while AS5498A provides requirements for detection of icing conditions, challenges have been identified relative to detection thresholds, particularly for low LWCs (less than 0.05 g/m3) [38], that should continue to be considered.

Continued research and development into robust and accurate discriminators that can alert crews for flight into Appendix O icing conditions are needed to facilitate Detect-and-Exit compliance, or certification to only a specific portion of the Appendix O atmosphere. Unrestricted operations would also benefit from these types of detectors, as other means to comply with the regulations may depend on an in-situ understanding of the natural environment (for example, performance limitations at the arrival airport).

Conclusions

The certification rules for Part 25 transport category airplanes for Appendix O icing conditions, particularly those concerning drop distributions with MVD greater than 40 μm, currently preclude certification of innovative and sustainable aircraft designs. As the aviation industry strives for climate neutrality and net-zero greenhouse gas emissions by 2050, it is imperative to identify the existing research gaps that hinder compliance with the requirements outlined in CS 25.1420/14 CFR 25.1420, and either close those gaps or find alternate means of addressing the airplane-level safety issue if addressing the gaps directly is not practical. The analysis presented herein has revealed critical areas where focused research and development efforts are necessary to ensure safe operations in complex icing environments. Key gaps identified include:

- Validated computational and experimental capabilities for both protected and unprotected surfaces for Appendix O icing do not exist. This precludes the ability to use these tools for configuration development and certification.
- Existing, state-of-the-art tools currently predict substantial aerodynamic degradation due to SLD ice accretions. Use of these predictions for Certification may lead to significant increases in operating speeds compared to the existing in-service fleet, to the point where these faster speeds would themselves lead to a reduction in safety.
- No research has been found that could be used as validation for deployed surfaces, heated surfaces, or on aircraft of the size and speed representative of large transports.
- Specific gaps for experimentally modeling large drop conditions in icing tunnels include:
    - The test section size may be insufficient to model the real-world impingement limits, both from a physical standpoint and also with respect to the size and uniformity of the cloud
    - The test section air speed may be too low to model real-world splashing effects.
    - droplet trajectory and velocity may significantly deviate from the oncoming flow.
    - The droplets may not be truly super cooled upon reaching the test section.
    - The LWC attained for drop sizes greater than MVD of 40μm can be up to four times greater than the upper bound of Appendix O
    - validated scaling methods and calibration standards for both protected and unprotected ice shapes in large drop icing conditions do not exist.
- The Detect-and-Exit certification path requires exciting *all* icing conditions if Appendix O icing is encountered, which is of significant concern for the stability of the mass transportation system and would discourage airlines from improving the sustainability of their fleet.
- Having natural icing flight test plays a significant role in the certification process is impractical given the difficulty in finding sufficiently representative atmospheric conditions.
- Certification reliant upon flight test and engineering judgement is impractical as data are needed data early in the design phase to ensure the airplane-level effects are considered and mitigated.

- Icing tankers that can produce droplet clouds representing the full Appendix O environment do not exist, further precluding the ability to use full-scale flight testing as a means of certification.
- Viable means to discriminate between Appendix C and O conditions, or between different portions of Appendix O, do not exist. Discrimination of drop sizes less than 40µm where significant overlap between the Appendix C and O envelopes exists is especially challenging.

The following should be considered when attempting to address the gaps highlighted in this paper:

- As addressing each gap outlined herein is expected to be a significant undertaking, the MICG has developed an alternate, pragmatic approach to enable the safe certification of innovative aircraft designs that should be considered in the near term while SLD ice prediction technology continues to mature [1].
- Given that large transport aircraft are responsible for a gross majority of greenhouse gas emissions in the aviation sector, it is of the utmost importance that future research be tailored to include the systems, scale, and flight conditions common to these configurations in addition to those of smaller transports if meaningful progress towards aviation sustainability is to be achieved.
- Although the Twin Otter does not represent the size and speed of large transport aircraft, developing comparisons of numerical simulations with the flight and IRT results should be conducted as it would be a valuable initial datapoint from which to gain a better understanding of the relative accuracy of the codes.
- Predicting the impingement limits, bulk mass, ice height, general shape, and gross airplane-level aerodynamic impacts, rather than attempting to match small-scale features such as feathers and scallops, should be the goal for tools that can be used for Certification to Appendix O.
- Future calibration and validation of existing experimental facilities should consider:
    - If the test section sizes, airspeeds, and cloud uniformity conditions are sufficient to capture the real-world impingement extents of model’s representative of large transport aircraft.
    - If the droplets impinging on the model are truly super cooled
    - How the droplet trajectory and velocity deviate from the oncoming flow, and if corrections can be developed.
    - Development of validated scaling methods and calibration standards for both protected and unprotected ice shapes in large drop icing conditions.
    - Development of validation databases for computational models to address droplet physics behaviors such as mass loss.
- Consideration should be given to relaxed droplet size distribution requirements (that still fall within the flight test data scatter) in favor of improvements in other parameters such as LWC, droplet temperature, and the resulting overall airplane-level aerodynamic effect.
- Appropriately representative engineering safety standards, or alternate means of compliance, should be defined as being practically applied using current state-of-the-art technology. This could include:

    - Development of more rational encounter scenarios via statistical evaluation of both atmospheric data and real-world operations
    - Generalized, surrogate ice shape definitions applied via MoC to ensure safety with guidance around practical application, allowing time for direct compliance methods to mature.
    - Other practical and rational ways to evaluate D&E from conditions determined to be unsafe via Airplane Performance Monitoring or gross discrimination.
- Continued research and development into robust and accurate discriminators that can alert crews for flight into Appendix O icing conditions is needed to facilitate Detect-and-Exit compliance, certification to only a specific portion of the Appendix O atmosphere, and unrestricted operations.

Addressing these research gaps, or considering alternate and more pragmatic means, is essential to enable successful certification of innovative aircraft designs capable of operating safely in Appendix O icing conditions. By prioritizing these initiatives, the aviation industry can not only enhance safety and performance but also contribute significantly to achieving sustainability goals. The path forward requires collaboration among manufacturers, regulatory authorities, and research institutions to ensure that the next generation of aircraft addresses the safety concern in an actionable and practical manner.

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