Engine Icing Working Group
Industry Guidance on Means of Compliance for Engine Operation in Ice Crystal Icing

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1. Introduction

The FAA sent a letter to the Aerospace Industries Association (AIA) on 21 November 2016 requesting a retasking of the Engine Icing Working Group (EIWG). The retasking request was for the EIWG to provide recommendations for developing guidance material to assist applicants with showing compliance to 14 CFR §33.68. The EIWG responded to the FAA via a letter sent by the Aerospace Industries Association on 1 June 2017 and agreed to the following tasks proposed by the FAA:

- Identification or development of ground facility ICI simulation and test techniques, representative of atmospheric conditions that cause these engine events.
    - The EIWG will provide recommendations for incorporation into the FAA guidance material (AC20-147A) regarding ice crystal icing engine testing at a ground test facility, with regards to ground test scaling and other key considerations. The recommendations will consider knowledge gained from exposure to recent ICI in-service events.
- Development of appropriate turbine engine or component tests and analyses of representative environmental exposures of ICI conditions, and
    - The EIWG will provide recommendations for development of appropriate simulated altitude tests for full engines, rigs and components. The recommendations will consider knowledge gained from exposure to recent ICI in-service events. The EIWG will focus on recommendations specific to the engine operation during testing and matching relevant atmospheric conditions at altitude. In addition, the EIWG will provide recommendations for development of appropriate analytical methods and associated validation requirements, and conservative assumptions, as appropriate.
- Proposed changes to existing advisory materials that would incorporate the knowledge gained from exposure to recent ICI in-service events, associated test techniques, and experimental data.
    - The EIWG will address this item by providing recommendations for updating Advisory Circular AC20-147A. These recommendations will include output from items (1) and (2), in addition to updates to the Susceptible Features and Mitigation Features lists based on knowledge gained from exposure to recent ICI in-service events.

The tasks that the EIWG agreed to focused on the engine operation during testing and matching relevant atmospheric conditions at altitude. As such, the EIWG did not consider test facility requirements, design or calibration. The EIWG suggests that such work on test facilities be considered for investigation by another working group, such as the AIR6189 (Reference 11) activity led by the SAE EG-1E committee.

In order to limit the workscope further for the EIWG, the following types of engine events were addressed in the following document:

- Mechanical damage
- Flameout
- Surge
- Rollback

While engine probes are also susceptible to ICI, engine probe icing was determined to be tangential to the engine failure mode scenarios. Also it is thought that this would best be addressed by a group primarily consisting of probe manufactures and probe test facilities, with assistance from engine manufacturers. For further information on engine probes see the AIA's Engine Icing Working Group Report on Engine Probe Icing (Reference 13).

In general, the EIWG also limited the scope this document's applicability to turbofan engines. However, some sections are applicable to other types of turbine engines; please refer to the individual sections for specific applicability statements.

Each of the following Sections were developed by the EIWG within subcommittees in order to address the retasking request. These sections provide recommendations to help Airworthiness Authorities and applicants determine if and how various means of compliance may be used for demonstrating compliance with the engine ice crystal requirements defined in 14 CFR §33.68 and §25.1093.

The FAA, EASA & TCCA has participated on this AIA committee; however, conclusions stated within this report do not necessarily represent the views of the authorities. Once this report is submitted to the FAA, the FAA has stated that they will review the final conclusions, respond to the recommendations and decide as to how to proceed.

It is highly suggested that the applicant read through the entire set of industry recommendations before proceeding; different sections may apply to each unique applicant as it is possible to use a combination of means of compliance to achieve certification.

2. Background

Numerous aircraft engine power loss events have been linked to ingestion of ice crystals at high altitudes. Although postulated back into the 1950's, this correlation was significantly strengthened after a review of commercial aviation data from the 1990's to mid-2000's where 62 incidents were identified to be associated with Ice Crystal Icing (ICI)(Reference 1). It is now accepted that ice crystals entering the engine core can accrete on the warm surfaces of the compressor which can result in engine rollback, flameout and/or mechanical damage (Reference 1, 2). A similar phenomenon can be seen with air data probes which can also foul in ICI conditions. Starting from approximately 2008, significant advances in testing capabilities and instrumentation in the ICI field have enabled research to better understand the ICI accretion phenomenon. This section discusses the current state of that knowledge to provide the reader with a background understanding of the ICI accretion phenomenon. A detailed bibliography is provided at the end of this document, along with an outline of the nomenclature in Table 1.

Table 1: Nomenclature Associated with ICI Literature

Term	Description
%melt	Mass percent that is liquid water in a mixed phase flow
AOA	Angle of attack
DOF	Depth of field
DvXX	Diameter below which XX% of spray volume occurs
FOV	Field of view
Glaciated	Air laden with fully frozen ice particles, i.e. no liquid water
ICI	Ice crystal icing
IKP	Iso-kinetic probe

Term	Description
IWC	Ice water content (g/m3)
LWC	Liquid water content (g/m3)
M#	Mach number
Mixed phase	Combination of liquid water and ice particles in the air. The liquid water can be melt on the ice particles or separate drops.
MMD	Median mass diameter, diameter below which 50% of spray mass occurs
MVD	Median volume diameter, diameter at which 50% of spray volume occurs
MW	Multi-wire probe (aka multi-element probe)
Po	Total pressure
PIV	Particle imaging velocimetry
PSD	Particle size distribution
RH	Relative humidity
SWD	Supercooled Water Droplets
TAT	Total air temperature
TWB	Wet-bulb Temperature
TWC	Total water content (g/m3)

2.1. Significance of liquid water (i.e. %melt)

Dry ice particles have not been observed to stick or accrete to unheated surfaces in any significant quantity to cause aircraft performance degradation. This is why ice crystal conditions are not an issue for external, unheated surfaces such as the fuselage. The ICI accretion phenomenon requires liquid water for accretion to occur. The presence of liquid water, typically due to the partial melting of ice crystals, leads to a mixed-phase condition. Research has shown there can exist an accretion plateau related to the amount of ice cloud that melts (%melt) – see Figure 1. Too little water (low %melt) and the accretion will not nucleate and grow as it is too dry; too much water (high %melt) and the surface will run wet but not be able to nucleate and grow, provided the water doesn't supercool. Currie et al (Reference 3, 5) demonstrated an accretion plateau by mixing a fully glaciated ice particle laden airflow with a heated airflow to create a natural melt of the ice particles as would occur in the flow path of an engine.

In test facilities, the %melt of the injected cloud is typically controlled by varying the temperature and also the humidity of the air (Reference 28, 29). By increasing the humidity, the wetbulb temperature1 (further described below) was raised and the %melt increased without changing any of the other test parameters2. Test articles and airfoils were exposed to these partially melted ice clouds to observe when and how much ice would form on the surfaces, e.g. (Reference 3, 5, 8, 9, 7, 10). In these works, the growth rate was measured at the stagnation region of the test articles using video recordings of the leading edge (LE) growth of the ice accretion versus time. Knowing the collision efficiency at the stagnation region allows the maximum growth rate to be calculated (i.e., growth rate if all particles hit and stick). The ratio of the actual measured growth rate to this calculated theoretical maximum gives the sticking efficiency. Figure 1 shows a representation of how sticking efficiency or icing severity varies with %melt (ratio of LWC to TWC) resulting in an accretion plateau.

The %melt is a difficult measurement to make in a mixed-phase cloud. Typically, the TWC is measured at the tunnel centerline (same flow line as the stagnation point where the growth was measured) and the LWC is measured using a heated element probe described in Reference 6. The measurement of LWC has significant uncertainty as it likely does not sense the entire water film on an ice particle and it also has a false response to the ice (Struk P. T.-C., 2015).

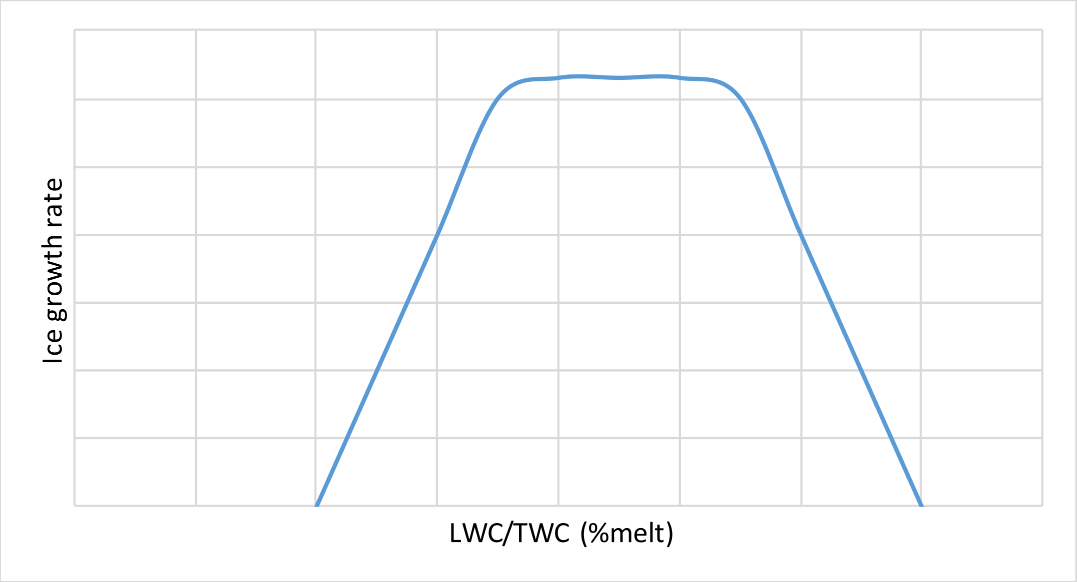

Figure 1: Representation of ice growth rate with liquid-to-total water content ratio.

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[1] The wetbulb temperature is the temperature the ice particle “feels” adding in the evaporative cooling effect.

[2] It is important to point out that in engine-icing test facility there is a thermal coupling between the airflow and the cloud since ice particles and/or water droplets are injected upstream of the test article (Reference 48,49). This means that the cloud-off conditions like air temperature and humidity may change by the time they reach the test article once the cloud is activated. A common observation is a reduction in TAT and increase in humidity due to evaporation with wetbulb temperate remaining roughly constant. Such changes should be accounted for when interpreting test results.

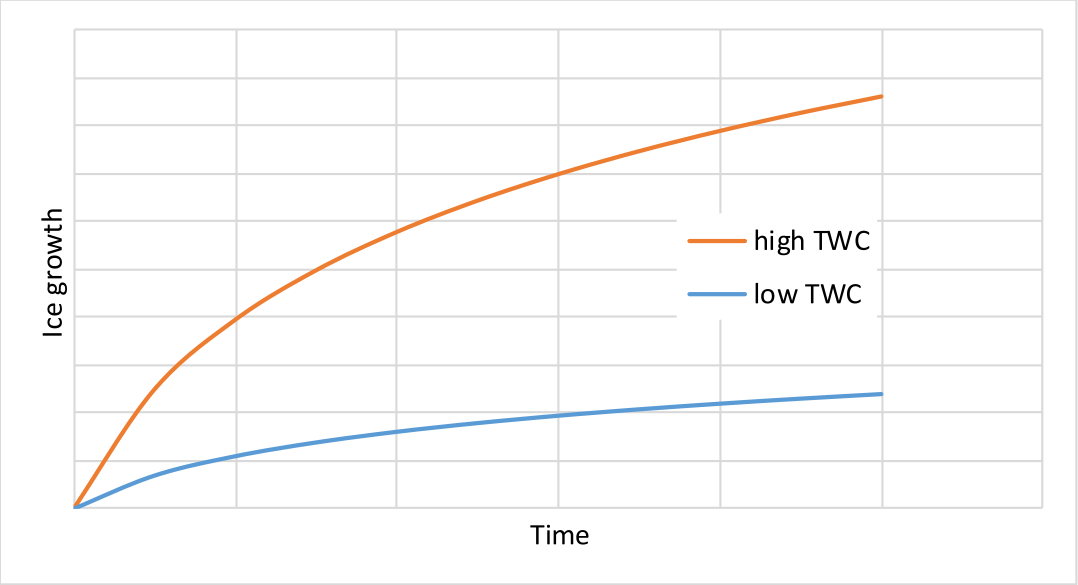

Figure 2: Representation of ice growth versus TWC

2.2. Significance of total water content

Total water content (TWC) is the measurement of the concentration of ice and water in the airflow. Typically the units are in mass of ice in a given volume of dry air, e.g. g/m3. Experiments have shown that the accretion growth rate increases with TWC with a representation of this phenomenon shown in Figure 2 (see Reference 8 for an example of a component-test). In this type of testing, the growth rates are measured from video of the ice accretion at the LE of a test article. In this example, the TWC roughly doubles but the growth rate is more than triple showing the sticking efficiency can change with TWC. It is postulated that this increase in sticking efficiency is due to a flux effect where at higher TWC's, there are more particles that bounce and interfere with incoming particles to slow them down making them more likely to accrete. Although reasonable and a phenomenon known in the grit blasting industry, there is limited ICI accretion data to confirm this.

These experiments also showed a minimum TWC below which, growth would not occur for a wetbulb temperature >0 ºC. However, in these non-growth conditions where the surface runs wet from melting ice, the surface temperature at the region of accretion was the same whether it was an accretion event or not (Reference 9). Therefore, temperature cannot be used on its own to identify when accretion occurs.

2.3. Significance of wetbulb temperature

The formal definition of wetbulb temperature is the temperature of a wet surface from which water is evaporating but is otherwise adiabatic. The wet-bulb temperature is a function of the surrounding air temperature (also known as the dry-bulb temperature), air pressure, and moisture content (i.e. relative humidity). The term "local" sometimes is used to qualify wetbulb temperature and refers to a specific location in the engine where all three of these parameters are known and the local wet-bulb temperature can be calculated. The wet-bulb temperature is calculated by equating the rate of convection heat transfer to a surface with the heat loss by evaporation. The equations and further assumptions used to calculate wet-bulb temperature appear in academic text books as well as the engine-icing literature and the interested reader is directed there (e.g. Reference 10).

A major source of liquid water inside the engine is from the particles melting due to heat transfer with the air. However, this type of melting can only occur if the wetbulb is above 0 ºC. The wetbulb temperature can be thought of as the temperature of a wetted or iced surface (including water droplets and ice particles themselves) achieved through evaporative cooling. If all the liquid water comes from melting due to heat transfer with the air, then growth can only occur downstream of location in the engine where the wetbulb is above freezing. This type of ice crystal icing has characteristics of wet-snow or slush and can have periods of growth and shed due to the loosely adhered ice. However, there are other potential sources of melt that are outlined in Section 2.5.

Accretion is possible if the wetbulb is below freezing and if there is melt from other sources, e.g. heated surfaces both upstream and/or at the accretion location. Another accretion scenario is when the flow accelerates dropping the wetbulb from above freezing to below with liquid water present. This later mechanism was demonstrated at higher M# (~0.6) tests (Reference 8). This type of growth is similar to supercooled liquid water accretion where growth starts immediately, is better adhered to the surface, and has a continuous type growth and not the grow-shed initiation common with wetbulb above freezing (Reference 9). A representation of both the continuous growth and build-shed icing is shown in Figure 3.

It is important to note that the wetbulb temperature change due to evaporation is magnified at altitude as lower pressures can increase evaporative cooling thus making it easier to lower the wetbulb temperature below the TAT. Furthermore, the rapidly warmed air inside a compressor can have a low relative humidity enhancing evaporation.

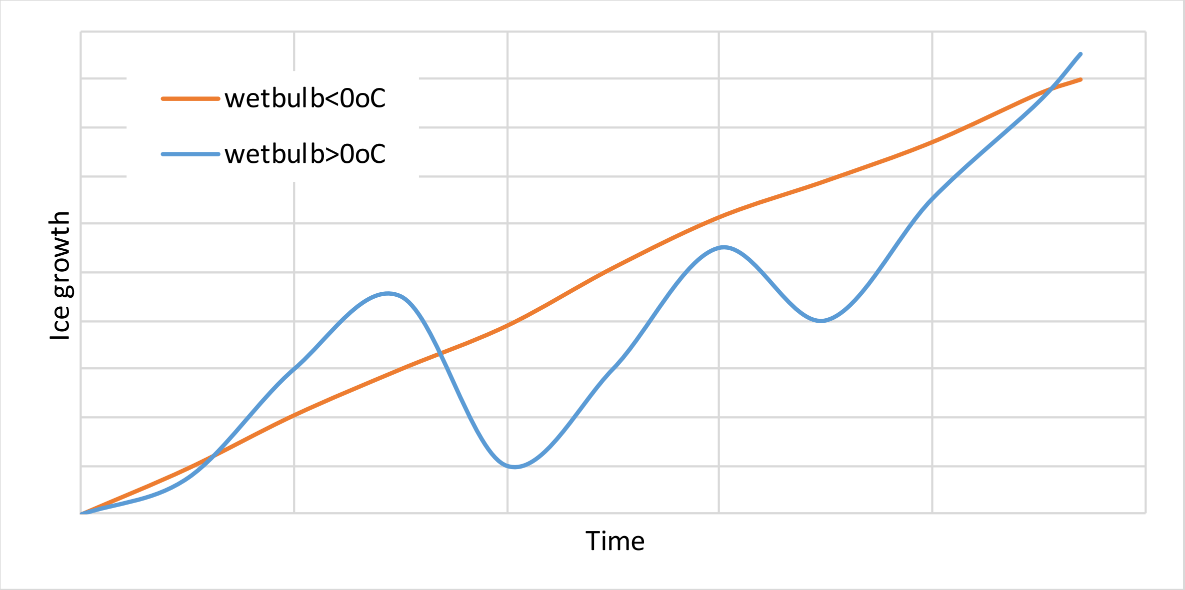

Figure 3: Representation of different ICI accretion growth characteristics for wetbulb above (grow-shed initiation) and below freezing (continuous growth)

Table 2. Test conditions for endwall bleedslot ICI accretion tests

Run	p_o [kPa]	Mach	To [C]	T_{wbo} [C]	IWC_i [g/m3]	LWC_i [g/m3]	Grind Config
13_244	44.8	0.25	7.5	1.0	17.0	0	A (small PSD)
13_277	44.8	0.25	7.9	1.4	17.0	0	C (medium PSD)
13_258	44.8	0.25	8.0	-1.8	4.5	3.0	A (small PSD)

2.4. Significance of Erosion

The sticking efficiency model developed by Currie can predict the growth rate and the geometry of the accretion (Reference 5, 8). However, the model is empirical and needs to be calibrated to the specific Particle Size Distribution (PSD) and a range of ICI conditions. Given that these models include an erosion term, it is expected that the growth rate would be affected by PSD due to the change in erosive characteristics with particle size, specifically that larger or faster particles would cause more erosion. A major implication here is that the PSDs and the local velocities in the engine need to be understood in order for appropriate sticking efficiency models to be developed and validated. In addition, morphology may have an effect on erosion but there currently is no known published data to quantify this effect. Fortunately, the range of PSDs and morphology that need to be understood may be small given that a high level of breakup is expected to occur in rotating turbomachinery upstream of the accretion sites although insufficient published data is currently available to confirm.

2.5. Correlating engine and environmental conditions

An overview of the key parameters that affect ICI accretion have been outlined. However, these generally refer to the local conditions at the accretion site. What is happening upstream to create that accretion condition is key and is very complex in a gas turbine compressor. To help in correlating the two, Table 2 outlines the key accretion parameters along with engine and atmospheric parameters that could potentially affect them. As discussed in the introduction, this synopsis is the current state of knowledge and as research continues in ICI, there will likely be additional information to augment what is provided here.

Table 3: Outline of critical ICI accretion parameters and the environmental and engine parameters that can affect them

Local Accretion Parameter	Environment or engine operating parameter
TWC	Freestream IWC concentration Freestream IWC distribution PSD-may affect ballistic characteristics and the ice cloud concentrating effects Operation that may change the concentrating effects (e.g. centrifuging)
LWC/TWC	Wetbulb (P/T/RH)-affects amount of melting caused by the air PSD-smaller sizes will melt more Upstream heated surfaces adding liquid water content Heat flux on accretion surface
Erosion	Aircraft and engine flow velocities that affect particle velocity PSD[3], i.e. larger sizes=more erosion Morphology
Surface Temperature at Accretion Site	Pre-cooling, e.g. LWC or low TWC's before TWC of concern attained, can cause accretion to initiate sooner so more accretion for fixed test time Geometry affecting local recovery temperature Heating or cooling from other side of accretion surface Transient, e.g. hot to cold on descent

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[3] PSD and morphology affects expected to be minor given the level of breakup expected in high speed rotating turbomachinery typically seen upstream of the accretion sites but insufficient published data available to confirm

3. Addressing Uncertainty in Means of Compliance

The certification demonstration should include a development of the appropriate points to test in a test facility. The points can be determined either by using a critical point analysis (CPA) or by other means such as a Design of Experiments (DoE) or service history of legacy designs.

Regardless of what method is employed, a top-level strategy in dealing with uncertainty is required. The uncertainty can be divided into three areas: in-service event data, test facility, and analytical tool uncertainty. In-service uncertainty is present when trying to understand the conditions an engine experienced on a flight event. These conditions include icing conditions such as Ice Water Content (IWC) concentration in the atmosphere, and the flight conditions including aircraft Mach number (M#), altitude and ambient temperature. Uncertainty also exists in determining the engine response to the atmospheric condition, such as the engine accretion location (or in some cases, when no ice accretion occurred). When using experience from legacy engine programs to apply to derivative and new engine programs, the uncertainty may increase because the engine differences should be assessed. Uncertainty is also present in the test facility and its replication of the natural environment. In all cases, if the uncertainty is large, additional validating analysis and/or data can be used to help reduce and characterize it for environmental threat level, operating conditions and engine effect and test cell engine response.

Generally, both specific and cumulative uncertainty can be addressed by either additional test data or the use of multiple analytical tools with varying levels of validation, or in some cases making conservative assumptions to address uncovered higher levels of uncertainty. An uncertainty assessment is typically done as a qualitative assessment and not quantitatively. Therefore, an expert knowledge of the environment and its impact on the engine is essential in making judgments in this qualitative assessment. The reason a qualitative assessment is best suited for assessing uncertainty is that there are many complex components to a compliance proposal, which includes not only the environment and its effect on turbine engines, but also current capability to model and simulate these effects. Therefore, the current state of the art knowledge and simulation capability lend themselves to a qualitative uncertainty assessment.

3.1. In-Service Event Data Assessment

Understanding aircraft and engine operating conditions at the time of any ice crystal icing encounter is critical for understanding ice crystal events. Detailed analysis of measured in-flight data, if available, will reduce the uncertainty levels. If the conditions of an encounter are not known, or for a new engine with no history, then a range of conditions should be considered for altitude, airspeed, temperature and engine speed which should encompass the actual weather and operating conditions and therefore drive down the uncertainty. However, additional conditions beyond a specific in-service event may need to be considered for testing, to assure a complete assessment of the engine in an ICI environment.

The environmental threat level can be characterized by several parameters shown in Figure 1. Ice Water Content (IWC) is a highly valued parameter and can be determined by (in order of more to less certainty):

- Measuring the IWC
- Using engine parameters to determine the IWC by matching the engine flight data cycle to flight data
- Assuming a threat using the Appendix D environment

In most cases, the IWC data is not available; therefore, it must be estimated or assumed. Using the engine cycle to estimate the IWC has more uncertainty than measuring IWC directly, however, engine cycle effects are typically very accurate, and the additional uncertainty can be characterized by performing a sensitivity analysis by varying cycle parameters and determining the variation in IWC that may need to be considered for testing. If the

IWC is unknown and needs to be assumed, Appendix D provides an environmental definition on what values to use, but this may result in increased uncertainty potentially requiring either additional test points, or conservative IWC values. This extra conservatism can be used to account for uncertainty in the atmospheric IWC.

In most cases, the accretion location is not known; therefore, it must be estimated or assumed. Using analysis in combination with some test data can be an effective strategy when trying to reduce levels of uncertainty. If the accretion location needs to be assumed, then selecting a location in the engine that is most critical for engine flameout, rollback, stall/surge or mechanical distress could be used, but this may result in either additional test points, or an overly conservative approach.

3.2. Accretion Location Uncertainty in an Engine

Using analysis in combination with some test data can be an effective strategy when trying to reduce levels of uncertainty. If the accretion location needs to be assumed, then selecting a location in the engine that is most critical for engine flameout, rollback, stall/surge or mechanical distress could be used, but this may result in either additional test points, or an overly conservative approach.

The effect of ICI on the engine can be characterized by several parameters. Accretion quantity and location is a highly valued parameter which can be determined by (in order of more to less certainty).

Accretion locations and levels in an engine can be assessed by:

- Measuring the ICI accretion quantity with instrumentation such as camera or other ice detection probes can provide a rough estimate of accretion thickness
- Using engine, rig and/or component tests if appropriate to determine likely accretion locations
- Using engine cycle model match to engine data to understand how the engine rematches from resulting engine blockage (accretion)
- Modeling the melting of ice crystals based on engine stage by stage conditions (e.g. inter-stage pressure and temperature from compressor stage loading calculations or from additional instrumentation) and targeting most likely melt ratio as the accretion location
- Use derivative model where the baseline model shows susceptibility with a known quantity and therefore assume the derivative model would also accrete the same quantity.
- Assuming worst case accretion locations and quantity in the engine resulting in additional conservatism.

In most cases, the accretion location is not known; therefore, it must be estimated or assumed.

3.3. Choosing Test Points to Address Uncertainty

Cumulative qualitative uncertainty should be considered when trying to replicate flight conditions. If a field event is not reproduced in a test cell, it does not necessarily point to deficiencies in the cell but could be due to accumulated uncertainties. The cumulative uncertainties can come from other sources in the understanding and modeling of the event. Other sources could include the understanding of the flight environment, imprecise analytical tools, unknown detailed engine cycle effects in ICI, and differences between the in-flight engine cycle to the cycle of engine in the test cell.

Uncertainty will exist when simulating flight conditions in a test facility. Since the test points may be based on flight event data, validation data described could be obtained during the certification test so that it is not a single point demonstration. After the validation data is obtained, any additional uncertainty that remains can be reduced by varying the test parameters. Field event data may be used on engines with a known field issue but also on a derivative engine and a new centerline engine, when applicable. On derivative and field engines, additional tests and analysis should be used to relate the field event data to the engine being tested. This analysis may consist of:

Atmospheric threat level studies to determine if the field event engine's aircraft flight envelope and engine's power range can be used to define areas of susceptibility of the derivative or new engine's intended aircraft installation envelope.

Engine threat level studies to determine if the field event engine's cycle characteristics can be used to define areas of susceptibility of the derivative or new engine's cycle characteristics.

Geometric/flowfield studies to determine if the field event engine's geometric and flowfield characteristics can be used to define areas of susceptibility of the derivative or new engine's intended geometric and flowfield characteristics.

The above analytical studies are defined in more detail in Section 4.

3.4. Installation Effects Discussion

The guidance in this document is focused on the engine turbomachine and hence will be the primary responsibility of the engine manufacturer. It is however the intent that it serves both 14 CFR §33.68 and §25.1093, i.e. that when an engine is found compliant to §33.68 according to the proposed guidance, no additional demonstration is required to certify the installation of this engine on an aircraft under §25.1093(b). Indeed, the behavior of the engine in ice crystals condition is essentially dependent on the design characteristics of the engine turbomachine with limited influence resulting from the installation the aircraft.

The likely installation effects are those that could affect the ice crystals threat entering the engine:

The concentration of ice crystals being ingested into the engine can be affected by any scoop factor created by the airframer-installed engine nacelle inlet

The engine installation location may also influence the ice crystals threat. There is a potential for more pronounced ingestion effects for fuselage-mounted engines versus wing-mounted engines, in particular for engines that would be facing boundary layer ingestion of ice crystals

For non-Pitot type inlets, the configuration of the inlet should be taken into consideration.

These effects can be mitigated by adequate coordination between the engine and aircraft manufacturers such that they are taken into account in the testing/analysis demonstration carried out by the engine manufacturer. Air inlet scoop factor or additional concentration factor due to specific engine installation on the fuselage can be agreed between both parties as an input to the proposed compliance work.

While the guidance in this document is focused on compliance for §33.68, consideration must be given to any effects resulting from engine installation on Transport Category aircraft and certification considerations for compliance to §25.1093(b).

Some considerations resulting from installation effects include differences in installation location. There is a potential for more pronounced ingestion effects for fuselage-mounted engines versus wing-mounted engines. This could be an issue for engines that are facing boundary layer ingestion of ice crystals.

Other installation effects are listed below:

- Any scoop factor created by the airframer-installed engine nacelle inlet; this can affect the concentration of ice crystals being ingested into the engine.
- Use of engine measurements for aircraft control. For instance, it might be acceptable to have an error on the order of 2 psi on P2 for the engine's control system, but could cause unacceptable levels of error for aircraft flight speed measurement.

- Engine components used to support aircraft systems operation such as valves or controls which could be affected by ice crystals.
- For tail-mounted engines in particular, whether the intake ice protection system is suitable for ice crystal and snow operation.

3.5. Installation effects specific to turboprop engines

For turboprop engines, the ice crystal threat is strongly affected by its installation. The engine company should consider the following characteristics. The air flow with ice crystals first passes through the propeller that is typically not certified with the engine under Part 33. Ice crystals enter the aircraft inlet duct with a swirl angle given by the propeller, and continue their path throughout the inlet duct, where there could be a Foreign Object Damage (FOD) by-pass door, reaching the engine under-cowl plenum. The engine plenum is typically a volume where the flow sees various non-symmetric obstacles such as aircraft truss, engine’s oil, fuel and air pipes, etc. These obstacles generate special ice crystal trajectories that eventually reach the engine compartment via the compressor inlet. There may be sources of heat which may lead to ice crystal particles melting. Many turboprop engines have also a FOD screen at the compressor inlet that may also influence the crystal trajectories reaching the compressor. The ice crystal threat to the compressor inlet is likely to be very asymmetric circumferentially due to the complex trajectories of the particles. In order to carry out the turboprop certification for Part 33, the aircraft installation and engine plenum geometry have to be taken into account to define the actual threat to the engine. Once the actual level of ice crystal threat is defined by detailed 3D analysis or test, for a specific aircraft installation, some margins could be added to define a conservative ice crystal threat that could be valid also for different installations, as far as further analyses or tests demonstrate that the certification of an engine for a given aircraft installation with added margins is valid for other installations, as the added margins take into account geometry differences that may result into higher ice crystal threat to the engine.

4. Industry Recommendations for Analysis MOC

4.1. Introduction

The Analysis sub-group guidance applies to turboprop, turbojet, and turbofan engines.

4.2. Identified failure modes due to Ice Crystal Icing

The EIWG Analysis sub-group addressed the failure modes shown below that were identified as having a high priority. For further explanation on why these failure modes were chosen, please refer to the Appendix Section **Error! Reference source not found.**.

- Compressor mechanical damage resulting from ice impact
- Compressor surge resulting from ice shedding
- Combustor flameout resulting from ice shedding
- Engine roll-back due to gas path blockage
- Loss of thrust control due to freezing of delivery pressure line

4.3. Suggested Procedures to Address Failure Modes

4.3.1. Philosophy of the Suggested Approach

For each addressed failure mode, the Analysis sub-group suggests an analysis procedure to be used by the applicant. This is intended as a guideline only. Each procedure is broken down into several steps. The procedures are constructed in such a way that for each step a conservative alternative may be used if the applicant does not have a validated tool available. Examples of conservative approaches are provided for each step. Depending on an applicant's circumstances a different conservative approach may apply.

These procedures were devised without regard of the engine type to be certified and are therefore intended to be applicable for all gas turbine configurations.

Two categories of tools might be used in ICI analysis:

- Well-understood tools (e.g. pure CFD tools) for which validation is already widely treated in the literature. Those tools are out of the scope of the EIWG analysis sub-group.
- Specific ICI tools for which validation is not straightforward and that fall into the EIWG Analysis sub-group scope. The procedures below discuss those types of tools.

4.4. Detailed Procedures

4.4.1. Compressor Mechanical Damage from Ice Impact

Figure 4 provides a flowchart representing an analysis process to avoid compressor mechanical damage from ice impact. Each vertex is numbered and corresponds to a step in the analysis, or to an alternative. The comments following the figure apply to the corresponding numbered vertex.

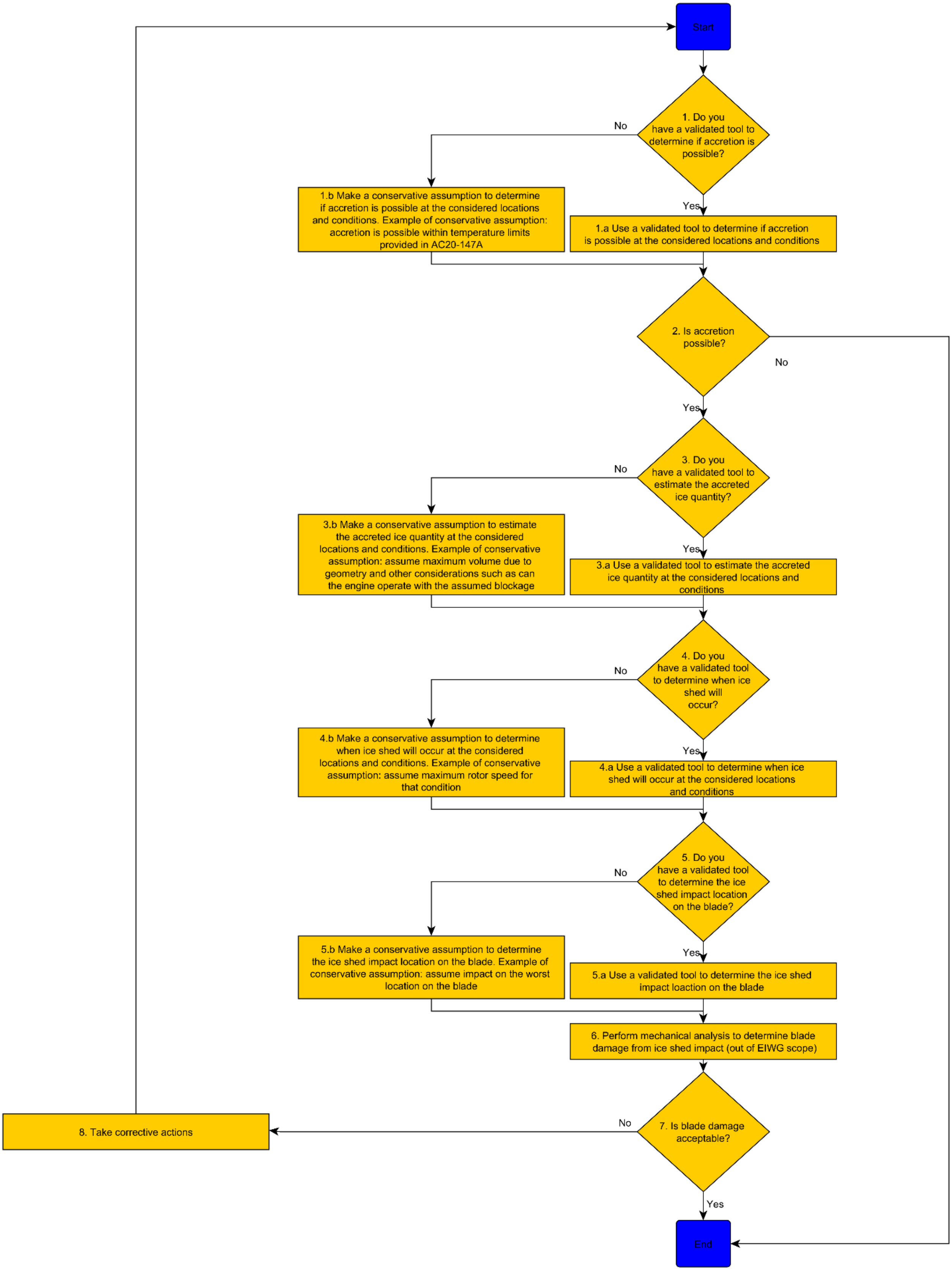

Figure 4: Process flowchart of analysis procedure to avoid compressor mechanical damage from ice impact

2. The applicant may consider the ice crystal particle quantity extracted by variable geometries when assessing ice crystal accretion possibility downstream those variable geometry in the engine core path.

4. The accreted ice may shed due to various reasons such as ice accumulation in steady state up to a certain ice layer thickness, a change in engine conditions (e.g. acceleration), or a change in the environment (e.g. ice cloud exit).

5.a. and 5.b. The outcome of these steps might be that the ice shed does not impact the blade (due to it's own trajectory or to the fact that variable geometries may extract the ice shed before it reaches the considered rotating row). Therefore, the outcome of the next steps of the analysis would be trivial.

8. Corrective actions may be a blade redesign, the implementation of a mitigation technology or any other action that would result in modifying the analysis outcome.

4.4.2. Compressor surge from ice shedding

Figure 5 provides a flowchart representing an analysis process to avoid Compressor Surge due to ice shedding. Each vertex is numbered and corresponds to a step in the analysis or to an alternative. The comments following the figure apply to the corresponding numbered vertex.

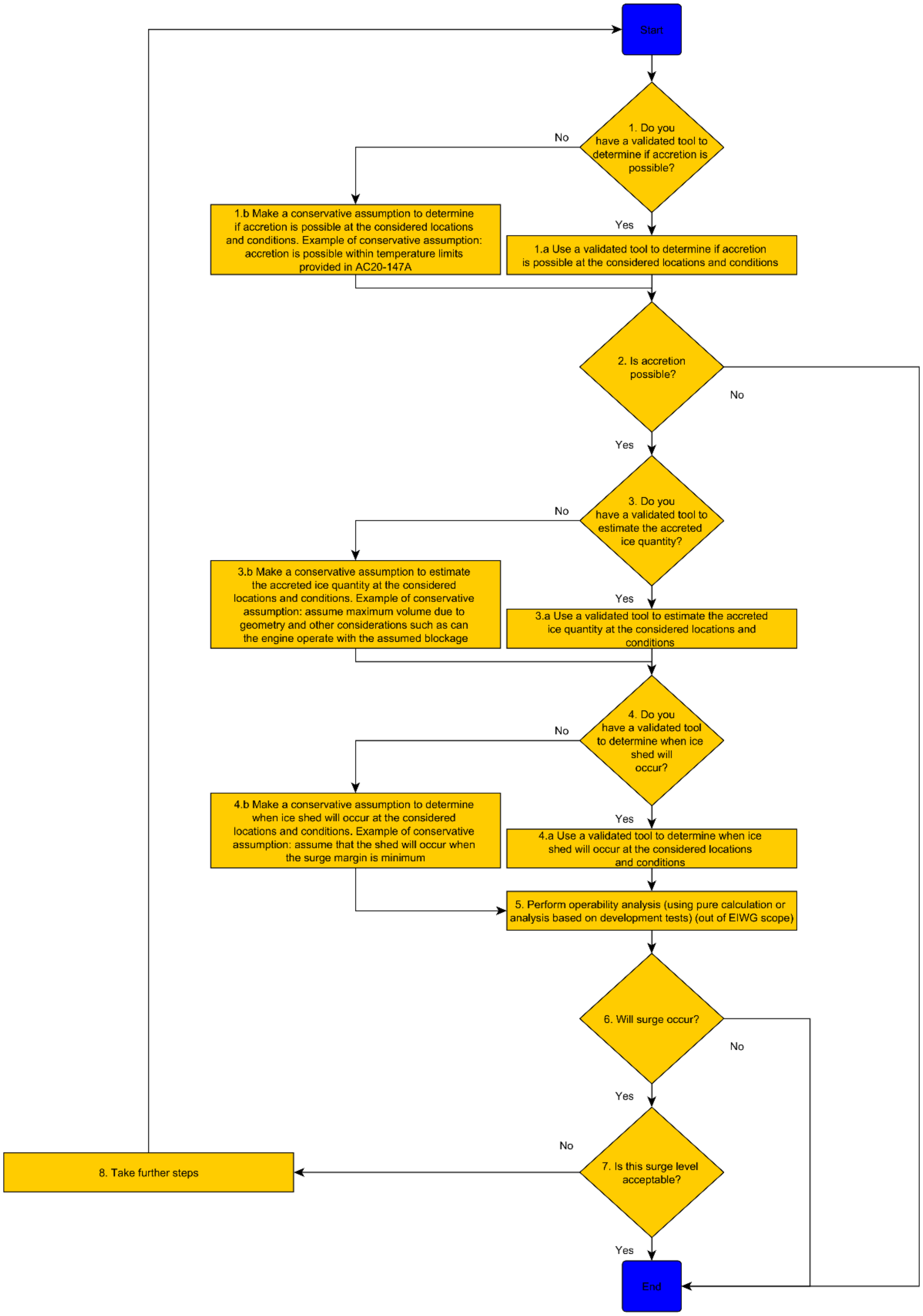

Figure 5: Process flow chart of analysis procedure to avoid compressor surge due to ice shedding

2. The applicant may consider the ice crystal particle quantity extracted by variable geometries when assessing ice crystal accretion possibility downstream of those variable geometries in the engine core path.

4. The accreted ice may shed due to various reasons such as ice accumulation in steady state up to a certain ice layer thickness, a change in engine conditions (e.g. acceleration) or a change in the environment (e.g. ice cloud exit).

5. The operability analysis in itself is out of the EIWG scope; however, the applicant may consider the fact that ice sheds might be extracted by variable geometries (e.g. bleed valves) when assessing operability impacts downstream of the variable geometries in the engine flowpath.

7. The definition of an acceptable surge in ICI conditions, consistent with AC 20-147A, is a recoverable surge that:

- Is self-recovering without flight crew action, and
- Would not mislead a flight crew into believing they need to take action due to noticeable non-momentary thrust loss, and
- Would not cause unacceptable stresses or operability effects either at steady-state conditions, or during acceleration. This includes: blade distress or bending that might result in immediate or long term blade failure. For example, if a compressor blade clashed with a vane during a surge event that could lead to engine failure sometime after the surge or in a follow-on flight.

8. Further steps may include the implementation of a mitigation technology or any other action that would result in modifying the analysis outcome.

4.4.3. Flameout from Ice Shedding

Figure 6 provides a flowchart representing an analysis process to avoid flameout due to ice shedding. Each vertex is numbered and corresponds to a step in the analysis or to an alternative. The comments following the figure apply to the corresponding numbered vertex.

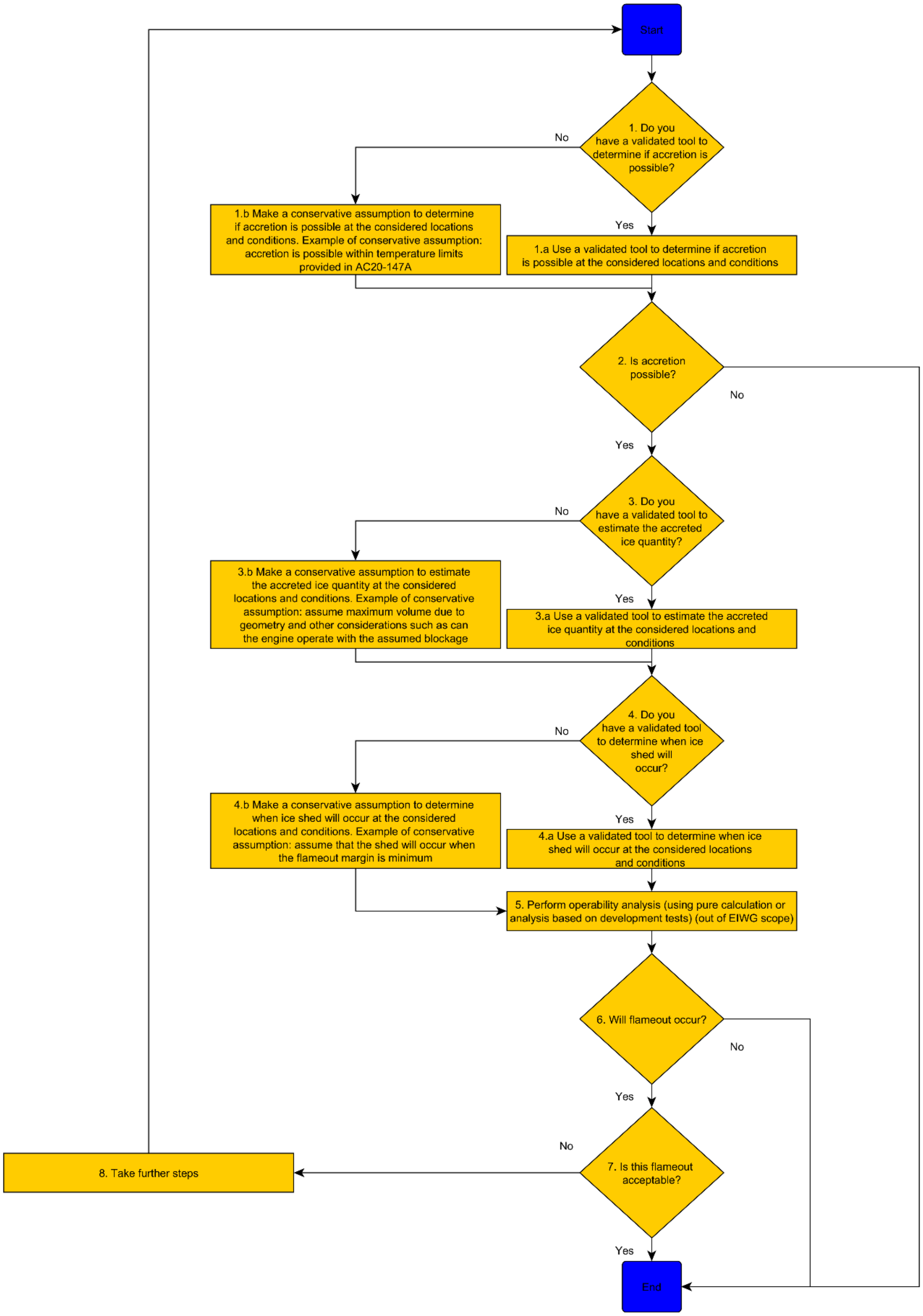

Figure 6: Process flow chart of analysis procedure to avoid flameout due to ice shedding

2. The applicant may consider the ice crystal particle quantity extracted by variable geometries when assessing ice crystal accretion possibility downstream of those variable geometries in the engine core path.

4. The accreted ice may shed due to various reasons such as ice accumulation in steady state up to a certain ice layer thickness, a change in engine conditions (e.g. acceleration) or a change in the environment (e.g. ice cloud exit).

5. The operability analysis in itself is out of the EIWG scope; however, the applicant may consider the fact that ice sheds might be extracted by variable geometries (e.g. bleed valves) when assessing operability outcome downstream of those variable geometries in the engine core path (for example, will the ice shed reach the combustor).

7. The definition of an acceptable surge in ICI conditions, consistent with AC 20-147A, is a recoverable surge that:

- is self-recovering without flight crew action, and
- would not mislead a flight crew into believing they need to take action due to noticeable non-momentary thrust loss, and
- Would not cause unacceptable stresses or operability effects either at steady-state conditions, or during acceleration. This includes: blade distress or bending that might result in immediate or long term blade failure. For example, if a compressor blade clashed with a vane during a surge event, which could lead to engine failure sometime after the surge or in a follow-on flight.

8. Further steps may include the implementation of a mitigation technology or any other action that would result in modifying the analysis outcome.

4.4.4. Rollback Due to Gas Path Blockage

Figure 7 provides a flowchart representing an analysis process to avoid rollback due to gas path blockage. Each vertex is numbered and corresponds to a step in the analysis or to an alternative. The following comments apply to the corresponding numbered vertex.

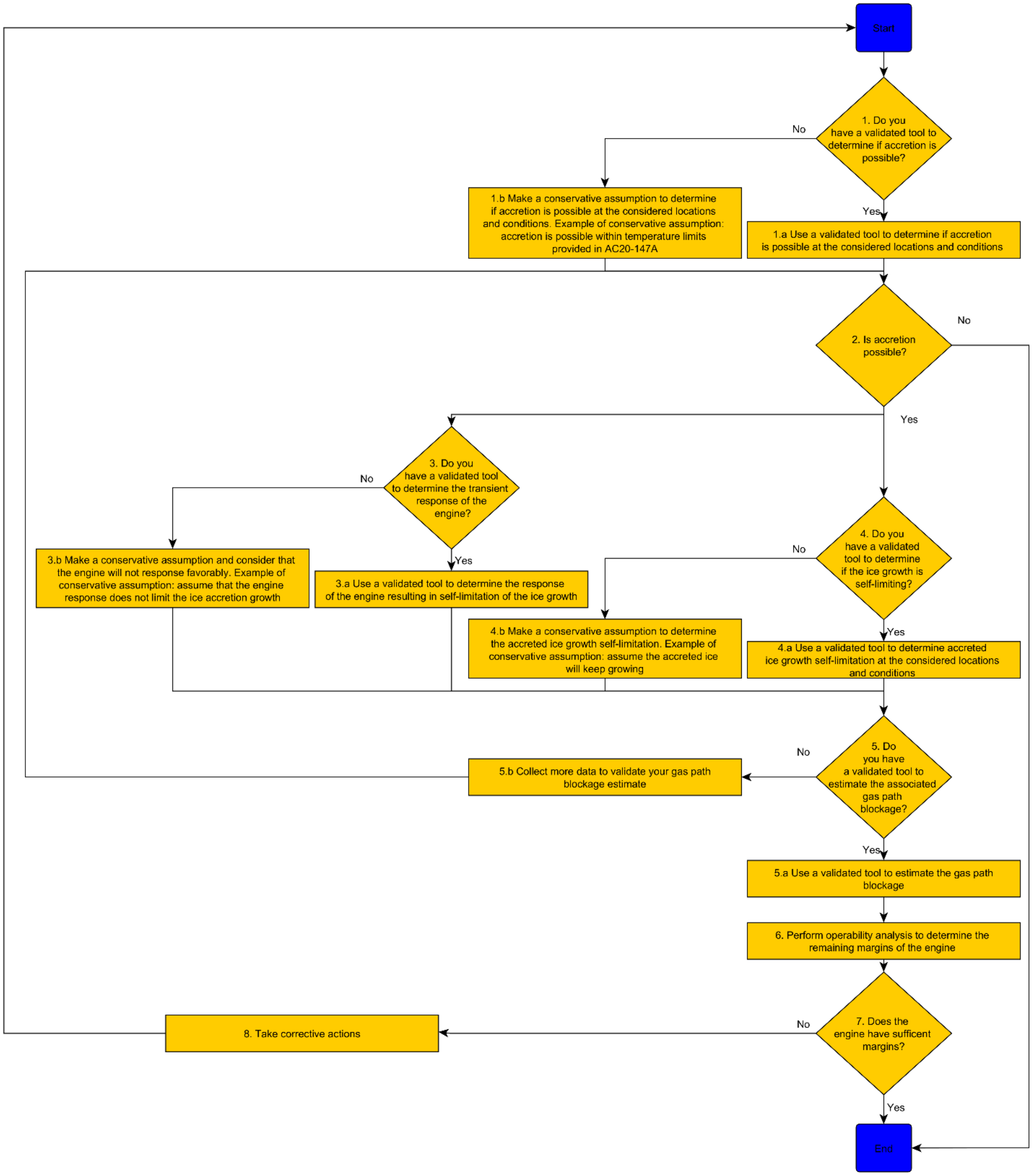

Figure 7: Process flow chart of analysis procedure to avoid rollback or loss of thrust due to gas path blockage

3. The applicant may consider any possible cycle effects and potential control responses to flowpath blockage that might result in self-limitation of the ice growth.

4. The applicant may consider natural shedding or self-limiting growth due to changes in local conditions that may limit the amount of blockage independently from the engine response.

5.b. As a conservative option is not yet available, the Analysis sub-group recommends obtaining additional data (e.g. perform partial tests on the location of interest) to conservatively estimate the ice growth and resulting maximum blockage. Comparative analysis may also be appropriate.

4.5. Resulting list of elementary analysis tools

The following list of elementary analysis tools have been identified from the previous flowcharts:

- A tool to determine if accretion is possible
- A tool to estimate the accreted ice quantity (and resulting blockage)
- A tool for shedding analysis
- A tool to determine ice shed trajectory and impact location

Discussion regarding validation of tools examining mechanical capability and operability effects is beyond the scope of this guidance.

4.6. Generic validation procedure for analysis tools

4.6.1. Introduction

The purpose of this section is to suggest to the applicant a generic validation procedure in several steps. This procedure is applicable for the validation of the elementary tools that are listed in Section 4.5 but is not limited to them. Indeed, it seems to this sub-group that suggesting a specific validation process to every elementary tool listed above may not be pertinent since there might be several validation paths for each elementary tool depending on the applicant’s experience and knowledge.

Instead, the Analysis sub-group focused on providing a generic validation procedure for an analysis tool that would capture “phenomena of interest”. A “phenomenon of interest” is not, strictly speaking, the phenomenon that one wants to estimate; however, it can be a phenomenon that indirectly, possibly in combination with other parameters, allows to conservatively estimate it. For example, to determine if accretion is possible on a specific location, one may rely on validated tools that estimate Ice Crystals impingement, if those tools predict no impingement on that specific location, then it would be enough to determine that accretion is not possible. Similarly, to conservatively estimate the accreted ice quantity on a specific location, one may rely on validated tools that estimates ice crystal impingement and assume that all the impinging particles will accrete.

The following proposed validation procedure mentions TRL stages (Technology Readiness Level). These were adapted from a TRL scale specifically defined for numerical tools. Like the original NASA TRL[4] scale, this scale has nine levels, but several of those levels were skipped in the following proposed validation procedure. Indeed the skipped levels are related either to pure numerical and computational aspects (TRL 2 and TRL 3 that deal with model implementation and writing computer programs) or to maturity stages that go further than the scope of the EIWG Analysis sub-group (TRL 8 and TRL 9).

Note that field experience might be considered as a validation means of compliance. However, the ultimate steps of the following validation process entail a physical understanding. Therefore, if those validation steps are achieved relying purely on fleet data, then the generic validity of the model would be hard to demonstrate because the validation would only rely on engine specific data. To go further in the validation process, the applicant may need to back up to a lower TRL level to use this model for a different engine.

4.6.2. Validation steps

The Analysis sub-group proposes a generic validation process in several steps:

- **Step One (TRL 1):** Identify the underlying physics of the phenomenon of interest.
    - The applicant has a proposed model (e.g. equations to solve) that provides an indicator of the phenomenon of interest (e.g.: a Boolean or a probability of accretion, impingement indicator)
    - The applicant has a proposed domain of validity (i.e. an interval for each physical parameter entering into consideration in the equation set) for which the equation set is valid
    - These elements (equations + validity domains) come from fundamental physical understanding or empirical data or a combination of both (from literature, from the applicant's own fleet experience, from the applicant's own tests).
- **Step Two (TRL 4):** The applicant compared the results provided by their tools to component tests not necessarily representing an actual part (e.g. a spherical test piece, or arbitrary profile) and:
    - The tool predicted the phenomenon of interest within a certain margin. Parameter adjustments might have been necessary to achieve full accuracy.
    - Those test cases are different from those that were used to establish the model (Step One: TRL1).
    - The applicant is expected to have an almost complete knowledge of the test environment.
    - The proposed validity domain of the models does not have to be fully covered by those tests.

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[4] NASA TRL Definitions: https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

- **Step Three (TRL 5):** The applicant compared the results provided by his tools to component test representative of a generic engine part (e.g. vane sector to a generic engine) and:
    - The tool accurately predicted the phenomenon of interest within a certain margin. Parameter adjustments are not possible at that stage.
    - The applicant may not have a complete knowledge of the test environment but has to compensate for the lack of knowledge by uncertainty margins.
    - The proposed validity domain of the models have either to be fully covered by those tests, or if they are not, apply conservatism to the model outside of the domain.
- **Step Four (TRL 6):** If the applicant designed a model unique to a particular engine, then showing that the model meets TRL 6 should require minimal effort, versus applying a model from a different engine. Engine level effects are taken into account (e.g. upstream effects from the zone of interest). The results provided by the tools are compared to the engine or equivalent representative machinery tests (e.g. rotating rig, available fleet data, engine test, module or part test), and the tool predicted the phenomenon of interest within the proposed uncertainty margin with no additional adjustments, or the uncertainty margin has to be increased. The applicant can show that part of the tool (some phenomena of interest) may be valid for engines of similar design.
- **Step Five (TRL 7):** This maturity level is sufficient for use for certification regardless of the application. To reach that stage, the applicant shall extend the validity of their tool by making sure that none of their models or components are based on engine specific parameters (e.g. geometry, speed, design features like heated parts, engine control features) or are independent of the design of the engine.
    - This may be done by physics based analysis or by experience with a wide variety of design and geometry.

4.7. Conclusions and Recommendations

In this work, the Analysis sub-group focused first on identifying and prioritizing all the possible non-desirable behaviors and failure scenarios that could occur following ingestion of ice crystals in an engine. Then, for every failure mode that falls into the highest priority level, an analysis strategy was proposed in order to demonstrate acceptable behavior of a new engine regarding this specific scenario. For each step of the proposed strategies, the applicant could either use a validated tool or, if no validated tool is available at the moment, a conservative alternative is suggested. Following this step, a list of potentially helpful elementary tools was made. Finally, a generic validation procedure was proposed. This procedure might be applied for each of the elementary tools identified earlier or to any component of the tool.

5. Industry Recommendations for Simulated Altitude Test Means of Compliance

5.1. Introduction and Scope

This document provides background information on topics relevant to performing a simulated altitude ice crystal test on a turbofan engine. While turbojet and turboprop engines were not initially considered within the workscope of this sub-group, the recommendations may be applicable to those engine types. It provides some detailed information in some of the areas and offers references for further information on related topics. Rationale behind the recommendations is offered. Guidance for working with both known field events and new centerline engines is discussed. Information on existing and potential future altitude engine test facilities is provided. This report also provides a discussion on the various areas of uncertainty and options to mitigate them. Topics that are relevant to the subject of simulated altitude ice crystal engine testing, but that are outside of the scope or the schedule of the report effort are discussed in the Appendix. The guidance given in this report should provide a party interested in evaluating the need and ability to perform a simulated altitude engine ice crystal test with enough information to make some informed decisions about pursuing such a test.

The objective of the Simulated Altitude Test sub-group is to identify key parameters to reproduce in-flight ICI in turbofan engines in an altitude test facility, and to provide recommendations to ensure that data from a simulated altitude test is applicable to demonstrate acceptable operation in flight per 14 CFR§33.68 and §25.1093.

The objective of the recommendations is to provide an applicant with an introductory overview of topics and challenges that should be considered when performing a simulated altitude ice crystal icing test on a turbofan engine.

The ultimate objective is to provide recommendations for an applicant attempting to use a simulated altitude engine icing test facility as a means of compliance to the Ice Crystal Icing requirements found in 14 CFR §33.68 and §25.1093. These recommendations provide guidance to the applicant that would help them run a successful test.

5.2. Rationale for Performing a Simulated Altitude ICI Engine Test

There are many benefits to performing a simulated altitude test. Running an engine in a simulated altitude test facility provides more realistic environmental conditions and engine conditions than can be achieved by sea level ground testing, pure analysis, or even flight testing in certain circumstances. The ability to control altitude/pressure, air temperature, and ice particle size and concentration allows the test facility to more closely replicate the environmental conditions that exist during actual flights. The ability to control the engine to any condition ensures that a realistic engine condition can be achieved.

Expanding on the topic of control of environmental conditions in an altitude icing tunnel, it is realized that this capability provides many benefits in and of itself. Cloud simulation eliminates any seasonal schedule delays that are typical of in-flight test planning. It also eliminates the process of meteorologists searching for the right, or close enough, cloud to fly through. The aircraft transit time to get to the cloud after it is found is also eliminated. In addition to the schedule advantages of an altitude facility over flight testing as discussed earlier, an altitude facility also offers a safer test experience than flight testing.

Cloud simulation also allows the applicant to simulate the environmental conditions desired. For the applicant who is investigating a known field issue, this allows the applicant to modify environmental parameters individually to find the right combination of individual parameters that result in replicating the field event. For the applicant who is dealing with large levels of uncertainty, the ability to easily vary parameters provides a way to understand and characterize parameter sensitivity which can help to mitigate uncertainties. Quick and easy control of environmental parameters can also provide an efficient way to determine engine design sensitivity to ice crystal icing parameters.

There are several advantages of a simulated altitude test over a sea level ground test. Currently, it is uncertain if any sea level ground test can provide representative enough altitude conditions to accurately represent the accretion and shed physics that take place during an actual in-flight icing event. One of the primary differences between the altitude and ground environments is the air pressure and density. It is unclear at this time how these large differences affect the build and shed physics of accretion, and how the differences can be compensated for in a ground test. Testing in an altitude test facility eliminates that unknown. A ground test facility can also be limited by seasonal ambient temperatures.

Simulated altitude test facilities can control most of the environmental parameters related to ice crystal accretion; however, there are some parameters that currently cannot be replicated compared to a natural cloud, such as crystal size, morphology, and temperature. Please refer to Section 5.4 for more details.

The other limitation of simulated altitude testing is the lack of availability of test facilities. Currently, there are only a couple of test facilities in the world that can perform these tests and they are limited to engine size and flow requirements. There are no such facilities for engines with large fans, although testing clipped fan rigs or compressor rigs in such facilities may be possible. Moreover, only a limited number of tests can be performed in a given year in the available facilities, further limiting the ability to test.

While these downsides can range from a major difficulty / barrier to a minor inconvenience, there seem to be enough benefits to a simulated altitude engine icing test that applicants may consider these advantages and disadvantages when determining their plan for demonstrating compliance with the ice crystal icing regulations.

5.3. Rationale for Ranking of Parameters

The parameters that define an ice crystal icing encounter can be described in two groups: first, the environmental parameters, including aircraft flight parameters and the icing environmental parameters, and then engine operating details.

The environmental parameters that should be considered are:

- Aircraft flight parameters, consisting of
    - Altitude,
    - Mach number,

    - Total air temperature (TAT)
- Icing environmental parameters consisting of
    - Ice Water Content (IWC),
    - Liquid Water Content (LWC),
    - Relative humidity,
    - Particle temperature,
    - Particle size,
    - Particle size distribution and
    - Particle shape.

The highest value environmental parameters are: altitude, TAT, and IWC. It should be noted that Aircraft Mach number can also be a high value environmental parameter, because TAT defines the inlet conditions into the engine and can be derived from aircraft Mach number and static air temperature.

The engine operating detailed parameters are:

- Flight phase including engine power level,
- Accretion location,
- Wet bulb temperature at accretion location,
- Ice crystal melt ratio at accretion location,
- Engine cycle parameters prior to cloud entry,
- Engine cycle parameters at peak threat in the cloud,
- Anti-icing system performance, and
- Engine bleed extraction.

The highest value engine operating parameters are: flight phase including engine power level, accretion location and, engine cycle parameters prior to cloud entry. These are the most highly valued parameters that can be used to understand root cause of a known field event or to set up the simulated altitude test.

5.4. Particle Properties

Particle properties (i.e. size, size distribution, shape and temperature) are currently considered less important for accurate environmental simulation. Given the current knowledge on today's turbofan engines, it is generally accepted with limited data that particle breakup occurs during travel through initial rotating (and stationary) blade rows for all turbofan engines until it reaches a small enough size that minimal interaction with the blade rows occur. This breakup also means that particle size distribution and shape within the cloud are of lower value as well. However, other engine types may not experience this level of breakup, and additional analysis can be used to show how particle size and distribution play a role in the proposed testing. . The initial particle temperature is currently considered to be less critical, and is very difficult to measure.

The applicant may discover that particle size and temperature are important for their particular configuration. If particle size is critical, the selection of the ice crystal generation equipment may play a role such as whether one uses a grinder or spray bar facility to generate ice crystals by freezing water droplets. The same can be said for the criticality of understanding particle temperatures, which can rise rapidly through the rotating stages of turbomachinery, increasing the melt ratio and therefore possible accretion. However, if particle temperature is critical for an application, then the testing would have to be defined to clearly identify the initial temperature of the particle. Future research may provide additional insight into the influences of dynamic particle morphology on accretion effects.

5.5. Facility Descriptions

A simulated altitude icing test facility could supply an engine with a range of atmospheric conditions to replicate known in-flight ice crystal accretion events in a turbofan engine. It also allows assessing engine sensitivity to ice crystal conditions for a derivative or a new centerline engine that requires ice crystal validation.

NASA’s PSL-3 is currently the only altitude test facility that has ICI capabilities which can accommodate small turbofan engines, clipped fan configurations, and driven rigs. For lower airflow requirements, the NRC RATFac altitude facility has ICI capabilities. Other facilities, such as Arnold Engineering Development Center (AEDC), may be available in the future. The AEDC Altitude Simulation Test Facility (ASTF) can accommodate large engines, however they currently do not have full capability for ice crystal icing testing. For more detailed information on each test facility, please refer to the Appendix Section 2.1.

5.6. Testing to Address Known Field Events (KFE)

Testing of engine modification(s) designed to address known field events in ICI is a special subset of engine certification. In general, after an operational engine is determined to be susceptible to ice crystal accretion that led to an in-flight event, a root cause and critical path analysis would be performed. This includes a comprehensive series of testing and analyses that are aimed at pinpointing the engine operating conditions, the environmental conditions, and the location within the engine where ice crystal accretion occurs. This analysis generates data that could minimize the engine operating window where events occur and correspondingly reduces the test envelope at the facility where the certification data is generated. Certification of an engine modification designed to address a field event should be a two-step process. The first step is to demonstrate that the event can be replicated in the altitude testing facility. Then the modified engine should be tested for the condition(s) that caused the in-flight event and then expanded to cover the entire operation envelope using a critical point analysis to determine additional test points.

5.7. Environmental Factors

Environment factors associated with ice crystal field events include flight conditions and icing environmental parameters. Flight conditions are altitude, total air temperature, and Mach number. These ambient parameters are generally recorded by the aircraft or the engine control systems, so they are not difficult to obtain from the event. These parameters are very important to be simulated in the test facility because they define the way the engine operated just prior and during the event. Estimation of IWC is possible using the engine cycle model. For further description of this process, please refer to the Uncertainty section. (Reference 4).

The icing environmental parameters are difficult to measure and simulate in the test facility due to the nature of how ice particles are generated; for example, the time a water particle resides in the cold air in the test facility is much shorter than its counterpart in nature. An ice shaver system may be used in the test facility to generate ice crystals that more closely simulate the size and the crystal temperature in nature, by controlling the initial ice block temperature. However, the rate of crystal generation is limited to the shaver capacity. Testing in a pressurized environment would also add complications to the ice supply line which controls the rate of crystal generation as well. As a result, providing a constant supply a large quantity of specification ice crystals during a full engine test is a major challenge in an engine test facility. It may be a feasible option for a low quantity rig testing ice crystal setup. Current technology suggests that the ice particle temperature, shape and size distributions in the facility are not expected to be precisely simulating the natural environment. Fortunately, altitude testing of known field event due to ice crystal blockage suggested that only the ice water content is the most critical parameter to replicate. For field events other than internal blockage, this mitigation effort will need to be reassessed when setting up the facility for testing, due to limited data at other failure modes. Wet bulb temperature is a parameter that is very influential in the melting of ice crystals and thereby controlling the ability of ice crystals to stick on the engine internal surface. Therefore, it should be accounted for in developing certification test points. The uncertainties resulting in not fully understanding and simulating the remaining ice particle characteristics can be mitigated by compensating factors to increase conservatism (see Section 5.12 for further discussion on compensating factors).

5.8. Engine Operational Factors

Detailed engine operating parameters are recorded when a root cause and critical path analysis is performed. These parameters are of high value for the understanding of the cause of the event, the location of ice accretion and in simulating and replicating the event in the test facility. These parameters include primary data like flight phase, engine power level, cycle information prior to cloud entry and the changes in engine cycle after cloud entry. Secondary information includes anti-ice and bleed air systems operation. This information would also be useful in pinpointing the ice accretion location. When the ice accretion location is known, ice accretion factors (like local air wet bulb temperature and ice particle melt ratio) can be deduced.

For the modification evaluation step of the testing program, engine operation parameters are to be expanded to cover the entire engine operation envelope. Again, a critical point analysis should be used to define test points that ensure that the modification would be tested in the field event simulated conditions.

5.9. Discussion on New Engine Certification Programs

New engine certification programs are required to comply with the same regulations for the ice crystal environment, regardless if the engine is a derivative or a new centerline. For engines that are a derivative of an engine that has had in-service field issues, it should be shown that the design features associated with any field issues have been addressed in the derivative engine design. For all other derivative engines, the steps to certification should be the same as a new centerline engine. Because no direct field events exist to help define test points, consideration should be given to an applicant's service experience of all engine types, both positive and negative. For example, if an applicant had service issues on an engine component such as a compressor of a non-similar engine, then the cycle conditions can be used to help identify test points with similar cycle conditions for similar ice accretion and shedding potential in the engine to be certified.

For compliance by simulated altitude test, the first step in the certification process should be to define the engine features susceptible to ice accretion. These features may influence the CPA.

In addition to the identifying susceptible features and conducting a CPA, test point selection will also be based on the applicant's experience, both positive and negative. The test cell should have environmental and flow capability consistent with the purpose of the certification testing. Environmental parameters that should be reproduced in the test cell are:

- Altitude
- Aircraft Total Air Temperature (TAT)
- Aircraft Mach number (M#)
- Cloud Ice Water Content (IWC)

Additional environmental parameters of lower criticality that should be simulated if possible, for the stated test purpose are:

- Liquid Water Content (LWC)
- Particle Temperature
- Particle size
- Particle distribution
- Particle shape
- Relative humidity

These parameters are of lower criticality due to the following reasons. Events specifically linked to mixed-phase icing have not been common. In addition, conventional icing testing is used to demonstrate engine capability in supercooled liquid. However, if an applicant has events related specifically to mixed-phase icing, or if a susceptible engine feature is directly related to mixed phase icing, then LWC may be more important and additional consideration should be given to it. Particle temperatures are very difficult to determine in typical icing facilities using a water spray rig. Larger droplets may not freeze out entirely. However, if an ice shaver is used, colder particle temperatures can be achieved. Because of fragmentation of particles by engine hardware, particularly rotating airfoils, particle size, shape and distribution is of lower importance than concentration. As the particles migrate further aft in the turbomachinery, the particle sizes get smaller. However, if a susceptible engine feature is more forward in the engine (i.e. the first rotating stage or even upstream hardware), then the value of particle size, shape and distribution may be more important and additional consideration should be given to it.

The engine details that should be simulated in the test cell are:

- Flight phase
- Engine power level
- Dry cycle parameters, or cycle parameters prior to cloud entry

Additional engine details that may need to be simulated if possible are:

- Cycle parameters at peak icing threat
- Bleed extraction
- Anti-icing system status

Given uncertainties with particle temperature and morphology, the engine or altitude cell conditions may need to be modified from the in-flight conditions in order to correctly simulate the accretion location. See Uncertainty section for more details on managing this.

The peak icing threat usually occurs later in the cloud, with most ICI accretion beginning prior to the peak threat, so the cycle parameters at the peak icing threat may not be critical. (Reference 2).   ICI accretion also can occur upstream of any bleed offtakes making bleed extraction less critical from one perspective, however bleed may have beneficial or non-optimal aspects that should be evaluated. Anti-icing heaters are typically off during ICI encounters, so anti-icing system status may not be critical. However, if an engine bleed or anti-icing system generates more susceptible features, then the criticality of engine bleed and/or anti-icing system status may be more important and additional consideration should be given to it.

It is important to understand the operating envelope of the intended aircraft installation. The envelope should include altitude, temperature, Mach number, aircraft weight range, corresponding power range, and installation concentration effects of ice crystals.   Detailed discussions with the air framer are required at this step to ensure that the complete aircraft flight envelope is considered and its associated effect on engine operation and the control system. If the engine is expected to go into multiple aircraft applications, then consideration should to be given to expanding the aircraft operating envelope as appropriate to cover all planned installations.

5.10. Critical Point Analysis

Except for a direct simulation of a known field event on an in-service engine, test point selection involves defining test points within the Appendix D envelope to replicate in the altitude test facility. The altitude, TAT and aircraft M# are used to set the aircraft flight conditions for the environment. In addition, IWC must then be specified. The options are listed below and have varying levels of uncertainty (see Uncertainty section):

- Applicant experience: Use the engine cycle model matched to applicant service data to understand the approximate water to air ratio and back out the IWC.

- CPA based on event data of similar/derivative engines.
- CPA based on points of interest within the ice crystal envelope as described below.

The ice crystal critical point analysis (CPA) will follow the main guidelines provided in the “AIA/EIWG Subcommittee on Engine Probe Icing” document, more specifically Appendix 1, Ref. 13. The present section provides a summary of the CPA while more details are described in Appendix 1. Note that only fully glaciated conditions are considered herein, see Additional Considerations section for the discussion on mixed phase.

An applicant without sufficient background information can follow this recommended process. This is a starting point but should not be considered as sufficient for complete evaluation of an engine’s ice crystal exposure.

The first step of the CPA consists of defining multiple points of interest within the ice crystal envelope. An analysis on these points of interest is performed such that only the most critical points are retained for altitude testing. It is recommended to use the 21 points defined in Ref. 13, which cover the corners and the middle region of the extended Appendix D ice crystal envelope. Figure 8 shows the points of interest on the altitude/temperature envelope while Figure 9 presents the same points on the maximum total water content (TWC) versus the altitude envelope.

The second step of the CPA requires the applicant to consider a range of aircraft speeds and a range of engine power settings on each point of interest. It is recommended to obtain engine cycle data for the following engine power levels: Cruise, Hold, and Flight Idle Descent. These power levels should be considered over a range of aircraft gross weights.

The final step of the CPA is to select the most critical ice crystal points based on the ambient total water capture including concentration factors at the engine core, and cloud extent. It is important to cover a range of temperatures, a range of TWCs and engine operating characteristics in the selection.

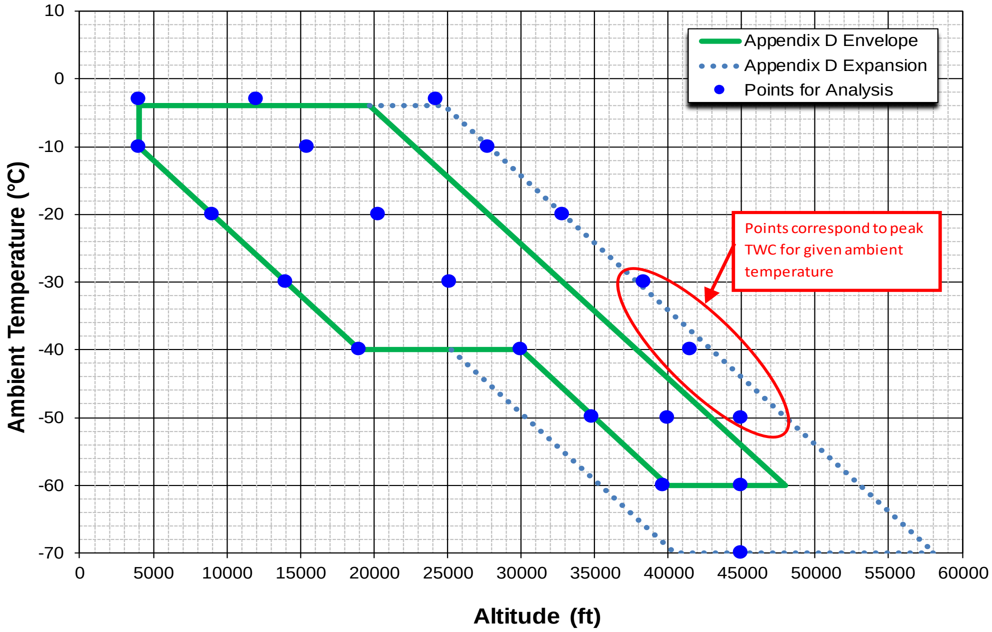

Figure 8: Points of interest on the Altitude/Temperature ice crystal envelope.

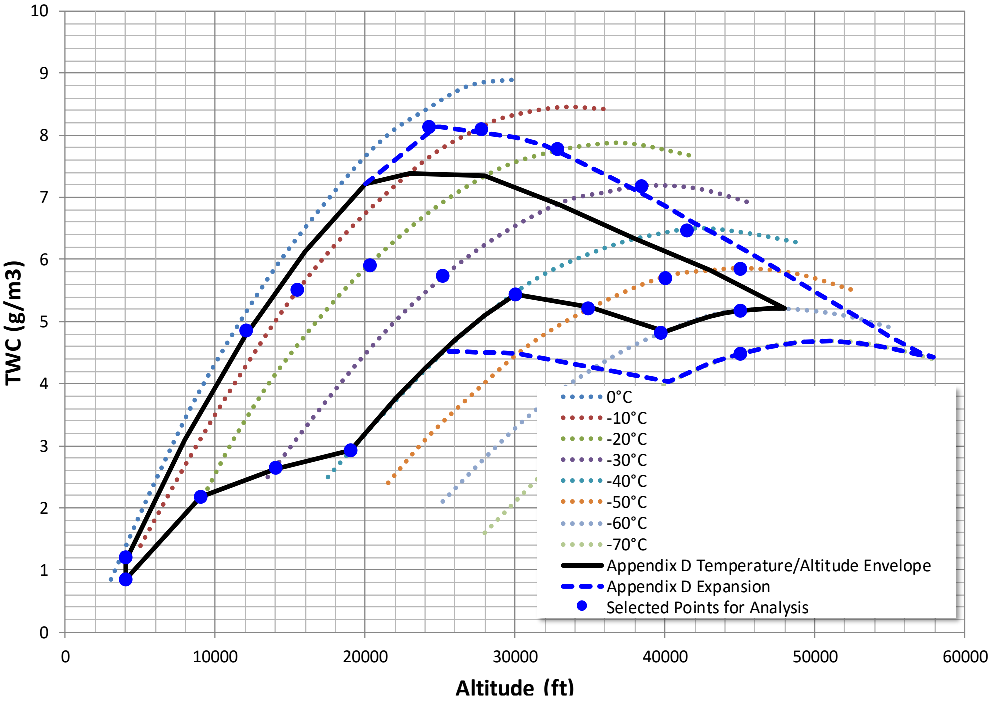

Figure 9: Points of interest on the Altitude/TWC envelope.

5.11. Discussion on Simulated Altitude Testing to Evaluate Mechanical Damage

A key item required to understand the engine's operation in ice crystal icing is to evaluate the engine for mechanical damage resulting from internal ice sheds. Since mechanical damage is considered the most severe effect of ice crystal icing, a more conservative approach should be considered using the uncertainty principles discussed in Section 5.12. When selecting test points, two different test objectives can be used: testing to validate analysis, or direct test event or critical point demonstration. Since the test may result in mechanical damage, it is critical that engine manufacturers evaluate the risk carefully including all levels of uncertainty (see Section 5.12) and using appropriate test procedures. The risk is that it is possible that the test asset could be damaged beyond use with only one test point. If mitigating design features are incorporated into the engine's design to address either predicted damage or a known previous damage vulnerability to ice crystal icing, then the risk of potential damage should be sufficiently addressed such that the engine can be more fully tested to show the design mitigation's efficacy.

For a known field event engine issue, a direct test demonstration is typically used, but it can also be used to evaluate a critical point for new or derivative engine. The objective of the simulated altitude test is to determine if an engine modification has eliminated the engine issue. To do this, the environmental and engine conditions of the field event should be replicated in the altitude test facility. However, as noted above, a significant risk exists for engine damage, so a different approach is needed. The objective of the replicated test is to show that the ice accretion is in the appropriate location and has accreted in sufficient quantity to cause the field event damage. The test could be planned with instrumentation (e.g. cameras, icing sensors, and pressure and temperature sensors as applicable) that can monitor even small amounts of accretion. The test point time should be sufficient to obtain the onset of ice accretion. The accretion location and size can be characterized, and a determination can be made on the next test point. If ice accretion exists, the test time can be increased while carefully evaluating the instrumentation for indications of accretion large enough to cause mechanical damage. The test could then be halted, and the ice accretion location and buildup rate can be used to determine if a sufficient replication of the field event occurred. If no ice accretion is observed, then the simulated altitude environment and altitude engine conditions can be adjusted within reasonable tolerance to the expected event conditions to try to observe ice accretion.

Once it has been demonstrated that the test can replicate the field events appropriately, then the test with the updated engine can be run. The objective of the test is to show that the ice accretion was eliminated or sufficiently reduced to a level that the engine can tolerate the ice shed.

Test points to show damage tolerance should be completed in a sequence from less risky to more risky conditions. The test points selected should include points where accretion is not predicted to occur as well as where it is predicted to occur. In addition, given the level of uncertainty, additional test points should be used to help increase the confidence. An option for risk mitigation is to characterize an accreted ice mass after a test point and do a mechanical assessment of the critical engine condition to determine the mechanical acceptability.

A test that has the potential to damage the facility should be avoided, while for a facility that may be able to absorb engine surges without doing damage to the facility components a test could be pursued.

A hierarchy of test scenarios is provided below that should be considered by the engine OEM and the facility when developing a test plan:

- No damage to the facility, no damage to the engine
- No damage to the facility, acceptable damage to the engine OEM
- No damage to the facility, unacceptable damage to the engine OEM
- Damage to the facility, fatal damage to the engine

5.12. Altitude Test Facility Uncertainty

The altitude test facility also has uncertainty associated conducting a test. First, a facility may have limitations in the capability to replicate the desired atmospheric icing conditions such as IWC and cloud uniformity, which can result in different ice accretion or engine response characteristics than in-flight. If the facility cannot meet the target IWC, a compensating factor can be applied, i.e. changing the time of the test. Another factor is the thermal coupling between the cloud and the air flow which can effect test conditions; for example, the total temperature can drop due to the evaporation of water droplets. Uncertainty also exists when trying to replicate steady state and transient engine response. For steady state tests, ice accretion may change the flow characteristics of the engine requiring a compensation to the icing supplied to the engine to maintain IWC. Also, most test facilities cannot change conditions very rapidly and if transient effects such as engine rotor acceleration/deceleration contributed to field events, then any testing may need to include additional points to accurately capture the icing threat and reduce uncertainty during transient engine operation. Instrumentation used to measure engine parameters may also introduce uncertainty that can be related to classic sensor uncertainty and the sensor's effect on the parameter being measured, such as when using intrusive sensors.

5.13. Conclusions and Recommendations

Many different parameters are used to define an ice crystal encounter and the guidance provided in this document shows which parameters are the most important as well as which are the most difficult to determine. Future research may give insight into parameters which are lower value and can also reduce the difficulty of determining them. Test facilities capable of simulated altitude tests are discussed. Other facilities may be available currently and in the future. Two types of engine tests are described: one addressing known field events and one addressing a new certification, which includes both new centerline and derivative engines. Since some of the results of an ice crystal icing encounter could be mechanical distress, test points and execution should be specified carefully to ensure that damage to the test article does not result in a failed test. Since there some of the parameters that describe ice crystal icing are difficult to obtain, understanding the uncertainty is key and must be factored into the testing. Finally, a description of the items that this working group considered is detailed as a starting point for future work.

6. Industry Recommendations for Ground Test Means of Compliance

6.1. Introduction and Scope

This document summarizes the outcomes of the discussions held within the EIWG ground test sub-groups. It first provides a view on the type of engine failure scenario that the group thought could be reasonably addressed with a sea level test. It then details the results of the group work performed to identify and characterize a list of parameters that would need to be replicated in an engine ice crystals ground test aimed at demonstrating the engine behavior in an altitude condition. This work and related groups discussion confirmed the group members' opinion that great challenges remain as of today before being able to conclude that an engine ice crystals ground test can be robustly used as a means of compliance to replicate an engine behavior in an actual ice crystals encounter at altitude. A dedicated section of the report aims at providing more details supporting this opinion. Some discussions occurred within the group around possibility to use a ground test in the context of addressing a Known Field Event vs. being used in new Engine Certification context. The report contains wording summarizing the highlights of these discussions. Finally, a conclusion and group recommendation is provided.

The objectives of the Ground Test sub-group were:

- To identify key parameters to reproduce in flight ice crystals ice accretion in turbofan engines in an sea level test facility, and to provide best available guidance on how they could be adapted to perform a meaningful Sea Level test.
- To provide Airworthiness Authorities and Applicants with an introductory overview of topics and challenges that should be considered when performing a sea level ice crystal icing test on a turbofan engine.

The sub-committee identified difficulties in making the engine ice crystals icing ground test a robust certification means of compliance with the current Industry knowledge. The sub-committee considers, on the other hand, that this tool can provide valuable inputs to the applicants for validating analytical models. The guidelines/recommendations provided by the sub-committed in this report can be used by the engine manufacturers when setting ground test experiments for analytical tool validation.

6.2. Engine Effects to be addressed in a Ground Test

In accordance with the AIA 1 June 2017 letter to the FAA, the Ground Test sub-committee reviewed the following possible engine effects as those that a sea level test would have to address:

- unacceptable engine damage;
- unrecoverable engine surge;
- an engine flameout which requires flight crew intervention; and
- rollback due to ice accretion in the gas path causing unacceptable power loss

The group quickly chose to work on providing guidance for a possible sea-level test, considering mechanical damage as the first priority. It was also noted that mechanical damage and aerodynamic blockage are interconnected (dependent on ice build-up on a single stage).

For mechanical damage, the key is to be able to reproduce:

- Ice mass of solid ice accreted at a specific location at the instant of shedding
- Engine rotor speed at the time of shedding

These two characteristics could be replicated in a sea-level test.

The surge/flameout threat was considered a more complex issue (related to shedding and involving several stages) more tied to the altitude conditions, and probably more difficult to actually replicate at sea level. An altitude rig test and/or analysis and/or water ingestion test could be more adequate to address this threat.

In the case of a new engine certification program, two flight cases would have to be considered for mechanical damage:

- Steady state cruise case (covering also the holding condition)
- Idle descent case

6.3. Identification and Ranking of Key Parameters for a Ground Test

The Ground Test subcommittee agreed upon a list of key parameters for consideration during a sea level engine test in ice crystal icing conditions. These parameters were then assessed for their necessity in defining or determining an engine ground test; "high ranking" parameters were identified as critical to a ground test definition, whereas "low ranking" parameters were desirable but not critical to a test design. The complete list is available in the table hereafter with the selected ranking as well as:

- An identification of the parameters identified by the sub-group as needing additional research to better characterize their influence and how they could be adjusted/adapted for a sea level test
- Consideration from the sub-group about the engine and facility parameters that would need to be controlled or adjusted to match a given condition at altitude.

Table 4: Key Parameters for a Ground Test

Parameter	Ranking	Need for additional research before a ground test can be set up with reasonable level of confidence (Yes/ No)	Engine Parameter	Facility Parameter
Ice/water impingement rate (3D impingement contours)	High	No	Primary: Shaft rotation speed (LP/IP/HP), engine compressor airflow rate, engine thrust/power level. Secondary: Bleed schedule, Compressor Variable Stator schedule	TWC, T_{amb}, Air velocity, Particle Size Distribution
Need to correct for fan/bypass centrifuging	High or compensate by changing TWC at engine inlet plane	No		TWC
Bleed particle extraction	High	No		
Unrepresentative upstream ice accretion conditions (YES/NO) - Creating an ice mass threat for downstream rotor stage that would not be present in flight	High	Yes		
Local melt ratio	High in principle but could be low as far as accretion limits are fulfilled	Yes	Shaft rotation speed (LP/IP/HP), engine compressor airflow rate, engine thrust/power level	OAT

Parameter	Ranking	Need for additional research before a ground test can be set up with reasonable level of confidence (Yes/ No)	Engine Parameter	Facility Parameter
Evaporation	High	Yes	Engine power setting	OAT
Upstream temperature history	High	Yes	Primary: Engine power setting. Secondary: variable geometries, power offtake levels	OAT
Upstream surface interaction (interaction of ice particles with iced stages upstream of the location of interest)	Low (cover only erosion effect + flow field effect + particle trajectories differences)	No		
Any surface heating and temperature (including temperature of dry vane/wall surface)	High	No	Engine power setting, heat sources extractions (e.g. electrical heating, oil/air temperature…). Controlling the secondary air system or cavities or cavities temperature (A-sump & B-sump)	Ambient air or shop air (at any regulated temperature) for heating/cooling of the engine casing and vanes, OAT, non-type-design added insulation
Local wet bulb temperature (total? static?)	High in principle but could be low as far as accretion limits are fulfilled	No	Primary: Engine power setting, compressor airflow rate. Secondary: variable geometries, power offtake levels	OAT

Parameter	Ranking	Need for additional research before a ground test can be set up with reasonable level of confidence (Yes/ No)	Engine Parameter	Facility Parameter
Drag acting on ice before shedding point	Low at same engine power level or corrected shaft speed	No	Engine power setting	
Ice quality and shape	Low for the same mass of ice	No		OAT
Ice axial speed at impact	Low at same engine power level or corrected shaft speed	No	Shaft rotation speed (LP/IP/HP), engine compressor airflow rate, engine thrust/power level	
Maintain local particle drags constant	Low at same engine power level or corrected shaft speed	No	Engine power setting	Initial particle size; Particle generation method (e.g., shaved ice vs freeze- out)
Radial particle distribution inside the engine	Low at same engine power level or corrected shaft speed	No		Particle Size distribution. Initial particle size; Particle generation method (e.g., shaved ice vs freeze- out)

6.4. High Ranking Parameters

The parameters determined to be high ranking as per the table above are discussed in more details hereafter.

6.4.1. Parameters with no technology gaps

The first part of the discussion relates to the parameters that were also determined to be sufficiently defined that no additional research would be needed before a ground test could be set up with a reasonable level of confidence.

6.4.1.1. Ice/Water Impingement Rate

Replicating the correct range of ice/water impingement rate (3D impingement contours) from the test facility on the engine surfaces is important in order to show that a test of adequate severity is being executed on the engine at a sea level test facility. The impingement rate should be consistent with Appendix D conditions. Certain facility parameters which could influence the impingement rate include Total Water Content (TWC), Tamb, air velocity, and the particle size distribution (PSD) of the ice crystals. If using spray-bars, care should be taken to ensure the cloud is fully glaciated at the test article. Other considerations include having an appropriate minimum TWC threshold to cause accretion in the engine. There may also be a maximum TWC threshold which would cause continuous accretion and not allow for a steady-state equilibration of ice crystal accretions, which would therefore make test duration critical to a maximum accretion size.

The primary engine parameters which might require adjustment to accommodate or modify the impingement rate were identified as the shaft rotation speed(s) (LP / IP / HP), the engine compressor airflow rate, and the engine thrust or power level. Secondary engine parameters which could assist in adjusting the impingement rate include bleed schedules and the compressor variable stator vane schedules.

6.4.1.2. Centrifuging Correction Factor

The subcommittee decided that a ground test would need to be able to calculate a correction factor to modify the facility TWC used for engine testing to allow for fan or bypass centrifuging effects. It was noted that modifying the TWC at the engine inlet plane could potentially lower this parameter’s high ranking. Adjusting the centrifuge correction factor should be possible by maintaining a constant engine shaft speed of interest while changing the TWC at the engine inlet.

6.4.1.3. Bleed Particle Extraction

It was noted by the subcommittee that unrepresentative upstream ice accretion conditions may result in creating an ice mass threat for a downstream rotor stage during a ground test that would not be present in flight. Ensuring that bleed extraction design features are in use during ground testing is therefore a key condition to be considered during a ground test. Bleed offtake geometry and its extraction capabilities depend on the specific design features of each engine. Bleed extraction acts on ice crystals in the airflow as well as on shed ice.

6.4.1.4. Engine Surface Temperature (Surface Heating and Temperature)

Control or modification of engine surface temperatures during a ground test would be important in order to remain as similar as possible to in-flight surface temperatures. These temperatures could be controlled from facility parameters such as testing to particular ambient air temperatures, or introducing temperature-regulated shop air to heat or cool the engine casing or vanes, or adding non-type-design insulation to protect engine surface temperatures from the potentially large temperature delta between sea-level testing and temperatures experienced in flight. Engine parameters which would assist in controlling surface temperatures, including those of dry vane/wall surfaces, include the engine power setting, or heat source extractions such as electrical heating or oil/air temperature control systems. For example, surface temperature control within the engine could be accomplished via either controlling the secondary air system or cavities' temperature (A-sump & B-sump), or other means of surface temperature control if necessary.

6.4.1.5. Local Wet Bulb Temperature

The local web bulb temperature was determined to be a high ranking parameter in principle, however the importance of this parameter may decrease as limits of accretion are explored and defined. The main impact on wet bulb temperature is reduced evaporative cooling due to higher pressures at sea level. The wet bulb temperature would be influenced by outside air temperature (OAT) of the facility, especially if it is an outdoor facility; most current sea level icing test facilities are outdoors. Engine parameters which would influence wet bulb temperature include the engine power setting and compressor airflow rate. Secondary engine parameters which could influence local wet bulb temperature include variable geometries, or power offtake levels. It was noted that ambient humidity is considered to have a secondary effect as air travels downstream through the compressor.

6.4.2. Parameters with Technology Gaps

The following parameters which were identified by the Ground Test subcommittee were categorized as having a technology gap, i.e. these parameters are currently not well defined for an engine test, and industry believes they would require additional research before a ground test could be set up using these parameters.

6.4.2.1. Local melt ratio

The melt ratio of liquid water content to total water content (LWC/TWC) was determined to be a high ranking parameter in principle; however, the importance of this parameter may decrease as limits of accretion are explored and defined. As with the local wet bulb temperature described above, the local melt ratio would be affected by the outside air temperature of the test facility. Local melt ratio would be affected by the engine shaft rotation speed (LP/IP/HP), engine compressor airflow rate, and engine thrust/power level. Recent research has indicated that plateau thresholds exist for accretion – if the atmosphere is either too wet or too dry, accretion will not occur (Reference 21, 22, 23, 24, 25, 26). These parameters can move the LWC/TWC ratio and therefore could move the environment on or off the accretion plateau, or change the location of the melt ratio plateau within the engine. Adjusting either engine or facility parameters to match a local melt ratio would affect other sea-level test conditions, such as air velocity, particle centrifuging, impingement location, as well as affecting how those parameters relate to in-flight conditions.

6.4.2.2. Evaporation at Accretion Zone

Another consideration is knowing the evaporation in the gas path close to the location of interest. Evaporation of water at the accretion site would be affected by the test facility's outside air temperature and the engine power setting. It is necessary to be able to match the cooling effect of evaporation in-flight at a sea level facility. Ambient humidity is considered to have a secondary effect on wet bulb temperature at the accretion site, since it is anticipated that testing will be accomplished at colder temperatures (wet bulb temperature near 0 C).

6.4.2.3. Upstream Temperature History

The upstream temperature history would be affected by the test facility outside air temperature. The power setting was identified as the primary engine parameter which would affect the upstream temperatures within the engine, however secondary engine parameters include variable geometries, and power offtake levels.

6.4.2.4. Unrepresentative Upstream Ice Accretion Conditions

One consideration when conducting a sea level test is the possibility of creating an ice mass threat for downstream rotor stage that would not be present in flight, i.e. a false positive. Unrepresentative upstream ice accretions are not easy to influence without affecting the accretion at the location of interest. One possible mitigation is to monitor the surfaces of interest with ice detection sensors in order to provide useful information to aid in decision-making (e.g. whether it is appropriate to stop a test, or in order to improve understanding of test outcomes or in-service events).

A consideration for sea level test facilities is that engines may have to be run at sub-idle power settings in order to replicate the temperature rise profile throughout the gas path due to reduced evaporative cooling effect with denser air vs. being in-flight.

6.4.3. Low Ranking Parameters

The following parameters were identified by the Ground Test subcommittee as "low ranking" parameters as far as a sea level engine test is concerned. None of the following parameters were determined to require additional research before use in a ground test definition.

There are three further categorizations of the low ranking parameters. The first category included those parameters identified as low ranking when the engine power level or corrected shaft speed is maintained at a constant setting.

6.4.3.1. Maintaining local particle drags constant

This parameter would be affected by initial particle sizes at the test facility, as well as the facility's particle generation method, e.g. shaved ice vs. freeze-out created ice particles. The engine power setting would affect the local particle drag. A consideration to note is that adjusting for outside air conditions or the particle sizes in order to match particle drag may have an influence on the local melt ratio at the location of interest.

6.4.3.2. *Radial particle distribution inside the engine*

While the centrifuging effect of ingested ice was addressed above in the “high ranking” parameters, the radial particle distribution inside the engine is addressed down here. The distribution would be affected by test facility parameters such as particle size distribution (PSD), initial particle size, and particle generation method as described above.

6.4.3.3. *Drag acting on ice before shedding point*

This parameter would be influenced by engine power setting. However, if the engine test is limited to only identifying accretion, then this parameter is not important. If ice shedding is a consideration, the drag force of the ice is equally important to thermal effects, since drag is ρV2.

6.4.3.4. *Ice shedding velocity at impact*

The relative velocity of the shed ice pieces when they impact the engine rotating components would be influenced by engine parameters such as shaft rotation speeds (LP/IP/HP), engine compressor airflow rate, and engine thrust/power level.

6.4.4. Upstream Surface Interactions

The second category of low ranking parameters included the upstream surface interaction; that is, the interaction of ice particles with iced stages upstream of the location of interest. This parameter was identified as having effects on erosion, flow field, or influencing particle trajectories. The upstream surface interactions are not easy to influence without alternating the accretion at the location of interest. One possible mitigation is to monitor the surfaces of interest with ice detection sensors in order to provide useful information to aid in decision-making (e.g. whether it is appropriate to stop a test, or in order to improve understanding of test outcomes or in-service events).

6.4.5. Ice Quality and Shape

The third category of low ranking parameter was the ice quality and shape. This parameter was discussed as being low ranking for the same mass of ice, and being influenced by the outside air temperature (OAT) of the facility. Currently, the known effect of local temperature is on shedding. Ice from ice crystals is either from glaze or a mixed phase. The quality of shed ice is not expected to change much.

6.5. Challenges of Performing Engine Ground Tests in Ice Crystal Icing Conditions

Discussions within the sub-committee identified the difficulty of assessing operability issues with a sea level test, and the need to identify the key reasons for challenges associated with testing for compliance to 14 CFR Part 33 Appendix D conditions in comparison with 14 CFR Part 25 Appendix C. Some examples of these difficulties were comparing the physics associated with ice crystals vs. supercooled water droplets, and assessing a high altitude threat versus a mid/ low altitude threat.

The variables affecting a ground level engine test are divided in the following groups:

- Facility ambient variables, including engine inlet conditions:
    - Ambient temperature (SAT): this is limited on the lower end. Several engine ICI events occurred at altitudes higher than 25,000 ft. and ambient temperatures lower than -30°C (Reference 2). It is almost impossible for the existing ground level (non-refrigerated) test facilities to test at ambient temperature below -30°C. In ground test facilities the inlet air velocity is very low, therefore the facility SAT could simulate the altitude TAT; however, this is still not sufficient to test the whole range of flight SAT that goes down to -60°C at various Mach numbers.
    - Inlet IWC: this parameter can be adjusted either to match altitude conditions or generate different values than altitude for possible compensation.
    - Inlet particle size distribution: this parameter can be adjusted either to match altitude conditions or generate different values than altitude for possible compensation.
    - Inlet particle shape: this parameter can be adjusted either to match altitude conditions or generate different values than altitude for possible compensation.
    - Inlet particle temperature: this is a difficult parameter to control as depends on the ice crystal generation method (grinder or freeze-out of liquid droplets sprayed with nozzles) but it is not impossible.
    - Test duration: this parameter can be adjusted.

Inlet particle shape and inlet particle temperature both present a technical challenge to be controlled in order to match a given flight target, also in an altitude simulated test facility. The two technologies developed and matured at NASA and NRC to generate an ice crystal cloud (i.e. ice shaver and liquid droplet freeze-out approaches) could be transferred to a ground level facility.

On the other hand, there is no way to control the following parameters: altitude, flight speed and humidity. For humidity, it could be possible to increase the relative humidity, but not to reduce it. However, it was agreed within the group that humidity was a 'low' ranking parameter for a ground test.

Altitude (hence air density) and flight speed are the parameters that pose the key challenges for a ground test. This is further illustrated by the consideration detailed below.

Ice crystal rig tests carried out at NRC RATFac test facility at various ambient pressures (e.g. 34.5kPa and 69kPa) generated different ice accretion characteristics. Attempts to change other parameters, such as the melt ratio, in order to compensate for the altitude variation and obtain matched ice accretion were successful (e.g. [REF2]). However, similar adjustments are difficult in an engine ground test for a specific internal stage of a compressor, as changes will affect upstream stages, in particular for the high ranked parameters. The higher air density at increased pressure increases the dynamic pressure "q" for a given air velocity, which could reduce accretion growth by stripping ice and/or water from the accretion surface, either continuously or intermittently as shed events. This outcome is consistent with the aero-engine industry's understanding.

6.5.1. Internal compressor stage parameters with high importance:

As presented in the previous section ice accretion in a compressor stage strongly depends on the following parameters:

- Ice crystal impingement rate
- Ice crystal centrifuging effect
- Bleed particle extraction
- Engine surface temperature
- Local wet bulb temperature
- Evaporation (parameter with knowledge gap)
- Upstream ice accretion (parameter with knowledge gap)
- Local melt ratio (parameter with knowledge gap)
- Upstream temperature history (parameter with knowledge gap)

The engine non-dimensional parameters, compressor spool corrected speed and corrected mass flow rate, cannot be adjusted independently, both have a strong impact on most of the nine parameters listed above (bleed particle extraction being an exception).

The impingement and centrifuging effects strongly depend on the velocity field. The rotor speed and the air flow rate both affect the velocity distribution into the gaspath.

The internal component temperature distribution depends on convective heat in the gas path that is driven by the air temperature and velocity.

Being able to control and adjust the engine parameters such that the resulting conditions at a given engine stage replicate the condition seen at altitude is the key challenge associated with a ground test. Some industry members' experience clearly confirmed this challenge and highlighted the risk of creating ice accretion at other engine areas than the one targeted by the test. This experience confirms the high risk of performing ground tests that would not be adequately representative of the actual engine condition in an ice crystals encounter at altitude.

The sub-group noted the proposed engine inlet total temperature scaling method proposed by NRC (Reference 3). As already noted above, the group highlighted the added difficulty of being able to reduce the engine inlet total temperature in a ground test, both due to the inherent temperature limits of the outdoor facilities and/or on the associated effect caused by reduced engine speed and thus gaspath velocities. The group also shared the view associated with other complicating factors identified by NRC and requiring additional work to evaluate possible ways of adjusting other parameters (like IWC) for additional compensation.

The overall conclusion is that even if some avenues have been identified for ‘altitude scaling’, additional research work is needed before a robust method can be defined. The group also felt that despite all efforts, some limitations may not be overcome (limitations in temperature range, air density effect, too complex interactions between the various parameters…). This could limit the scope of a ground test which, as already mentioned could be used to assess some failure scenario and/or in combination with other means (e.g. determine the amount of accretion, and assess the ‘worst risk’ of damage potentially caused by this accretion through other means).

6.6. Discussion on Known Field Events vs. New Engine Certification Program

The ground test subcommittee discussed the role of ground test for ICI certification for a new engine certification program and the complexities relative to addressing a known field event of a specific type, such as ICI events that result in mechanical damage. The additional variables that must be considered make the use of ground test for new engine certification a challenging and complex process that will require well developed analysis tools and new test methodologies.

Known field events may have a reduced investigative scope relative to new certification, due to an assumed understanding of the flight conditions that resulted in the icing event. Aircraft operating conditions can then be translated to engine operating conditions with known quantities for inlet pressure, temperature, Mach number, IWC, rotor speeds and other environmental and engine operating states. An ICI analysis tool can then be used to adjust the altitude operating condition to specific ground test conditions to simulate the engine conditions at the location of interest. However, new engine certification requires consideration of the full Appendix D envelope and a thorough understanding of the engine susceptibility to ICI. Therefore, all possible aircraft and engine operating conditions and all associated operating variables must be considered to properly assess engine susceptibility to ice accretion for engine certification.

The preferred icing certification process is to conduct a critical point analysis to determine the most critical ICI point or points within the Appendix D envelope. Conducting a CPA requires validated analysis tools that will properly model all engine and ICI variables to determine if ice will accrete within the engine compression system. Ground test could then be used to test specific flowpath conditions identified in the analysis.

If validated analysis tools are not available, it could be necessary to test to table points at various engine operating conditions to ensure a robust assessment of the Appendix D envelope. The challenges associated with reproducing ICI accretion/shedding phenomena on the ground (ref to Section 6.5) make the solution of table points testing impractical as of today.

6.7. Conclusion and Recommendations

The ground test subcommittee believes that ground test could be used today as a means to replicate and therefore address/correct ICI known field events that have resulted in engine damage or aerodynamic blockage. However, engine certification for ICI must also consider ice accretion that may result in other undesirable engine responses such as rollback, flameout, engine surge, control system-related icing, etc. These types of engine responses involve complex physics and at this time it is not clear if ground test is a suitable tool to test for these in-flight engine responses. More work is needed to develop methodologies and complementing analyses to determine if ground test can be used to screen for these types of undesirable engine responses. The use of ground test for new engine certification is a much more complex task than the use of ground test to address a known field event. Use of ground test for new engine certification will require well developed analysis tools that can be used to conduct a CPA to limit test scope, properly scale test parameters to translate altitude conditions to ground test conditions, and assure robust engine operation in ice crystal conditions.

The ground test subcommittee work produced a list of parameters to be considered when trying to replicate an engine altitude ice crystal encounter in a ground test. A ranking of these parameters has been defined thus enabling the applicants who would wish to use a ground test as part of their compliance process to concentrate on those that are essential.

The sub group has also identified among these parameters those for which additional research is considered necessary in order to better characterize their influence on test outcome and therefore develop an understanding on how ground test conditions could be adjusted to better replicate them. These parameters are:

- Evaporation
- Upstream ice accretion
- Local melt ratio
- Upstream temperature history

The sub-committee recommends that further research is funded to continue to assess the ice crystals physics into the engine with focus on these four elements.

7. Industry Recommendations Regarding AC20-147a Susceptible Features List

7.1. Introduction and Scope

Section 9.s. of AC20-147A provides information which may be useful to a certification applicant in performing a comparative analysis in support of type certification, particularly in respect of the susceptible design features and mitigation features which may exist in the engine to be certified. Although it is recognized that comparative analysis will be used less in the future than it is at present, it was felt that this section will continue to be useful in highlighting the design elements which may influence certification. As such, this section of the current document provides recommendations for an update to AC20-147A Section 9.s.1. and 9.s.2.

The scope of the sub-group was to consider potential alterations to AC20-147A Sections 9.s.1. and 9.s.2.

The susceptible features sub-group had representatives from General Electric, Honeywell, Pratt & Whitney, Rolls-Royce and Transport Canada. Output from the sub-group was presented to the wider Engine Icing Working Group and further comments were received from FAA, NRC and Textron.

The existing susceptible features list is in AC20-147A Section 9.s.1. It was considered that this list will continue to be of value to a certification applicant and to the certifying authorities in identifying design features which may represent challenges for demonstrating compliance with the regulations regarding ice crystal icing tolerance.

7.2. Updated List Recommendations

The sub-group has proposed the following update to AC20-147A Section 9.s.1., with updates to the existing list marked by underlining:

Susceptible Design Features. These features could include:

a) Stagnation points which could provide an increased accretion potential, such as frame leading edges especially if upstream vanes direct or concentrate impingement upon the frame leading edge.
b) Exposed core entrance (as opposed to hidden core).
c) High turning rates in the inlet, in the booster and core flowpath (particularly compound turning elements), such as flowpath concavity.
d) Protrusions into the core flowpath (for example, bleed door edges and measurement probes).
~~e) Deleted. (Accounted for in (j) and (k))~~
f) Narrow vane-to-vane circumferential stator spacing leading to a small stator passage hydraulic diameter.
g) Variable geometry with stagnation points outside flowpath that could lead to accreted ice re-entering the flowpath upon geometry movement.
h) Airfoils with low tolerance to soft body damage immediately downstream of a potential ice accretion location.
i) Engine control sensors and measurement systems which may be affected by operation in ice crystal conditions and which may result in unacceptable control system response.
j) Negative air temperature gradient along the gas path resulting in a potential accretion site downstream of melting.
k) Surfaces with low temperatures downstream of or coincident with where melting could have occurred.

7.3. Rationale for recommendations

Since the original publication of AC20-147a, understanding of engine behavior in ice crystal conditions has improved. With this improved understanding, further design features have been shown to represent potential increased vulnerability to ice crystal icing. The recommendations for updates reflect this improved understanding, also aiming to improve the clarity of some features. Elements of the previous mitigation features list have also been incorporated in their negative to describe the vulnerability for which the mitigation is intended.

Additional description was added to items (a) and (c) in order to improve clarity for the feature concerned.

Item (e) previously read “Unheated surfaces on booster and front core stages”. As understanding of the ice crystal icing phenomenon has improved, the industry has learned that while ice crystals remain solid, there is limited possibility for ice accretion. Rather, it is necessary for some liquid water to be present in order to present an accretion threat, this liquid water normally being supplied through melting of the ice crystals. As such, the presence of heating upstream of a surface at a lower temperature has the potential to exacerbate the accretion risk and thus the lack of heating of surfaces can be beneficial. (Conversely, if heating is adequate to ensure that downstream accretion cannot occur, it will clearly be of benefit.) Rather than simply deleting item (e) from the susceptible features list, it was considered that the list should be updated to reflect the new understanding. Therefore, (j) is introduced to cover the scenario in which the air flowing through the compression system experiences a temperature reduction downstream of a region warm enough for melting to occur but upstream of an area cold enough for accretion, and (k) is introduced in consideration of a heated surface being upstream of a low temperature region. (k) also includes the scenario in which a heated surface may also be the accretion site itself.

Item (g) represents learning from in-service operation, in which it has been shown that ice accreted outside the main gas path, for instance in a bleed offtake, can potentially re-enter the gas path at a later time, thus representing impact and operability threats to downstream components.

Item (h) is the inverse of item (g) in the original mitigation features list.

Finally, it has been shown through in-service experience that engine control sensors may misread in ice crystal conditions and that this may have an adverse effect on engine operation. This is reflected in item (i). It is important to note that the issue for engine operation is not necessarily the functioning of the sensor itself if the control system is able to function satisfactorily in the presence of a sensor error. Examples of sensing which may be vulnerable to misreading in ice crystal conditions include temperature and pressure sensors and systems, such as T2, P2, T25 and P3. Following measurement errors, this may directly lead to degradation of engine control. The applicant should also consider specifically whether a measurement error in ice crystal conditions may lead to the inhibiting of ice protection systems. Also to be considered is that, in the case of measurements such as T3, the probe may sense correctly but the control system behavior may not be as expected if only assessed in dry operation, following the effect of ice crystal ingestion on gas path parameters.

7.4. Mitigation Features

The sub-group considered whether the mitigation features list was of value to certification applicants or certifying authorities. It was felt that the list was of limited value and potentially misleading.

7.5. Updated List Recommendation

The subgroup recommends that AC20-147a Section 9.s.2. be deleted.

7.6. Rationale for Recommendations

As engines are now increasingly designed specifically to ensure tolerance to the ice crystal threat in flight, the approaches taken by each of the engine manufacturers will differ, and novel approaches are continually being developed. As such, it is not feasible to present a comprehensive list of potential mitigation design features which will cover the breadth of engine designs available now or in the near to medium-term future. Furthermore, the mitigation features will frequently be confidential in nature and hence their disclosure in a published document would potentially violate each company's intellectual property management requirements. A final consideration is that some features, such as heating, may be beneficial in one application and harmful in another and that the inclusion of such elements in a mitigation features list may be misleading.

Given these considerations, the recommendation from the subgroup is that a mitigation features list should not be included in an update to AC20-147A.

8. General Recommendations

8.1. Compressor Delivery Pressure line freezing leading to loss of thrust control

14 CFR §33.28 (engine control systems) covers pressure line freezing ((b) Validation—(1) Functional aspects, (b) Validation—(2) Environmental limits, (e) System safety assessment and (j) Air pressure signal). Also, AC 33-28 provides guidance to the applicant to avoid blockage due to freezing water (Chapter 12-2.a). Nevertheless, melted Ice Crystals are not specifically mentioned as a potential source of water in pressure line. Therefore, the EIWG Analysis sub-group recommends to explicitly list Ice Crystals as a potential cause of freezing in the CDP line in a future AC 33.28 version in order to catch an applicant's attention on the issue.

9. Conclusion

This document was developed by the Engine Icing Working Group (EIWG) to address the FAA task letter sent to the AIA on 21 November 2016. It provides recommendations for development of appropriate simulated altitude tests for turbofan engines to help applicants perform rigorous engine assessments regarding ice crystal conditions and is meant to be included in a larger set of recommendations that can be used to demonstrate compliance with the engine ice crystal requirements defined in 14 CFR §33.68 and §25.1093.

Glossary

Acronym	Definition
2D	Two-dimensional
3D	Three-dimensional
AEDC	Arnold Engineering Development Center
AIA	Aerospace Industries Association
AIAA	American Institute of Aeronautics and Astronautics
AOA	Angle of attack
ARAC	Aviation Rulemaking Advisory Committee
ASTF	Altitude Simulation Test Facility
CPA	Critical Point Analysis
DoE	Design of Experiments
DOF	Depth of field
DvXX	Diameter at which XX% of spray volume occurs
EASA	European Aviation Safety Agency
EIWG	Engine Icing Working Group
FAA	Federal Aviation Administration
FOD	Foreign Object Debris, Foreign Object Damage
FOV	Field of view
HP	High Pressure
ICI	Ice crystal icing
IKP	Iso-kinetic probe
IP	Intermediate Pressure
IWC	Ice water content (g/m3) The measurement of the mass of ice in a cloud per unit volume of atmospheric air. [g/m3]
KFE	Known Field Event
LE	Leading edge
LP	Low Pressure
LWC	Liquid water content (g/m3) The measurement of the mass of liquid water in a cloud per unit volume of dry air. [g/m3]
M# / M#	Mach number
MMD	Median mass diameter, diameter at which 50% of spray mass occurs
MVD	Median volume diameter, diameter at which 50% of spray volume occurs

MW	Multi-wire probe (aka multi-element probe)
NASA	National Aeronautics and Space Administration
NRC	National Research Council of Canada
OAT	Outside Air Temperature
Po	Total pressure
PIV	Particle imaging velocimetry
PSD	Particle size distribution
PSL	NASA Propulsion Systems Laboratory
RATFac	Research Altitude Test Facility at National Research Council Canada
RH	Relative humidity
SAT	Static air temperature
SLD	Supercooled large drops
SWD	Supercooled water droplet
TAT	Total air temperature
TCCA	Transport Canada Civil Aviation
TE	Trailing edge
TRL	Technology Readiness Level
TWC	Total water content (g/m3) The amount of LWC + IWC per unit volume of atmospheric air. [g/m3]
Twb	Wetbulb Temperature (definition Pete / Dan)

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Appendix

1. Analysis

1.1. Non-desirable behaviors

To ensure that the most important ICI failure modes are addressed by the group, a severity priority level was assigned to each failure mode from the following list of potential non-desirable behaviors:

- Outcomes resulting from ice accretion in the gas path:
  - Outcomes resulting from Ice shedding:
    - Compressor Mechanical Damage from Ice Impact
    - Compressor surge from ice shedding
    - Combustor Flame-out from ice shedding
- Outcomes resulting from ice accretion without shedding within the engine gas path:
  - Gas path blockage
  - Cabin air bleed system blockage
  - Bleed blockage
- Outcomes resulting from instrumentation effects:
  - Inlet total temperature misreading leading to thrust limiting
  - Inlet total temperature misreading leading to inhibiting of ice protection systems
  - Inlet total pressure misreading leading to loss of thrust control
  - Compressor delivery pressure line freezing leading to loss of thrust control
  - Gas path temperature misleading leading to variable geometry malscheduling
- Other outcomes:
  - Compressor tip or seal rubs leading to surge
  - Compressor tip or seal rubs leading to mechanical damages
  - Ice crystal accumulation in rotating cavities leading to high vibration
  - Surge due to continuous ingestion of Ice Crystals
  - Flame-out due to continuous ingestion of Ice Crystals

1.2. Priority scale

The applied severity scales with their definitions are described below:

- **Priority level 1:** There are records of such non-desirable behaviors that led to engine effects falling into one of the four categories on which the AIA group is focusing (see AIA June 1st letter to FAA),
- **Priority level 2:** There are records of such non-desirable behaviors but so far, as far as the sub-group members are aware, none of them led to engine effects falling into one of the four categories on which the AIA group is focusing,
- **Priority level 3:** As far as the sub-group members are aware, there are no records of such non-desirable behaviors. They have a lower priority level due to their hypothetical character.

1.3. Failure modes Addressed in Analysis Sub-Group

Every failure scenario identified in paragraph **Error! Reference source not found.** have been assessed a ccording to the priority scale defined above in Section 1.2. Table 5 summarizes the results of these assessments.

Failure scenario	Priority level
Compressor Mechanical Damage from Ice Impact	1
Compressor surge from ice shedding	1
Flameout from ice shedding	1
Rollback due to gas path blockage	1
Compressor delivery pressure line freezing leading to loss of thrust control	1
Ice crystal accumulation in rotating cavities leading to high vibration	2
Compressor tip or seal rubs leading to surge	2
Bleed blockage	3
Compressor tip or seal rubs leading to mechanical damages	3
Surge due to continuous ingestion of Ice Crystals	3
Flame-out due to continuous ingestion of Ice Crystals	3

Table 5: Summary of the Priority Assessments of Failure Scenarios

2. Simulated Altitude

2.1. Simulated Altitude Test Facility Descriptions

2.1.1. NASA Propulsion Systems Laboratory (PSL), Cleveland, OH

The NASA PSL provides experiment and evaluation capability in support of NASA's research and technology studies of turbine engine altitude performance, engine component evaluation and engine icing studies at altitude. In addition, the facility also supports the Department of Defense and private industry with engine and component evaluation and verification tests.

PSL includes two test facilities that are capable of simulating flight at up to 90,000 ft. and a maximum forward air speed of Mach 3.0 in PSL-3 and to Mach 5.0 in PSL-4. Each test cell is 24 ft. in diameter and 38 ft. in length. In 2012 PSL-3 was modified to include engine icing capability which enables ice crystals and supercooled liquid drops to be provided to the engine face using city water or de-ionized water to simulate icing events at altitude.

PSL-3 is a direct-connect facility that can accommodate engine and rig diameters of 24 to 84 inches. A facility layout is provided in Figure 10. The facility inlet air is provided by the NASA Central Process System (CPS) combustion air which delivers pressurized clean, dry, and ambient temperature air. The air passes through up to three parallel configured turbo-expanders which can cool the air to -50ºF, at a pressure of 25 psia, and flowrate of 110lbm/sec each for a total maximum mass flowrate of 330 lbm/s. The air can be injected with steam. This fully-mixed steam-infused air enters the plenum and passes through the icing spray bar grid where it is then injected with an icing cloud. The ice particles are formed by the rapid freeze-out of the water droplet cloud generated from the spray bar system. The tunnel walls are grounded in order to prevent the static cling of ice crystals on the wall. Once the air passes through the engine, the air is then exhausted into the chamber which is being pulled to 2.5 psia by the CPS altitude exhaust system. The facility conditions are set by adjusting the tunnel inlet pressure to achieve the desired Mach number and the exhaust pressure to maintain the altitude. The PSL-3 operating capabilities are shown in Table 6. When PSL-3 is configured for ice crystal icing tests, the separate bypass airflow is closed off to prevent any potential ice buildup in the bypass duct. Therefore under icing configurations the facility has limited ability to simulate rapid throttle movements. Additional details on the various PSL subsystems and capabilities can be found in the PSL Customer Guide Manual.

The icing systems consists of ten spray bars (Figure 11) which are installed in the PSL-3 inlet plenum, just downstream of the inlet screens and flow straighteners. The spray bars utilize two types of flow nozzles. They are both internally mixed nozzles using the differential between water and atomizing air pressure to set droplet size. See Figure 12 for nozzle configuration. The nozzles are similar to those used at the NASA Icing Research Tunnel, with differences in the discharge tube diameter. These different tubes allow for fine flow control. The smaller diameter nozzles, called Mod1 nozzles, are used for low flow conditions and the larger diameter nozzles, called Standard nozzles, are used for medium and high flow conditions. Each nozzle is flow checked and nozzles within +/- 2% of the average are used in the spray bars to provide a uniform water flow rate. There are 112 Mod 1 nozzles and 110 Standard nozzles. On each of the spray bars the nozzles are mounted 6” apart, so that every type of nozzles is repeated every 12”. Each spray condition utilizes one type of nozzles but each nozzle can be individually selected on or off so for a custom spray pattern and cloud intensity. The spray zones are divided into three zones so that pressure regulators can accurately set supply pressure and account for changes in pressure due to height.

Cloud Calibration— the facility offers a wide range of conditions available for testing, because of this a calibration is required for each icing entry. The calibration parameter space consists of based on reference 4:

- Inlet duct size from 24 to 84 inches
- Pressure altitude from 12.7 to 2.78 psia, corresponding altitudes from 4 to 40 kft
- Mach up to 0.8 or Air Mass Flow Rate from 50 to 330 lbm/s
- Inlet total temperature from -60 to +50 F
- Plenum relative humidity from ambient (0.3 to 3%) to 50%.
- Nozzle set, Standards or Mod1
- Water Pressure from 10 to 350 psid
- Air Pressure from 5 to 90 psid
- Water Temperature from 45 to 180 F
- Air Temperature from 45 to 180 F
- Water source from ‘city’ to de-ionized
- Spraybar Cooling Air Pressure, optional, from 5 to 30 psid

- Spraybar Cooling Air Temperature, optional, from -20 to 40 F

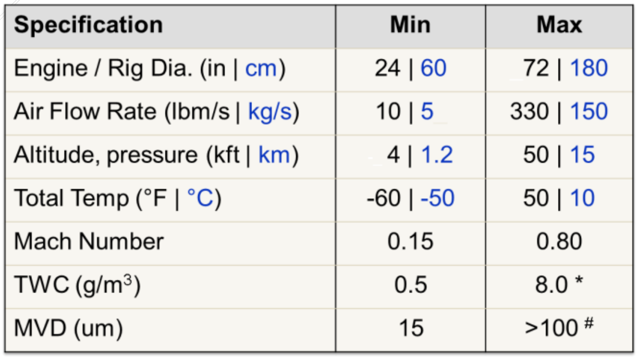
During a calibration, the cloud is characterized by documenting the uniformity, total water content, particle size, and (currently still under development) particle temperature. Aero-thermal measurements are also made at this time. PSL has conducted four cloud calibrations which covers a small region of the facility and Appendix D envelope, as shown in Figure 6.4. Details about the calibrations can be found in references 2-5.

Facility Limitations—Although PSL-3 has the ability a produce a fully controllable cloud at realistic flight conditions the facility does have several limitations that should be noted. The facility maximum mass flow rate is 330lb/s which limits the use of the facility to smaller engines, clipped fans or driven core rigs.

For transient conditions, PSL-3 cannot perform traditional rapid throttle movements when the icing system is installed. However, if the applicant can accept a slower throttle movement and an unsteady temperature profile, a throttle movement on the order of 30 seconds can be accommodated, depending on the flight conditions. The facility has demonstrated the ability to perform a descent, however during an ascent/ descent operation, similar to the rapid throttle movement, the facility cannot well maintain a typical temperature profile. Lastly, PSL has the ability to simulate a cloud transients. Depending on the change required, this can be instantaneous, or cloud momentarily off to load the new cloud profile. Currently, more testing is needed to understand and address modifications needed to improve the transient operations under icing conditions in PSL.

PSL-3 has shown it can produce fully glaciated crystals up to 80 µm MMD however environmental characterization have shown much larger size distributions. Previous tests in PSL have shown that the icing events can still be replicated presumably due to the particle breakup from the fan.

Icing Tests—PSL-3 was used to test the Honeywell un-modified ALF502 engine. The facility was able to successfully replicate the known power-loss field event. The facility replicated the flight and environmental conditions based on the available characterization of the test flight. The crystal particle size was not replicated. The facility also demonstrated ability to simulate peak cloud intensity and flight descent scenarios. Details on these tests can be found in PSL references 6 through 9.



Specification	Min	Max
Engine / Rig Dia. (in | cm)	24 | 60	72 | 180
Air Flow Rate (lbm/s | kg/s)	10 | 5	330 | 150
Altitude, pressure (kft | km)	4 | 1.2	50 | 15
Total Temp (°F | °C)	-60 | -50	50 | 10
Mach Number	0.15	0.80
TWC (g/m^3)	0.5	8.0 *
MVD (um)	15	>100 #

Table 6: PSL-3 Icing Capabilities (Ref 4)

* Evidence that probe under-measured

Particles larger than ≈ 100 µm are NOT fully glaciated.

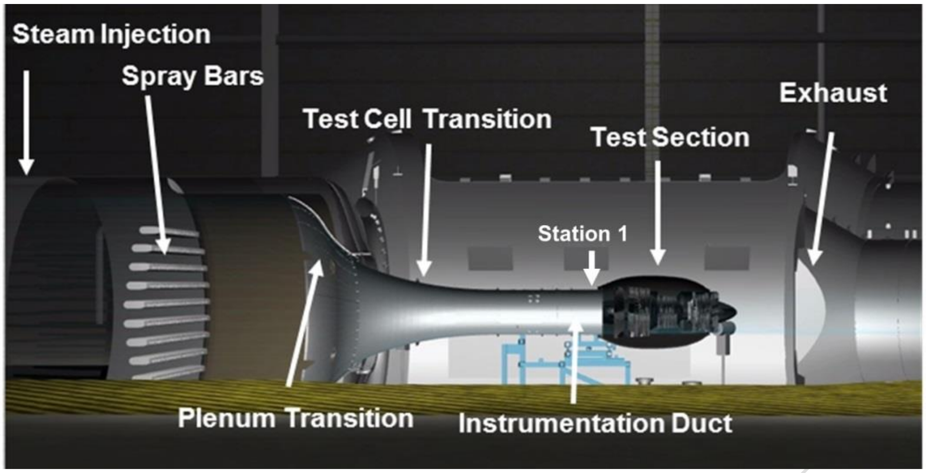


Figure 10: PSL-3 Facility Layout (Ref 8)

Figure 11: Spray bars mounted in PSL-3 inlet plenum (Ref 1)

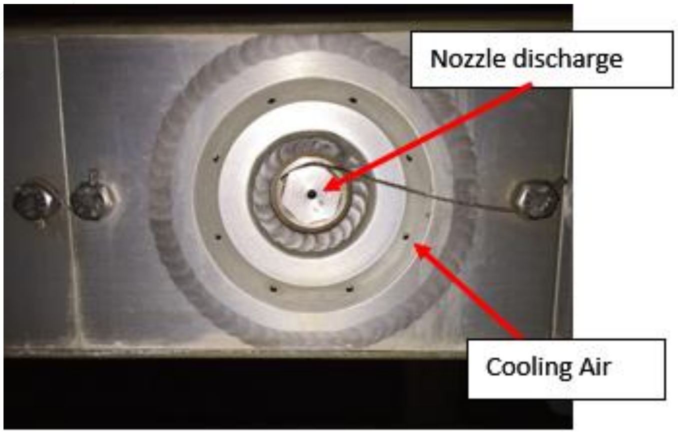


Figure 12: Spray nozzle mounted in spray bar (Ref 1)

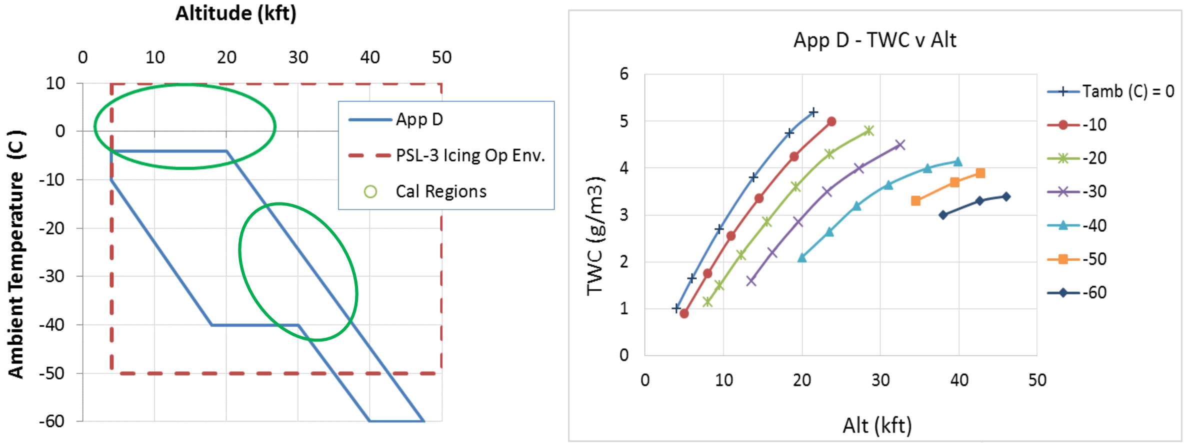


Figure 13: Cloud characterization regions to date with respect to Appendix D and PSL Icing Operating Envelope, based upon Ref 4

2.1.2. USAF Arnold Engineering Development Center (AEDC) Aeropropulsion Systems Test Facility (ASTF), Arnold Air Force Base, TN, USA

At the time of publication AEDC has not and does not perform Mixed Phase and Ice Crystal Icing engine testing. AEDC has collaborated with the NASA PSL-3 team to determine what efforts would be needed to be able to perform ICI testing in the Altitude facility. Depending on commercial customer support AEDC will evaluate the option to modify the facility as needed to perform MP and ICI icing tests. For more information please contact Stephen Arnold, Aeropropulsion Technical Advisor, at AEDC.

2.2. Additional Considerations

2.2.1. Simulated Altitude

These items are topics that came up during the team's normal discussions concerning Simulated Altitude Testing for Ice Crystal Icing as a potential MOC for 14 CFR §33.68. While these items were relevant to the topic, they are listed in this Appendix for future consideration. The reasons for non-inclusion in this version are the following:

- Low value / priority as determined by the either the EIWG group at large, or by the Simulated Altitude Test sub-group, in an effort to use the team's limited resources to capture the highest value topics within the 24-month timeframe for the project
- Current knowledge on a topic was too low to include meaningful guidance in this report

2.3. Future Considerations Regarding Compressor Component Test

Since this team had the most available knowledge concerning a full engine failure scenario, the team decided to focus on that scenario first. However, the team recognizes the large value in developing the processes and methodologies for compressor rig testing for ICI. Currently NASA PSL-3 is the only simulated altitude facility that has run ICI engine tests, which is limited to 330 lbm/sec airflow and 72” diameter. But since many of the ICI events occur at altitude where the physical flow requirement is lower than at sea level, this allows potentially larger engines to be tested. However, the compressors from those large engines could be run within those limits and could provide meaningful insights into ICI with that compressor. The other main benefit to performing an ICI test on a compressor rig is that a rig can typically accommodate more instrumentation, including cameras. One of the main issues that would need to be addressed would be how to adequately represent the effects of the fan upstream of the compressor in preparing the ice crystal flow into the core. These effects include short distance air and particle temperature rise and subsequent melting, and particle breakup and trajectory. The other main issue that would need to be addressed for a compressor rig test are the infrastructure needed to drive the rig.

To support the development of component tests, further research on mixed phase environments is needed.

2.4. Future Considerations for Mixed Phase Cloud Environments

The team’s starting scenario was to assume a fully glaciated cloud. That represents the majority of field events to date, and it represented a less complex scenario for the team to develop guidance on. If future field events are tied to mixed phase environments, it would be appropriate for a follow-on team to develop guidance specific to representing the mixed phase environment. Since testing with mixed phase represents a more complex test, test facilities would need to participate heavily in that effort.

2.5. Future Considerations to Evaluate Transient Updraft Effect (spike up in IWC), or an alternating cloud

The team’s starting scenario was a specific set of field events which occurred at steady state cruise conditions. It is unknown how many actual field events are due to the updraft effect, or to what extent the updrafts exist. As more field engine event data and atmospheric measurements become available, evaluating the updraft scenario can be started. For example, how do you pick the different levels of IWC in an updraft or alternating cloud? The updraft IWC level could be revisited after the ARAC effort is complete.

2.6. Future Considerations for Evaluating Climb and Descent Scenarios:

The team’s starting scenario was a specific set of field events which occurred at steady state cruise conditions. It was determined that the team should focus on steady state conditions, then once processes for that condition are well understood, the more complex scenario involving changing inlet conditions could be pursued. It is recognized that field events have occurred and are continuing to occur during climb and descent parts of the flight mission. As of the time of this publication, several difficulties have been identified for test facilities when attempting to perform altitude transients. Multiple parameters must be changed precisely and simultaneously throughout an altitude transient. While it is thought that altitude transients could eventually be attained, it was determined that pursuing that goal was beyond the time resources of the team. A potential option may be small stepwise changes to achieve simulated field events.

2.7. Additional Information on the Ranking of Parameters

The parameters that define an ice crystal icing encounter can be described in two groups: the environmental parameters, including both aircraft flight parameters and the icing environmental parameters, and then engine operating details. Each parameter has a level that describes the value in understanding and simulating an ICI encounter. The Value qualifier is given as a V1, V2, or V3, with V3 being the most important. In addition, each parameter has a level that describes the difficulty of understanding and simulating an ICI encounter. The Difficulty qualifier is given as a D1, D2, or D3 with D3 being the most difficult. The environmental detailed parameters (including the Value and Difficulty parameters) are:

- aircraft flight parameters, consisting of
    - altitude (V3, D1),
    - Mach number (V2, D1),
    - total air temperature (TAT) (V3, D1) and
- Icing environmental parameters consisting of
    - Ice Water Content (IWC) (V3, D2 for field data and V3, D1 for altitude test),
    - Liquid Water Content (LWC) (V1, D2 for field data and V1, D1 for altitude test),
    - relative humidity (V1, D2 for field data and V1, D2 for altitude test),
    - particle temperature (V1, D3),
    - particle size (V1, D3),
    - particle size distribution (V1, D3) and
    - Particle shape (V1, D3).

The engine operating detailed parameters (including the Value and Difficulty parameters) are:

- flight phase including engine power level (V3, D1),
- accretion location (V3, D3) for Field data, flight , (V3, D1 for controlled test)
- wet bulb temperature at accretion location (V1 if accretion location is known, or V3 if accretion location is not known, D2 for field data and V1, D1 for altitude test),
- ice crystal melt ratio at accretion location (V1 if accretion location is known, or V3 if accretion location is not known, D2 for field data and V1, D1 for altitude test),
- engine cycle parameters prior to cloud entry (V3, D1),
- engine cycle parameters at peak threat (V2, D3 for field data and V2, D2 for altitude test),,
- anti-icing system performance (V2, D1) and
- Engine bleed extraction (V2, D1).

The highest value (V3) environmental parameters are:

- altitude,
- TAT and
- IWC.

Aircraft Mach number is assigned a lower value of V2, because TAT defines the inlet conditions into the engine and can be derived from aircraft Mach number and static air temperature.

The highest value (V3) engine operating detailed parameters are:

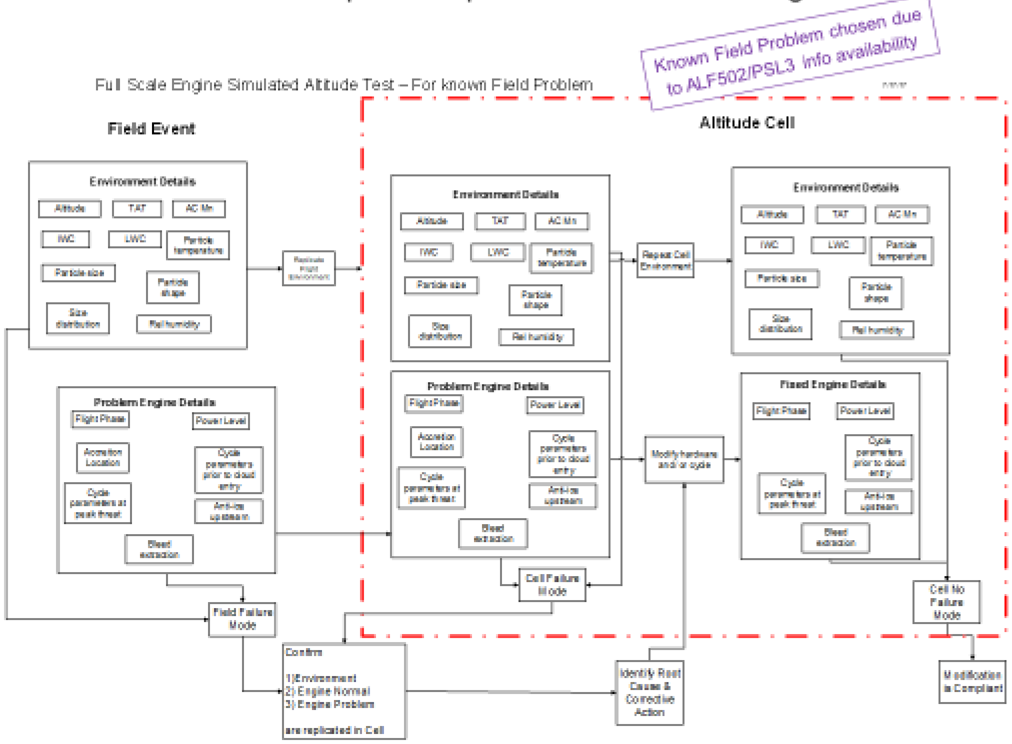
- flight phase including engine power level,
- accretion location and
- Engine cycle parameters prior to cloud entry.

These are the most highly valued parameters that can be used to understand root cause of a known field event or to set up the simulated altitude test.

Particle properties (i.e. size, size distribution, shape and temperature) are of lower value. Given the current knowledge on today's turbofan engines, it is generally accepted with limited data that particle breakup occurs during travel through initial rotating (and stationary) blade rows for all turbofan engines until it reaches a small enough size that minimal interaction with the blade rows occur. This breakup also means that particle size distribution and shape are of lower value as well. However, other engine types may not experience this level of breakup, and additional analysis can be used to show how particle size and distribution play a role in the proposed testing. If particle size is critical, the selection of the ice crystal generation equipment may play a role such as whether one uses a grinder or spray bar facility to generate ice crystals by freezing water droplets. The same can be said for the criticality of understanding particle temperatures, which can rise rapidly through the rotating stages of turbomachinery increasing the melt ratio and therefore possible accretion. The initial particle temperature is of lower value and is very difficult to measure. However, if particle temperature is critical for an application, then the testing would have to be defined to clearly identify the initial temperature of the particle. Future research may provide additional insight into the influences of dynamic particle morphology on accretion effects

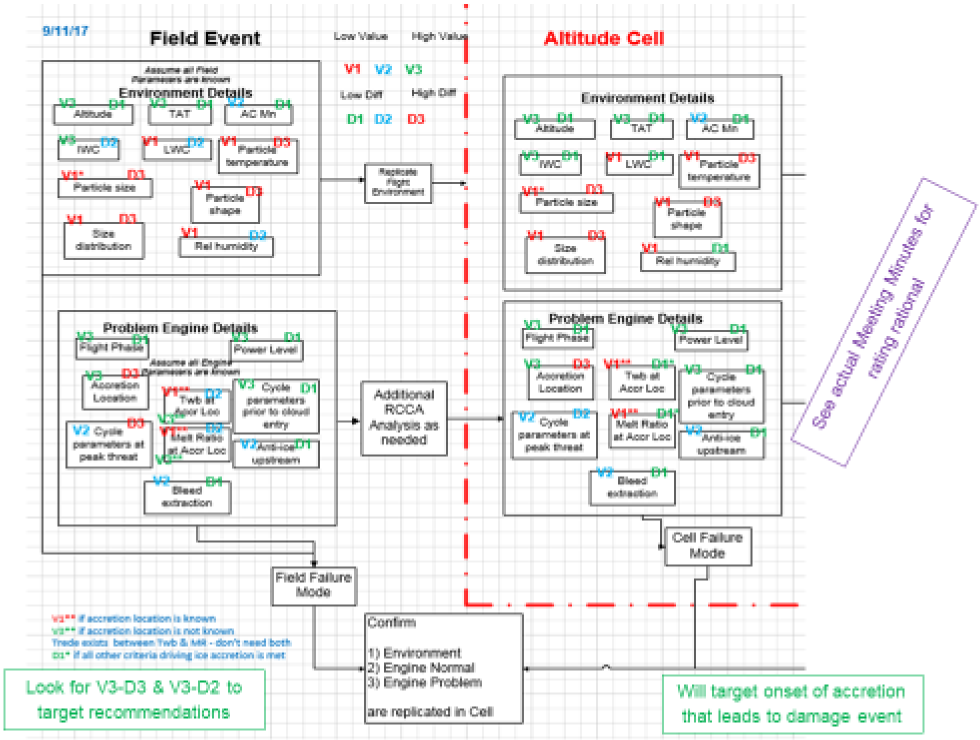
These Value and Difficulty rankings defined above can be used for guidance when assessing how much effort or importance to put into various parameters when preparing for a simulated altitude test.

Started with Process Map from April 2015 EIWG Meeting – Wash D.C.



Known Field Problem chosen due to ALF502/PSL3 info availability

Assigned a Value and Difficulty Rating to Each Parameter



Look for V3-D3 & V3-D2 to target recommendations

Will target onset of accretion that leads to damage event

See actual Meeting Minutes for rating rational