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Aviation Research Division
Atlantic City International Airport
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Engine Ice Crystal Icing Technology Plan with Research Needs

September 2020

Final report

U.S. Department of Transportation
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16. Abstract

This report identifies technology gaps and research needs for engine ice crystal icing. In recent years, substantial progress has been made (over 80 significant papers) toward an understanding of the physics of ice crystal icing accretion in engines. A survey of this literature is the basis for this report. This document uses an ice crystal icing case as an example to describe the icing processes while presenting new terms to facilitate precise descriptions. The icing case is for the Lycoming ALF502R-2, which was tested in NASA’s Propulsion Systems Laboratory. During the testing, the in-service failure mode was reproduced and video recordings of the internal engine icing phenomena were captured, one of which was made public. This video allows researchers to see for the first time ice crystal icing in an actual engine, providing an opportunity to re-focus research emphasis. Research needs are identified based on arguments presented in each section.

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Acronyms and Terminology[1]

Acronym	Definition
Air melt ratio†	Liquid water/total water entrained in the air at the accretion site
ALF502R-2	Lycoming engine which experienced rollbacks, serial number LF11 was used for the testing with video documentation
Anchoring	Freezing at the interface between the water and the wall (removal of the heat of fusion at 0^{o}C)
Anchored area	A portion of surface area at the wall under an ice deposit which is frozen
Bridging	Ice deposits which are supported in place by engine hardware, such as across the passage between two adjacent vanes
Cloud TWC threshold	A minimum total water content required to cool the surface sufficiently so that ice crystal icing occurs in an engine. This refers to the TWC entering the engine in a test or an aircraft cloud encounter.
Coalescing	To come together to form one mass. (A general term, to be replaced by more exact terminology once the process is understood.)
Comprehensive melt ratio†	Liquid water/total water, specifically all the water and ice at the local accretion site, involved in the heat transfer sufficient for no-shed ice growth
EGV	Exit guide vane
EHWG	Engine Harmonization Working Group – an Aviation Rulemaking and Advisory Committee active in 2003-2005 tasked to consider Mixed Phase and Glaciated Icing
EIWG	Engine Icing Working Group – an industry association under the Aerospace Industries Association for the purposes of coordinating icing research and means of compliance
FAA	Federal Aviation Administration
HAIC-HIWC	High Altitude Ice Crystals – High Ice Water Content a joint European and North American effort to measure atmospheric ice crystals
Harmless build/shed cycle†	Small ice deposits develop but shed as aerodynamic forces exceed adhesion forces (ice size is not a threat)
HPC	High pressure compressor
ICC	Ice Crystal Consortium – an industry association under the Aerospace Industries Association for the purposes of fundamental ice crystal research

[1] This document introduces a number of new terms meant to aid clear descriptions of the icing processes taking place, and to indicate clear differences with previous terminology. They may provide utility only for this document, and are not necessarily to be adopted by the scientists and modelers. These terms will be noted with a † symbol

Acronym	**Definition**
ICI	Ice crystal icing
IWC	Ice water content, grams of ice/cubic meter of dry air
LPC	Low pressure compressor
Melt Ratio	The ratio of liquid to liquid + ice as a percent by mass. See air melt ratio and comprehensive melt ratio.
MVD	Median volumetric diameter
No-shed ice growth†	Ice deposits continue growing, even in places where the harmless build/shed cycle was present previously
NRC	National Research Council of Canada
PSD	Particle size distribution
PSL	Propulsion Systems Laboratory, NASA Glenn altitude engine icing test facility
Qdot	Rate of heat transfer
RN	Research need
Slush	Ice particle impingement on a water film to form an unconsolidated 2-phase mass. If in motion, it is propelled by the airflow
Sticking efficiency	The fraction of the incoming ice and liquid water to a surface region which stays on the surface region
Twb	Wet bulb temperature
TWC	Total water content grams/cubic meter growth
Volume of interest†	A volume at the wall icing site which contains all the water, ice and ice deposits involved in the icing process, leading up to no-shed ice growth at that location

Executive summary

This effort was initiated in 2004, when the Engine Harmonization Working Group (EHWG) identified the primary cause of jet engine power-loss in icing was related to mixed-phase/glaciated conditions. In 2005, the EHWG developed the EHWG Mixed-Phase/Glaciated Icing Technology Plan V1.1. It included Task 3, which focused on identifying testing to "provide data and other information for engine manufacturers in their efforts to construct the necessary ice accretion models and tools for design and certification of new engines in Mixed Phase/Glaciated icing conditions." The database from these tests was envisioned to support the industry efforts for developing and validating the required ice crystal analytical tools.

Since 2005, research has been conducted in support of Task 3, both in North America and Europe. The purpose of the current revision to the Technology Plan, Task 3, is to identify remaining technology gaps and research needs for ice crystal icing. To date, significant progress has been made (over 80 significant papers) toward an understanding of the physics behind ice crystal icing accretion in engines. A survey of this literature is the basis for this report. The survey identifies the need to develop a common terminology, which is addressed in this revised plan.

Capitalizing on recent research providing video documentation of the complex icing phenomena, this document uses a known ice crystal icing case as an example and describes in clear detail the icing processes while presenting new terms to facilitate precise descriptions. The known icing case is for the Lycoming ALF502R-2, which has been tested in NASA's Propulsion Systems Laboratory. During the testing, the in-service failure mode was reproduced, video recordings of the internal engine icing phenomena were captured, and one of these was made public. This video allows researchers to see for the first time ice crystal icing in an actual engine, providing an opportunity to re-focus research emphasis. The ice crystal icing growth in the video has features that are different from the well-understood physics of supercooled droplet icing, chief among them the importance of time-dependent heat transfer at the wall.

The document is organized in order of the processes that take place as an ice particle in the atmosphere enters the engine and proceeds downstream to an icing site. As each aspect of the icing phenomenon is presented, existing research is identified and compared to icing phenomena inside the engine as shown in the video, with the goal of illuminating the physics that is still lacking. This revision provides the opportunity to highlight key icing processes that have not yet been the focus of research; among these are ice anchoring and the process by which an ice deposit does not shed and continues to grow.

Throughout the document, research needs are identified and italicized. The research needs are best understood in the context of the preceding arguments presented in each section. These arguments should be kept in mind if the research needs are extracted and presented in a stand-alone document. In order to leave the development of solutions to expert researchers, this plan only suggests research approaches in the cases where the problem boundary conditions are vital to the replication of the engine icing process. Similarly, this plan only suggests instrumentation needs when the measurement is vital to finding the solution to the research need.

1 Introduction

1.1 Goal of the plan

In 2005, EHWG Mixed-Phase/Glaciated Icing Technology Plan V1.1 [1] was developed by the Engine Harmonization Working Group (EHWG) before disbanding. The four general categories of research needs were stated as:

- Task 1. Instrumentation Development and Evaluation for High Ice Water Content
- Task 2. Flight test research and modeling for characterization of high ice water content environments
- Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments
- Task 4. Test facilities requirements for demonstrating engine compliance with Appendix D requirements.

In the 2005 document, the focus of Task 3 was the identification of testing to provide data and other information for engine manufacturers in their efforts to construct the necessary ice accretion models and tools for design and certification of new engines in mixed phase/glaciated icing conditions. The database provided by these tests was envisioned to support the industry efforts for developing and validating the required ice crystal analytical tools.

The current update is limited to Task 3 and does not change the overall goals as stated. This document will outline in detail the ice particle accretion process in a compressor flowpath based on recent work by many researchers, describe how well fundamental testing has reproduced engine conditions, and identify technology gaps at this time. Where possible, suggestions for focus of further research will be included. Knowledge of ice crystal icing is being continually improved; therefore, no plan can cover every detail. One aim of this plan is to foster discussion and debate over the fundamental ice crystal icing process, and the important factors in that process. Since this plan is based on currently public research, it is expected that it will be updated to include further discoveries meeting research needs.

1.2 Organization of the plan

There are several possible approaches to organizing an ice crystal icing (ICI) technology plan, all of which can be effective, but each with a different focus. Task 3 in the technology plan drafted by the Engine Harmonization Working group in 2005, and updated in 2008, focused on simulation methods. Organized by test methodology, it stepped through the successively more complex test methods by which the parametrization of ice crystal icing physics could be derived. Another approach could follow the Engine Icing Working Group (EIWG) document, “Engine Icing Working Group Industry Guidance on Means of Compliance for Engine Operation in Ice Crystal Icing” [2], which is organized by the possible means of compliance, from rig test to full-scale engine test to analysis, documenting the technology needs of each. There is some duplication between these two approaches, as simulation methods and means of compliance have common technology needs.

Since the focus of this technology plan is to identify technology needs for an understanding and parametrization of the fundamental physics of ice crystal accretion, this document is arranged in the order of the physical processes that affect an ice particle as it travels through the engine to the accretion site, followed by the accretion process itself. The current reality is that scientists and researchers have been able to study few details of the actual engine ice crystal icing accretion events due to proprietary concerns, and much of their understanding of the phenomenon comes from simulations at various research institutes. Thus, there are a variety of viewpoints as well as variation in terminology. Therefore, each section of this document begins with a detailed description of the ice crystal icing process (as known today) and definitions of existing and new terminology in an effort to introduce a standardized terminology. This revision comes at a moment when some very representative and useful public data is available, affording a very close look at the processes involved in ice crystal icing in an engine.

1.3 Meteorological conditions associated with engine events

The study of the meteorological conditions associated with engine power-loss and damage events has been underway since 2005 and addresses Tasks 1 & 2 of the EHWG technology plan. For a detailed description of the weather associated with engine events, the reader is referred to DOT/FAA/TC-18/1, *An Assessment of Cloud Total Water Content and Particle Size from Flight Test Campaign Measurements in High Ice Water Content, Mixed Phase/Ice Crystal Icing Conditions: Primary In-Situ Measurements* [3], section 3.2. *Observations and Hypothesis of Meteorological Conditions Causing Engine Events.* For the purposes of this document, it is important to understand that the hypothesis includes only glaciated conditions (no liquid water present), very small ice particles, and cold ambient temperatures (well below freezing). While the tasking for the work originally covered mixed phase and glaciated icing, the EHWG found that no appreciable supercooled liquid was present in the atmosphere for the engine events. The terminology “ice crystal icing” has been adopted and will be used here.

In 2006, Chow [4] proposed a hypothesis to explain the ice accretion phenomenon inside the engine, following successful resolution of the in-service issue.

Evidence gathered since this date have partially supported his theory, which will be repeated here, in order to emphasize questions that remain. Modifications or additions to the theory based on further research are indicated by insertions in square brackets.

> The exact mechanism for ice accretion is not fully understood at this time; however, a hypothesis was developed based on the flight test results as follows. As soon as the engine enters glaciated/mixed phase conditions, both liquid and ice particles coexist on the warm EGV surfaces. The presence of liquid on the surface slows down the ice particles, allowing heat transfer between the metal and ice particles to take place. Heat removed from the metal reduces its temperature until the freezing point is reached, and ice forms. After this point, it is contended that further impingement of liquid and ice particles on the metal surface would accrete as ice even with a local air temperature higher than 0 degrees C.
>
> Accretion will continue to grow as long as both liquid water and ice particles continue to impinge on the ice surface [or reach the accretion site by running back], increasing the size of the blockage until the engine can no longer function properly. It should be noted that liquid water is a necessary condition locally at the EGV for ice accretion to continue. If there is no liquid water in the air stream [or arriving from upstream], ice particles will bounce off the iced EGV surface in a way similar to what happens on the wing or the inlet of the engine. This phenomenon has also been observed in mixed phase icing tests with supercooled liquid droplets and ice particles performed by Al-Khalil et al. (2003)[5] in the Cox and Co. LeClerc icing wind tunnel. Since significant amounts of supercooled liquid water were not recorded by the weather instrumentation during the flight test, it is hypothesized that either only a very small amount of liquid water, ingested by the engine, is required for this process, or that the liquid water impacting the EGV is actually produced by the melting of minute ice particles as they pass through the front section of the engine. Further research is required to identify the source of this liquid (and describe how it runs back to the accretion site).

The hypothesis that both liquid water and ice particles are needed for ice crystal icing to take place inside the engine has been borne out through experiment. This update extends and modifies the hypothesis embodied in the quoted passage by demonstrating that the liquid may not need to be entrained in the air as it reaches the accretion site. An important addition to the hypothesis addresses the formation of a liquid and ice film moving along the wall of the compressor before forming an accretion site.

1.4 Description of ice crystal icing process in an engine

This document outlines the ice crystal icing process occurring in a generic two-spool turbofan engine, having a fan and a 4-stage low-pressure compressor (LPC). The design of the downstream components is not germane to this discussion.

A 4-stage LPC is chosen since air temperature rise and ice crystal fragmentation occurs prior to ice formation (accumulation or accretion) toward the aft end of the LPC. Temperature rise and ice crystal fragmentation are fundamental to the ice crystal icing phenomena and are boundary conditions present in smaller LPC's, such as the ALF502R-2 engine discussed below. Since the majority of icing events occur at cruise, the description will be for a case at high altitude and cruise power. This flight condition is chosen so that appropriate melting conditions occur toward the aft of the LPC. Specifying a specific engine location for the following discussion allows readers to develop a mental image of the topics addressed.

The local conditions of accretion are thought to be similar for all turbofans and all phases of flight, although the location in the engines may be different. Local conditions of accretion refer to the microscopic processes at the ice initiation and build-up point, and not to the mean line average airflow conditions at the same axial location in the engine. A video of ice crystal icing in the Lycoming ALF502R-2 engine provides a basis for discussion of the local conditions of accretion. This is the only publicly available video of ice crystal icing on a full engine at altitude conditions, and is from a collaborative project of Honeywell Engines, NASA and the Ice Crystal Consortium (ICC). The ALF502R-2 was instrumented and tested in ice crystal conditions in the NASA Propulsion Systems Laboratory altitude icing facility [6]. This technology plan makes use of this ALF502R-2 serial number LF11 icing video to illustrate aspects of the local ice crystal icing phenomenon to help illustrate research that may be needed to enable better understanding of the physics at the accretion site.

Prior to the acquisition of the ALF502R-2 video evidence, there was uncertainty as to whether icing within this engine would be representative of icing in other turbofan engines experiencing power loss and damage events in ice crystal icing. The chief reason was scale, since the ALF502R-2 is significantly smaller than the other large turbofans with ice crystal icing events. Due to its size, the ice formation in the ALF502R-2 resulted in a flowpath blockage, which caused the engine to rollback [7]. None of the other engines with known ice crystal icing events have experienced rollback. This is thought to be due to the fact that, in a larger engine, ice could not build up to a size to bridge across a stator passage as it had in the ALF502R-2. The dual stator rows featured in the fan booster are also unique to this engine, and therefore might make this engine behave differently from other engines with events. Figure 1 shows details of the ALF502R-2 Engine: with the icing site at the EGV in the left panel, and the the viewpoint of the video in the right panel.

Following the ALF502R-2 LF11 test, the local ice accretion dynamics were compared to other engine simulations and rig testing. Despite the factors described in the previous paragraph, the local ice accretion dynamics, in particular the onset of accretion and initial build-up, appear to be similar, and therefore likely to be common to all turbofan engines. Interpreting the ALF502R-2 video evidence must be done with care, however, since the ice buildup causes the engine condition to change or rollback to occur. Changes of the icing appearance with time must be carefully interpreted to determine whether they can be attributed to the cooling conditions resulting from engine rotor speed decay, which is not typically seen in other turbofans larger than the ALF502R-2.

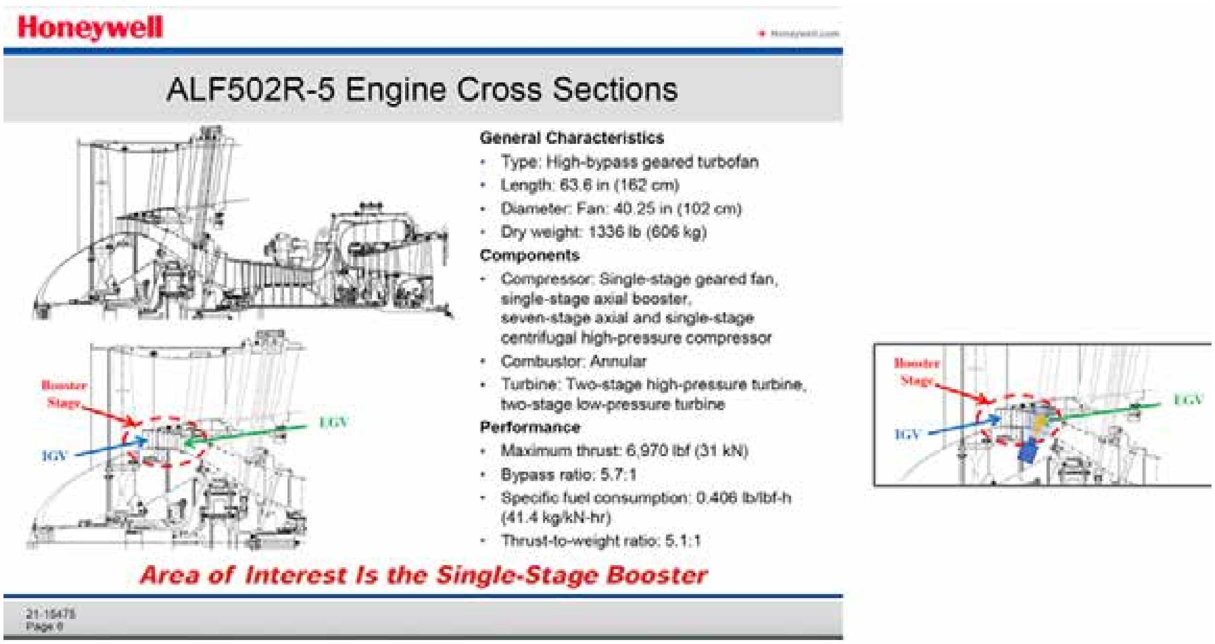

Figure 1. Details of the ALF502R-2 Engine and the video camera angle [7]

To relate the generic example engine to the ALF502R-2, it will be assumed that the icing site for this generic engine, like that for the ALF502R-2, is the last stator vane in the LPC and that the ice initiation begins at the intersection of the vane with the compressor case outer wall. The processes of particle dynamics, impact, and melting, which cause ice and liquid water to arrive at the icing site as shown in the ALF502R-2 video, can be assumed to occur in the generic engine. Therefore, the ALF502R-2 video can be used as representative of the local physical processes for onset of accretion and ice growth.

1.4.1 Priority icing sites for research based on in-service events

Beginning in 2005, the motivation for this work has been to understand and prevent engine powerloss and damage events occurring in airline revenue service. The most serious effect of ice crystal icing in an engine has been the build-up of an ice deposit that sheds and causes downstream compressor blade damage, affecting the continued safe flight and landing of the aircraft. Use of a generic icing site on the compressor outer wall intersection with a vane is particularly applicable to the problem of ice build-up and damage, as it focuses on a mass build-up along the wall at an obstruction. Subsequent shedding of the ice can cause downstream damage.

Another serious effect of ice crystal icing is the build-up of ice that sheds into the combustor to cause flameout (also known as combustor blowout). Experiments have shown turbofan annular combustors to be very resilient to water ingestion because in order to cause a combustor flameout, the flame must be extinguished in a 360-degree manner, or else the combustor will relight itself. This leads to the conclusion that ice crystal icing events that led to flameout must have had ice build-up in a 360-degree manner in the compressor and shed all at once. The compressor outer wall has potential accretion sites at obstructions such as vanes, but also has areas of blank wall without obstructions where ice must form if it is to have 360-degree coverage. To improve understanding of this case, the discussion in this document will include mechanisms for ice build-up on the compressor outer wall in areas where there are no obstructions (section 4.6).

Ice crystal icing engine events have also led to compressor surge, resulting from ice build-up creating a blockage that drives the compressor to stall. Investigation of the compressor wall icing site will contribute to the understanding of this mechanism as well.

This document will focus on the compressor outer wall icing site, because it is a location that exhibits all the key ice crystal icing processes and has been connected to many engine events. It is also chosen in a deliberate attempt to encourage research focused on this case. In contrast, ice build-up on vane leading edges is not thought to be a priority icing site (section 4.11).

1.4.2 Video analysis of the ALF502R-2 engine

Honeywell and NASA have made available the following video for analysis at the following link: https://www.youtube.com/watch?v=L_6HxvwHsdg. The conditions in the video are those that caused ice build-up and enough efficiency loss to be deemed similar to the rollbacks seen in revenue service.

The ALF502R-2 features a single-stage fan booster with two rows of exit guide vanes (EGV), placed one behind the other [7]. Three vanes in the second exit guide vane row, EGV2, are visible in the video camera angle (see Figure 1, right panel). The trailing edges of three EGV2 vanes are visible in the camera view that is looking from the hub toward the compressor case outer wall, i.e., the endwall. One passage between two EGV2 vanes at the endwall can be clearly seen. Part of a second passage is also visible; however, this passage features soldered instrumentation on the endwall, and so will not be considered. The view includes the endwall for about two chord-lengths downstream of the vanes. Terminology for the discussion can be found in Figure 2.

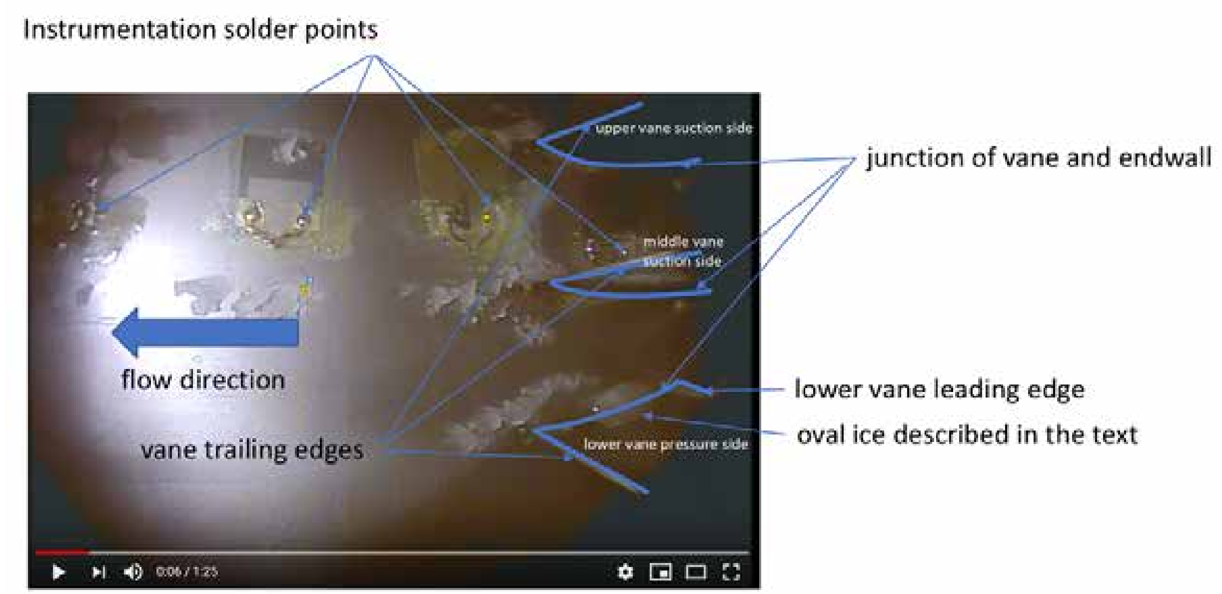

Figure 2. ALF502R-2 video screenshot, showing location of vanes and orientation of the flow

The following is a summary of the video documenting the dynamic nature of the icing phenomenon. The description will focus on ice in the passage between the middle and lower vanes, because ice between the upper and middle vanes may be influenced by the presence of instrumentation solder points on the wall. Indeed, the ice in that passage appears to initiate at local stagnation areas at the upstream solder points of all of the instrumentation. For reference to gauge ice buildup size, the EGV span is approximately 1.5 inches. The description outlines the overall icing phenomena, providing the reader a mental picture that will be the basis for more detailed descriptions later.

- At the start of the video, there is already a small oval ice formation at the lower vane pressure side where it intersects with the compressor outer case, or endwall. This location will be called the pressure side junction. At the onset, there is no ice apparent at the leading edge of the lower vane, the tip of which is in the video frame, but not visible yet due to lack of light.
- At time 0:06 the leading edge of the lower vane becomes visible as ice begins to form there, but sheds by 0:11, taking part of the pressure side junction ice with it; the aft portion of the ice at the pressure side junction remains in place.
- This ice formation at the pressure side junction grows into the passage and creates its own recirculation zone or turbulent wake, like a pebble in a stream. The recirculation zone allows ice particle impingement on the wall, creating an accretion site. The ice formation there grows forward to join the junction ice.
- The junction ice also grows along the endwall (circumferentially) into the passage, until the passage is covered at the endwall at the end of the video.
- Downstream of the vanes, ice forms in upstream-pointing triangular shapes, or “shark’s teeth.” These formations give clues to a local distribution of high total water content (TWC), with their leading edge aligned with a high concentration region coming off the vane pressure surface trailing edge.
- The ice that forms is wet looking, having the appearance of slush that has solidified. During the second half of the video, the appearance of water running behind the junction ice is visible. (As seen, for example, time 0:40.)
- At about 20 seconds in the video, the icing dynamics change from the building and shedding of small accretions to the building of accretions that do not shed but grow forward.

Sections 2 through 5 of this document outline the physical phenomena involved in the ice accretion process within the engine, as diagrammed in Figure 3. For each phenomenon, existing research is identified and summarized. Finally, research needs (RN) are identified and justified.

Discussion in this document is limited to those physical processes that are deemed to have a first order effect on the amount of ice and liquid water that arrives at the downstream accretion site.

Since the document is based on currently public research, it is expected that it will be superseded by further discoveries meeting research needs.

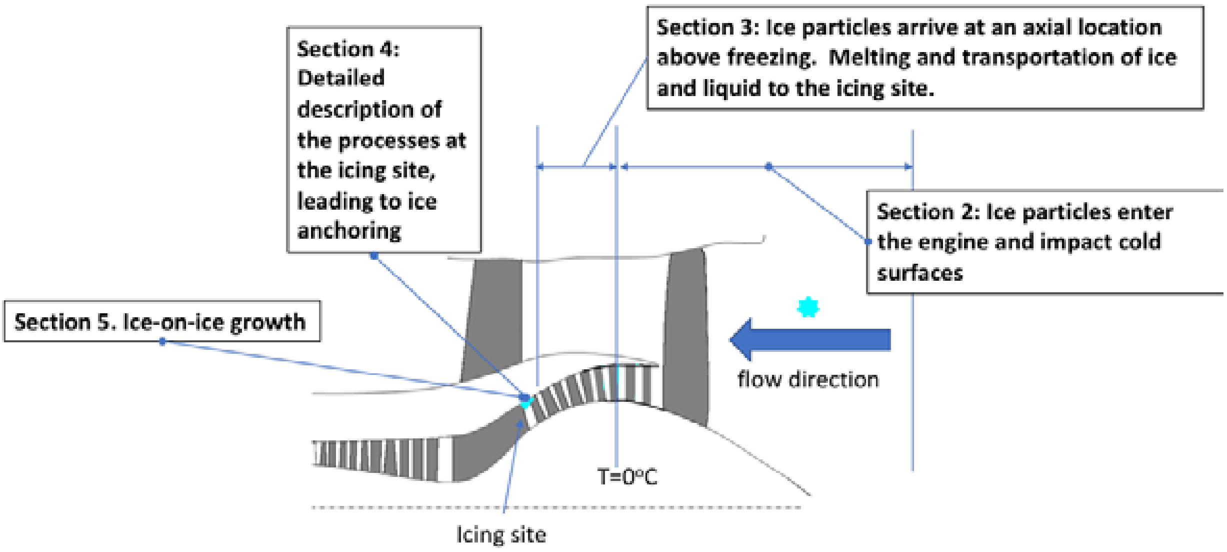

Figure 3. Generic example engine, example icing site, and the organization of this document

2 Ice particles enter and move aft through engine, in below freezing environment

This section outlines each of the physical phenomena at play as an ice particle moves aft through the engine, up until it reaches an above-freezing environment.

2.1 Ice crystal conditions in the atmosphere at high altitudes and cold temperatures

The EHWG Mixed-Phase/Glaciated Icing Technology Plan V1.1 referenced above led to a great deal of work to achieve the objectives of Tasks 1 & 2 – developing instrumentation and characterizing ice crystal icing conditions in the atmosphere at high altitudes and cold temperatures [8]. The chief outcomes of this work, which directly affect the understanding of the ICI accretion in the engine, are the characterization of ice water content of clouds [8], particle size distributions, and shapes and density of those particles [9]. The reader is referred to the references for an in depth understanding of the conditions in an ice crystal cloud. Coutris 2019 [10] reports that scientists are still investigating the particle size distribution and performing estimates of the median mass diameter (MMD) based on various mass-Diameter (m-D) relationships.

For the purposes of this plan, a reference cloud is used for the description of particle behavior, which depends on realistic particle sizes and shapes once ingested into the engine. The chosen reference cloud is glaciated (no liquid) and has a particle size distribution centered at 300 microns MMD, using the “area effective diameter” method of converting irregular shapes to diameter estimates as in Strapp [3]. Strapp states:

“Cloud ice particles sizes were found to span from sub-50 microns to larger than 5 mm. Particles images were generally irregular in shape, likely composed of individual and aggregates particles, with varying degrees of riming. Heavily rimed particles such as graupel were rarely observed, and hail was never encountered.”

RN1. Ice crystals in the ambient atmosphere - There is a need for a representative distribution for researchers and manufacturers to use for design and compliance. RN2, RN3, and RN4 identify the need understand what are the important aspects of the distribution that affect the ice accretion. When these processes are understood, a distribution for design and compliance may be chosen.

2.2 Ice particles enter the engine and impact cold surfaces

2.2.1 General description

As ice particles enter the inlet, larger ice particles will tend to follow an approximately linear path (ballistic trajectory), and smaller particles will tend to follow the airflow (aerodynamic trajectory), depending on the particle effective diameter and the airplane velocity.

Defining ice particle distribution in terms of effective diameter should be a good representation for the characterization of trajectory, unless much of the mass is made up of aggregates. For aggregates, which consist of chains of particles, the area effective diameter, depending on the longest side on a 2D image, would have a lower effective density for a given effective diameter than a solid particle.

The proportion of mass that takes the form of aggregates is not estimated in the references. However, since aggregates consist of chains of smaller particles weakly bonded together, they are highly likely to fragment ahead of the ice accretion site. For example, they may fragment when experiencing aerodynamic shear upon entering the engine inlet.

Some of the ice particles may impact the fan and be fragmented. Many other opportunities for fragmentation exist. For a large turbofan at high altitude cruise conditions, an ice particle is likely to pass several rotational stages of impact, compression and heating while traversing the first few stages of the LPC before passing into a zone where the air temperature is above freezing. Many fragmentation opportunities exist, and the ice mean mass diameter will grow smaller with the impact/fragmentation events. The likelihood of impact with hardware is high and there is a tendency for all particles size distribution to shift to smaller sizes prior to reaching the accretion site. This suggests that the proportion of aggregates may not affect the ice accretion process.

In the 1980's and 1990's researchers studied the impact of hail particles on engine surfaces, and developed many useful parameterizations for modeling hail trajectory and impact that can be found in the collection AGARD-AR-332 AGARD *Advisory Report No. 332 Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines.* [11]

While this report was limited to hail particles of diameter ½ inch and larger (ice crystals are significantly smaller and formed in a different manner), it is a very complete work and was the basis for the development of an analytical capability for engine companies to calculate hail trajectories and impact in the engine.

The list of parametrizations provided in chapter 5 of that document provides a checklist of topics needing either validation or adjustment for smaller size particles. Some of this work could be performed using sensitivity studies adapting parametrizations in the current hail trajectory and impact programs, rather than experimentation.

2.2.2 Ice trajectories in the air

Ice particle movement is determined by the application of aerodynamic drag forces against the inertial resistance to directional change. Inertial properties are tied to mass, therefore proportional to volume and size cubed. Aerodynamic drag forces are proportional to surface area and therefore to size squared. Larger particles behave more ballistically and smaller particles follow the airflow more readily.

The size of an ice particle and its ability to follow the airflow has an important bearing on the motion of the particles through the engine, and ultimately whether they reach the outer-wall icing site. The tendency of a particle to follow the airflow is a function of size, velocity and the curvature of the streamlines. Irregularly shaped ice particles, having a larger effective diameter and more surfaces to potentially catch the air, would behave more aerodynamically than a sphere having the same diameter. Spherical droplet research in an engine inlet [12] illustrates that for any distribution of drop sizes, there is a continuum of drop behavior, and the tendency for the drops is to follow the streamlines more closely the smaller they are. In the following section, even though ballistic particles and aerodynamic ones are treated separately, it should be kept in mind that in the engine there will always be a continuum of particle sizes, varying velocity gradients and geometry such that for every potential particle/geometry interaction there will be some ice mass in both categories worth considering.

Development of analytical methods for supercooled droplet icing, and hail trajectory modelling have resulted in the capability to calculate with a high degree of accuracy the trajectory of a spherical particle in an airflow. For calculation of trajectories of non-spherical ice particles, these methods need to incorporate an appropriate drag term for the particle morphology.

Because of the variety of shapes reported by LeRoy and others [9], researchers have tried using a particle drag based on spherical and non-spherical (ovoidal) approximations derived from the 2D shape captured by imaging, using drag functions from Ganser 1994 [13]. These have been applied to a small number of shapes.

Villedieu 2014 [14] identifies the important connection between ice particle melting rate in warm airflow and its non-spherical shape. To investigate this, he conducted an analytical study of the sensitivity of predicted ice wedge shapes to various spherical and ovoidal approximations of ice crystals. He found very little change in ice shape resulting from change in the approximations and attributed this to the dominant effect of ice crystal inertia. This suggests that if indeed ice crystal inertia is dominant, then the influence of ice particle shape and drag on trajectory can be studied in a setting without accretion physics modeling.

RN2 – Ice trajectories in the air - Perform a sensitivity study for various approaches for modeling the particle shape and drag using a particle tracking trajectory program (such as used by Villedieu [14]). Investigate the effect of particle diameter using a selection of particle sizes from the High Altitude Ice Crystals – High Ice Water Content (HAIC-HIWC) flight campaign. For both these studies, use as the measure of comparison the fraction of ice crossing the plane at the core inlet. This would provide data that could be used in the choice of cloud ice particle size distribution for design and certification.

2.2.3 Impact of ice particles on a cold surface and fragmentation

The parametrization of critical impact velocity for ice fragmentation based on particle diameter from the AGARD report [11] was extended to smaller particles down to 30 micron diameter by Hauk [15]. The Hauk results at smaller diameters resulted in a continuation of the curve of velocity vs diameter from the AGARD results, therefore adding confidence in the parametrization of critical impact velocity for ice fragmentation.

The AGARD report describes a parametric study that found breakup is primarily dependent on initial hail particle diameter and normal component of impact velocity. Parameters found not to be statistically significant include the following: hail temperature; surface – wet, dry, rough, smooth; and type of geometry – fan, spinner. Confirmation that these results apply to small ice particles, which are formed by different processes than hail, is needed.

Vargas 2019 [16] studied other parameters besides diameter and normal component of velocity, including particle temperature (-5 to -30C) and target temperature (22 to 200C). Preliminary results indicate a dependency on particle temperature; however, whether this temperature dependency applies to the regime being discussed here, with a below-freezing target, needs clarification.

2.2.4 Ice fragment size distribution and fragment dynamics

In the event that an ice particle does fragment, its size, velocity, and the angle of impact with the surface are important to the resulting mass reaching the downstream icing site along the outer wall. Several studies have looked at these factors [15, 17, 18]. All of these studies investigated ice impact on a flat plate, and found even with the simplest geometry, the nature of fragmentation is highly complex.

A cloud of fragments is produced by one impact, suggesting that a statistical approach to tracking the trajectories of the fragments may be the only computationally effective method. The size distribution of the fragments is important to the tendency to melt downstream. Vargas reports [16] “The bulk of the fragments equivalent diameter was concentrated toward the 10 micrometer equivalent diameter limit of the resolution.”

The velocity and direction of the fragments is important to the eventual arrival of liquid water and ice at the accretion site. With the number of fragments produced by one particle impact, some kind of statistical approach is indicated. As an example, an experiment could determine the categorization of the ejecta mass into broad size bins as a function of incoming diameter, velocity, and angle. The AGARD report [11] found that a Rosin Rammler distribution was able to model the fragment diameters as a function of the hail stone’s incoming diameter and the normal component of its velocity. The fragment’s exit angle and horizontal spread angle (see figure 5.15 in the AGARD report) are also needed and could be characterized using a statistical approach.

In the engine, the fragments of a particle resulting from impact with a rotational blade do not have to travel far before impact with another surface, whether it be the adjacent blade, the downstream vane, or the case wall. Therefore, many impacts must be tracked. The AGARD report on hail concluded that the exit angle for fragments is constrained to plus or minus 1 degree from tangent to the impact surface, and defined a debris spreading process. Guegan 2011 [17] conducted a thorough study of hail fragmentation down to sizes of 0.25 inches and confirmed the fragment exit angle reported by AGARD.

Small fragmented particles do not break up on further impact if they do not meet the critical impact velocity for ice fragmentation based on particle diameter. Therefore, after impact with surfaces in the LPC the fragmented particle size distribution may tend toward an asymptotic particle size distribution (PSD). Use of such a distribution at the accretion site would be a significant simplification for modelers and experimenters.

RN3 – Ice fragment size distribution and fragment dynamics - Statistical characterization of fragmentation based on particle diameter, velocity and angle, providing an understanding of fragment size, velocity and direction (angle from target and horizontal spread angle) for fragment diameters down to 5 microns. AGARD reports a parametric study that concluded hail fragment size distribution was dependent primarily on initial hail particle diameter and normal component of the impact velocity and developed a representation of fragment size distribution. Are these results relevant to smaller ice particles?

RN4 – Ice fragment size distribution and fragment dynamics - Does the distribution of ice fragments in the LPC approach an asymptotic PSD? This could be addressed as part of the sensitivity study outlined in RN7.

2.2.4.1 Ice particle bouncing

Vargas [16] reported "the bulk of the fragments equivalent diameter was concentrated toward the 10 micrometer equivalent diameter limit in the resolution." In an engine, the median mass diameter of the fragment distribution will become smaller with progress and impacts downstream. Many of the particles will quickly reach a size/velocity where they will no longer fragment, and their trajectories must be characterized. The AGARD Report defined a coefficient of restitution for bouncing particles based on drop test results. It may be that this data can be used directly for smaller particles, since the key factor – the elasticity of the ice and the target – can be assumed not to change with particle size, and researchers have found other aspects of hail particle dynamics relevant to smaller particles.

RN5 – Ice particle bouncing - Regarding the bouncing characteristics of small ~10micron fragments, can the existing AGARD results be utilized? Are there any other pertinent studies?

2.2.5 Centrifugal and flowfield effects on particles

Since known in-service events of engine ice accretion are at sites along the compressor outer wall, ice and liquid water is clearly transported to these sites. In the following description, attention will be given to processes that may cause the ice particle or fragments to migrate toward the outer compressor wall. A review of the flowfield conditions and an examination of processes that act on both ballistic and aerodynamic-sized particles follows.

The following brief synopsis of compressor aerodynamics is needed for the later discussion in this document. Failure to fully appreciate the need to consider more than one reference frame, that of the rotor and that of the stator, could result in incorrect conclusions about the primary forces and thermodynamic environment on the ice particle. For example, the heat situation on rotor surfaces is easily judged to be colder than it truly is if one does not take the proper view of the rotational frame of reference into account. Insight can be gained from a reference on turbomachinery aero- and thermodynamics covering the coexistence of the blade-relative rotating frame of reference with a stationary frame of reference is a characteristic of turbomachinery and described in textbooks on the subject [19]. By looking at a blade-relative rotating frame, air recovery temperatures experienced by rotors, as well as flow behavior, is best understood.

A stage of the LPC is comprised of a rotational set of blades (the rotor) followed by a stationary set of vanes (the stator). Individual blades and vanes have a cambered airfoil cross-section, and are twisted from root to tip to accommodate the higher rotational air speed at a higher blade radius and related radial variation of air at the stator. Both rotor and stator, seen from their respective rotational and stationary reference frames, act like diffusors, slowing the flow and converting the circumferential component of the flow to pressure rise. Seen from the stationary frame alone, a rotor adds swirl and energy to the airflow and a stator takes the swirl out. Looking at both from the viewpoint of the reference frame that rotates with the blade, the roles of rotor and stator are reversed. The same two reference frames can be applied to understand the behavior of particles. Particle behavior, with respect to the rotor and rotor row airflow, before impact, is the same as in a stator if seen in their respective airfoil-relative reference frames [20].

Each stator vane sees the wake of each passing rotor blade upstream. Downstream blades also are affected by the wake of upstream stages, although the effect diminishes with axial distance.

Even without ice accretion, the airflow is unsteady. Boundary layers build up on each blade and vane, and also on the compressor case walls.

<u>Ballistic-sized ice particles</u>

Ice particles that impact a rotor blade on the pressure side and bounce off, either undamaged or in the form of fragments, have picked up a considerable circumferential speed component, possibly more than the airflow alone would impart to a particle. Drag forces tend to bring its speed more in line with the surrounding airflow but its trajectory will maintain a straighter path than the airflow and therefore toward the outer diameter endwall.

The compressor flow-path may exhibit a curvature that reduces the effective outer-diameter endwall radius. This may either be due to contraction of the compressor case or to passage through the transition duct between the low-pressure compressor (LPC) and the high-pressure compressor (HPC). Particles lagging the imposed curving of the air flow will end up closer to the effectively reduced outer diameter endwall.

Particles coming to rest on a rotor blade are exposed to the centrifugal and Coriolis accelerations on the rotating blade surface. These sticking crystal particles may melt on the blade surface, which initially would be as warm as the recovery temperature of the surrounding air. This recovery temperature is close to the total temperature of the blade's rotating reference frame (not the total temperature of the stationary frame). Particles, either as crystals or as droplets of water film after melting, will move mostly in radial direction with a slight turning due to Coriolis effects, and will leave the blade tip and upper trailing edge in a sling-shot effect, impacting the outer diameter endwall.

The key influences that would cause a ballistic-sized ice particle to deviate from the airflow streamlines and migrate to the outer diameter endwall of the core flow path are:

- centrifuging of particles in circumferentially turning or "swirling" flow behind a rotor row (e.g. particles can't change direction with the air, and therefore follow a trajectory towards the wall)
- impact on and bouncing off of rotor blades
- particles unable to follow the air flow in a contracting flow path outer wall
- particles coming to rest on a rotor blade.

Evidence of ice particles deviating from the streamlines, and thus creating areas of locally high TWC concentration, can be seen in the ALF502 video. The TWC concentration is probably highest close to the vane trailing edge, where the gradient produced by the compound turning of endwall and blade is highest before downstream diffusion takes effect. The local area of high TWC causes an accretion downstream of the vane trailing edge.

Aerodynamic-sized ice particles

Consider the instant after impact and fragmentation of a single particle, on the pressure surface of a rotor: a cloud of small fragments is produced with a distribution as per Vargas [18]. Some of the fragments will be so small that they will not fragment again. Tracking the small fragments, they fan out from the impact site at a shallow angle with respect to the tangent to the surface at the impact site [11, 18]. Since the pressure surface of the rotor is concave and it is moving toward the fragment, the fragment exit angle is shallow with respect to the tangent to the surface. Thus, it is highly likely that the fragments will come in contact and possibly stay in contact with the rotor, so that their direction and momentum changes. Contact with the rotor will impart a centrifugal velocity, such that particles will tend towards the compressor outer wall. Small fragments may leave the rotor via its wake and be entrained therein, resulting in velocity vectors completely different from the overall flowfield. Immediately downstream is a stator row, with additional potential for impact and influence on the particle.

Some of these aerodynamic particles are readily melted in contact with a warm surface such as a rotor. Liquid water in contact with a rotor may film and move radially outward under the influence of a centrifugal force component and axially under the influence of a Coriolis force component. [11]

The key influences that would cause an aerodynamic ice particle to deviate from the airflow streamlines and migrate to the outer diameter endwall of the core flow path are:

- impacts with several surfaces
- encountering turbulent boundary layers
- encountering rotor and stator wakes.

At this time, it is not known to what extent these complex processes directly affect the amount of ice reaching the downstream accretion site along the outer wall. For this important accretion site, the compressor case at the intersection with the last vane, focus should be placed on the processes that move particles to the outer wall. Since the presence of liquid at the accretion site depends on melting, the production and transport of small particles that are likely to melt should be considered. (Melting is covered in sections 3.2 and 3.3.) Zones of locally high TWC may also be key to the accretion process, so ballistic particles must also be considered; thus, knowing the particle size distribution is therefore fundamental.

RN6 – Centrifuging and flowfield effects on particles. The above description outlines a possible mechanism by which ice could migrate to the outer wall, and possibly contribute ice or liquid to the icing site. Research is needed to quantify this effect – what percentage of the incoming mass arrives at the compressor outer wall? Once the magnitude of this effect is known, an assessment can be made of the degree of resolution of the flowfield that is needed to track these particles. A rotating rig experiment may begin to provide answers for one case of rotor impact and centrifuging. This experiment may help define the key factors for further modeling and parametrization.

RN7 – Centrifuging and flowfield effects on particles - An analytical study could be conducted to assess the amount of mass accumulating on the compressor wall. The results of fragmentation experiments such as those of Vargas [18] could be surveyed for the mass of particles with diameters below the critical diameter for fragmentation and also having a radial component to the velocity. A hail trajectory model could be updated with this distribution, and a proportion of mass on the wall could be estimated. This could be used to guide modeling approaches.

RN8 – Particle breakup assessment following impact with a rotational geometry. Any modeling approach requires validation, optimally from a rotating rig or full engine where particles impact a rotational stage and the fragments are affected by the local airflow and centrifuging. Until now, a challenge to the acquisition of the desired validation data has been visualization of particle size, velocity and direction pre- and post-impact with a rotational body. At the time of this writing, two experiments have good prospects of producing the desired data: an engine in NASA Propulsion Systems Laboratory (PSL) with tomography [21], or the National Research Council of Canada's (NRC) rotating rig and PIV laser imaging [22]; however, more work is needed to allow measurement of particles less than 20 microns.

3 Above freezing conditions, ice particle melting and transportation

3.1 General description

This section covers the phenomena that influence an ice particle as it travels through the engine from the axial location, where the air temperature goes above freezing, to the accretion site. In the generic example engine, there are one or more stages of temperatures above freezing and compression ahead of the accretion site. In this region of the engine ice melting occurs, and the liquid water and ice mixture necessary for accretion forms and then travels (by mechanisms examined in this section) to the accretion site, where it plays a significant role in the accretion process. A later section will be devoted to conditions for continued growth of the ice at the accretion site (ice-on-ice growth), as the presence of the ice layers adds properties and mechanisms that need to be included to fully understand the accretion process. The focus will continue to be on the representative accretion site at the intersection of the compressor outer case wall with the aft-most stator vane.

Ice and water moving downstream through the region where the temperature is above freezing at the axial location are subject to the same influences as noted in section 2.2.5 with the addition of the possibility of melting, water film formation on surfaces, and capturing of ice in the water film (resulting in slush) in motion propelled by the airflow.

The movement of slush will be examined in detail in section 4.4.

3.2 Melting of ice particles in the airflow

Many studies have helped characterize the physics of aerodynamic ice melting [23, 24, 25]. Struk et al. 2011[23] documented a connection between the onset of aerodynamic ice melting and the wet bulb temperature (Twb) of the air being above freezing. Hauk 2016 [15] has studied the aerodynamic melting of ice crystals using an acoustic levitator. This work provides the melting rate as a function of ambient humidity for representative conditions (Tparticle = -16C, Pressure = 1 Bar, T airflow = 20C, flow velocity 1-1.75m/s, Twb 6-10C). Scientists have already adapted their models of ice melting using Hauk's experimental results.

3.3 Melting of ice particles on the engine hardware

Section 2.2.5 shows that as ice travels downstream in an LPC, some fraction of the post-breakup ice fragments may have radial or circumferential velocity components after impact with a blade or vane. These fragments would have a tendency for migration toward the outer wall. Section 2.2.5 describes a possible mechanism by which small fragments can have extended contact with blades and vanes and the outer wall, which may be conducive to melting. The question of ice melting while in contact with metal surfaces must take into account how much contact there is, and how strong a heat source exists at the wall. However, some metal surfaces have limited capacity to melt ice. When the metal loses heat to melt an ice particle, that site must regain heat in order to go on melting more particles. Not all the metal hardware is in a position to have the heat replenished. In order for an engine metal surface to contribute significant melting, there must be a continuous source of heat.

Obvious heat sources such as heated spinners, sensors, and bleed air have been examined as potential contributors of melting, triggering ice crystal icing. The ALF502R-2 testing showed that even with the spinner heat deactivated, ice formed within the camera view, and resulted in rollback occurring only slightly more slowly than it had with the spinner heat active [6]. This proved the heated spinner was not the only source of water contributing to the ice formation. Likewise, in many engine events there is no obvious heat source in the engine forward of the icing site, other than the warm airflow. The question remains – can the engine hardware (blades, vanes or the outer wall) be a contributor to the melting of ice, which takes part in a downstream outer wall accretion, and if so how significant is it?

A rationale is now presented for how a rotor might produce continuous melting. In the preceding paragraphs, it has been shown that a cloud of very small fragments can be produced upon impact of ice crystals with a rotor. Because of their very small size, these particles can stay in contact with the moving rotor possibly long enough for them to melt. Hauk [15] completed some initial melting studies using a heated plate and found that very small particles readily melt. The heat removed from the surface of the rotor is continually replenished by heat from the opposite surface of the rotor, which is not subject to impingement. The thin rotor cross section of the metal can readily conduct heat. The rotor is still doing work on the airflow resulting in temperature rise. This mechanism would also apply to vanes, which would experience ice impingement on only one surface.

The compressor case wall is a possible source of melting only if the backside is exposed to a heat source. Examining the ALF502R-2 video time=0:40, there is evidence of melting under the ice deposit, suggesting that there is potentially a source of heat in the compressor case wall that could melt impinging small particles/fragments.

To summarize, it is known that ice accretes at the outer-wall icing site, and therefore ice and liquid water must be transported to the outer wall so that the icing takes place. The key question then is whether the melted water comes solely from aerodynamic heating, or whether contact with the metal also produce a significant contribution to melting.

RN9 – Melting of particles on the rotors and other engine hardware - The production of melted water by fragments in contact with above freezing engine hardware needs further study. Extension of the simple Hauk experiments on melting [15] could be coupled with the results of RN6, RN7, and RN8. Understanding how much mass ends up at the compressor wall in front of the accretion site could begin to clarify whether it is a significant contributor to the ice accretion mixture.

3.4 Melting of ice by other means

Based on experiments, Currie 2016 [26] described different ice accretion rates for test points at higher Mach numbers than lower ones, and conjectured that it might be associated with dissipation of kinetic energy on impact. The tests were performed for a hemispherical test article with the airflow Mach number in the range of M=0.4 to M=0.6. For these tests, the ice particles and liquid water drops reaching the test article were both entrained in the impinging airflow by the test apparatus.

RN10 – Melting of ice by other means - Further study is needed to see if impact energy significantly changes the amount of melting. A parametric study using a particle size distribution resulting from fragmentation Vargas [16] could be performed with one of the current generation of models [14, 27]. Understanding local particle velocity at the accretion site is key to this analysis and would be different for a leading edge than for a compressor outer wall accretion site.

3.5 Formation and behavior of water film

In the ALF502R-2 video, there is evidence of liquid water moving on the compressor outer wall. It appears as a thin water film, the nature of which is unclear, can trap ice fragments in the wake of the vanes. In the ALF502R-2 video, the process of creating the liquid which makes up the film is not readily observable; it may be ice fragmented by the fan and single stage booster, melted and centrifuged to the outer wall, or ice particles impinging on the wall and melting immediately upstream of the video camera. Film thickness and motion, as well as other aspects of this process, are also not well understood.

RN11 – Formation of water film - Is the AGARD [11] study on film thickness and shedding from blades applicable? What is the film thickness and liquid movement? Does the movement depend on rotor speed, variations in curvature as found in blade and stator vane geometry, outer flowpath geometry, temperature, or film thickness? Film thickness and movement may be studied in a rotating rig or full engine experiment with rotor stage heating, particle fragmentation, and centrifuging, to help determine the key influences.

3.6 Presence of liquid water affects the dynamics of ice particle impact and erosion

The presence of liquid on a surface will change the dynamics of ice particle/fragment impact and centrifuging. Hauk 2016 [15] conducted some initial studies of ice impacting a liquid film on a wall, and established that the impact velocity where no fragmentation occurs on a wall with a film is two times higher than on a dry wall. The film thickness used was 130 micron to 600 microns, roughly one to six times the median volumetric diameter (MVD) of the incoming ice particles. Hauk's work does not exhaust the subject; further understanding of the film thicknesses in engines is needed to define the boundary conditions of further experiments.

Currie [26] has documented changes in the accretion when comparing experiments where the melt ratio was varied and the ice particle mass flow increased. He attributes these differences to changes in the erosion of the accretion, and recommends "further work to relate the erosion properties of an accretion to its liquid water content (and possibly the freezing fraction), and then relate the latter to the freestream LWC/TWC and melting and/or freezing due to other energy sources. Those sources include heat transfer from the air, particle kinetic energy, the sensible heat of water droplets and ice particles, etc."

RN12 – The presence of liquid water affects the dynamics of ice particle impact - Extension of Hauk's study, once realistic film thicknesses for engines are defined. A study to define the film thickness needed to trap ice vs particle size. Define other effects such as splashing, bouncing and erosion.

RN13 – The presence of liquid water affects the dynamics of ice particle impact - A study of incoming partly melted particles, do they shed the water on impacting a wet or dry surface?

4 Detailed description of the processes at the icing site, leading to ice anchoring

4.1 Definitions key to this section

The following terms and definitions are important in understanding this section:

- Anchoring – freezing at the interface between the water and the wall (release of the heat of fusion at 0°C)
- Anchored area – a portion of surface area at the wall under an ice deposit that is frozen
- Harmless build/shed cycle – small ice deposits (such as the oval in the ALF502R-2 video) develop but shed as aerodynamic forces exceed adhesion forces. The shed ice accretion is small, not posing a threat to the engine.
- No-shed ice growth – deposits continue growing for a sustained period, even in places where the harmless build/shed cycle was present previously. When the ice accretion sheds at the end of this growth process, it may be large enough to pose a threat to the engine.

- Bridging – ice deposits that are held in place by engine hardware, such as the location across the passage between two adjacent vanes
- Wall – the metal hardware
- Slush – an unconsolidated 2-phase mass formed through ice particle impingement on a water film. If in motion, it is propelled by the airflow.
- Coalescing – coming together to form one mass. (A general term, to be replaced by more exact terminology once the process is understood.)

4.2 Introduction

Since the first hypothesis on the formation of ICI accretion in the engine was described by Mason, Strapp and Chow in 2006 [4], scientists have been trying to identify and describe the processes involved. Various approaches have been taken, ranging from describing and parametrizing experimental results on simple geometries, to extending the classic Messinger [28] model with new terms to cover the mixed phase setting and to include conduction of heat from the surface, which is typically neglected in many applications, e.g., LEWICE. Ultimately, these approaches may lead to an adequate and accepted understanding of the phenomenon. However, they have led to the use of terminology to describe the icing process as observed in a simulation rather than as occurring in a real engine. In order to identify research needs, in this section the ice crystal icing process from a real engine case is broken down into detailed steps, and those steps examined to determine the parameters at play and their relative importance. This should result in a common terminology to identify precisely the elements of the process being discussed. While the exact nature of the process shown is not perfectly understood, for the purposes of this document the ALF502R-2 video will be examined and described in order to develop a common terminology. This picture, and the ultimate terminology, will evolve with new knowledge, viewpoints, and experiments. The description starts by focusing on one site and stepping through the evolution of the ice growth and continues by breaking down the contributing processes by examining the ice initiation processes apparent in many locations from the ALF502R-2 video. Study of the video has led to the conclusion that the processes at the wall that lead to ice initiation and later anchoring and melting are different from the ice-on-ice growth, which occurs once the wall has been covered by an ice deposit. Section 4 will focus on the processes of ice initiation at the wall, and section 5 will cover ice-on-ice growth.

The ALF502R-2 video begins when ice has already begun to form at some locations; however, the initiation process can be examined throughout the video by focusing on other locations where accretions form and shed, or eventually anchor and grow. The surfaces have a wetted appearance prior to the ice formation, and it can be seen that impinging ice particles stagnate at a local initiation site. As noted in the video description, there is a time-based element to the process. This time-based evolution is connected with the heat transfer process at the wall.

Early on, small ice accretions form, but shed eventually. The term anchoring is defined here as freezing at the interface between the water and the wall. In the engine environment, a build-up of ice is subject to aerodynamic forces tending to push it downstream. It is postulated that in the initial stage the only way that ice deposits can remain static is that some portion of the interface of the ice deposit and the wall is frozen, or anchored. As soon as an ice deposit forms, there appears to be melting taking place at the interface, reducing the anchored area, and possibly resulting in shedding. Ice deposits are swept away before they grow to a large size. The term used for this is a harmless build/shed cycle. At some point there is a transition to a phase where ice deposits can remain in place due to one of the following processes: anchoring, the support of other ice, or by bridging across hardware, such as across two adjacent vanes. From this point, ice can continue to build up. This is termed the no-shed ice growth phase.

The word harmless in the preceding paragraph warrants further discussion. The size of an ice deposit that is no longer harmless varies with each engine’s downstream blade impact resistance, compressor and combustor stability, and other unique design features. The word harmless is used here to emphasize the phase in the process where accretions are readily shedding, and there is little build-up time.

To illustrate the ice growth and process changes with time, Figure 4 presents a series of still images from the ALF502R-2 video. In each image, a purple curve encompasses the volume where the key processes are taking place with ice growth. The term ‘volume of interest’ will be used for this volume, indicating that it contains all the elements involved in the icing process. For each successive image, the volume of interest changes due to the processes noted in the captions.

Figure 4. Still images showing the evolution of volume of interest with time

Figure 5 presents a diagram of all the processes that may contribute to ice growth or shedding. Two cubical elements represent the ice and the extent of volume of interest that is needed to capture all the processes involved. All of these processes will be presented in the subsequent paragraphs, and may all be taking place at the same time; however, to clearly describe them a sequential approach will be taken, beginning with the time history of heat transfer at the wall up until the transition to no-shed ice growth. The focus will be on the heat transfer processes that are affecting the cooling at the interface of the wall (metal hardware) and the air/water adjacent to it.

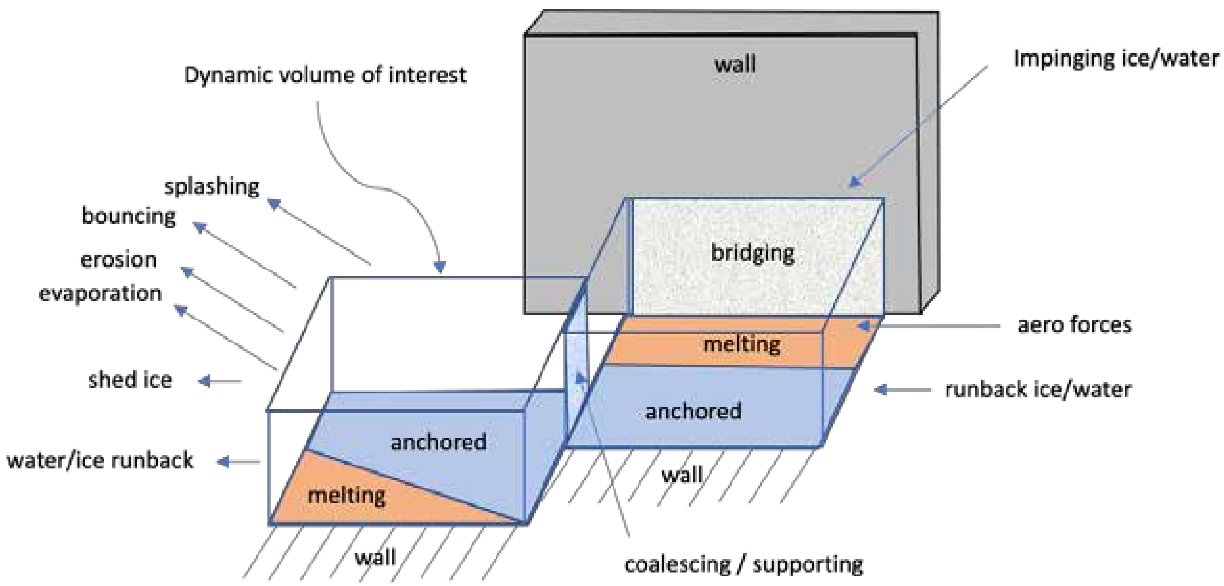

Figure 5. Diagram of a volume of interest and important processes

4.3 Liquid on the surface and convective cooling

The presence of liquid water on the wall is the initial condition for the process of capturing ice particles and subsequent wall cooling in the ice crystal icing process. The presence of a liquid-only film is a transient condition, because as soon as a liquid appears, ice particles can impinge and stick in the layer (see Figure 6). Liquid water from upstream arrives at the wall forming a liquid film, which is driven downstream by the airflow, cooling the wall. An example of liquid water on the wall can be seen in the ALF502R-2 video. At time=0:00 to the left (downstream) of the vanes, there is an overall wet appearance, and water can be seen streaming along the wall. This water may have entrained ice particles within it that are not readily visible. Depending on the film thickness, the liquid water may provide insulation of the wall from the air.

Experiments monitoring the wall temperature during ice crystal icing (Mason 2011 [29]) suggest that the liquid water on the wall drives the wall temperature. In that experiment, a wall-mounted thermocouple dropped to freezing after ice and water began to impinge on the surface. The temperature stayed at freezing when an ice deposit built up, and even after it shed. After ice shedding, the liquid film supplied from upstream was thick enough to drive the wall temperature, and the presence of warm air had no effect. If the wall temperature is driven by the liquid, then film-cooling technology (such as developed for turbine blades) can direct the study of the important physical parameters. The film can be an insulator from the warm air of the engine. The amount of cooling of the wall will be a function of the composition (water to ice ratio), thickness and velocity. Film thickness is an important parameter since the ability to trap impinging ice particles increases with film thickness, and increased ice content results in increased cooling. The film temperature is another unknown and is a function of the transport of water from upstream: does the liquid from melted ice upstream have time to warm? (The film may have entrained ice particles, as seen in section 4.4.) Parameters which are important in the field of turbine blade cooling apply to the motion of the film: the film-to-mainstream density, momentum and mass flux ratios, the turbulence intensity, curvature, and roughness.

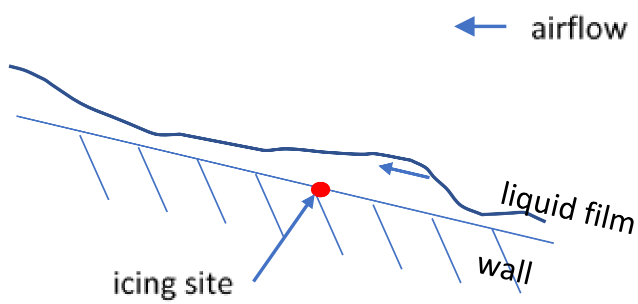

Figure 6. Diagram of liquid film moving on the wall at the icing site

4.3.1 The importance of wall boundary conditions

It is hypothesized that water present on the wall forms a moving film, which traps ice and cools the wall. The initial wall temperature and its thermal conductivity become important to the question of whether the wall approaches freezing temperature, and later, when an ice deposit forms, the wall heat flux will determine whether the ice at the interface with the wall begins to melt.

In the engine, the compressor case outer wall (or the backside of the wall at the icing site) at different axial locations is exposed to a variety of thermal conditions, from stagnant air, to warm hydraulic fluid where some mechanical systems are housed, to fan air (sub-freezing) near bleed systems. Each of the icing scenarios covered in this section is highly dependent on wall temperature and transient thermal conditions.

The material of which the wall is made may be another important factor in this process. Many of the popular alloys used in engine compressor casings are not highly conductive. This allows less heat to be conducted from the dry side of the casing to the wet side, enabling ice anchoring.

RN14 – Liquid on the surface and convective cooling - Water film thickness, motion and temperature need to be studied in a simulation, which includes appropriate engine wall temperature boundary conditions and materials. Boundary conditions for film thickness, motion and temperature should be drawn from a simulation that includes the breakup, centrifuging and melting of ice particles upstream, such as a full engine or rotating rig. (Studies can be conducted of areas where water is seen streaming and ice does not form– such as the wall aft of the EGV in the ALF502R-2). The ability to measure water film thickness is vital to the understanding of the cooling rate of the wall, and the contribution the film may make to the total icing mass.

4.4 Water and ice are present on the surface, moving as 2-phase flow, or slush

After a film forms on the wall, the next step in the ice crystal icing process is the impingement and sticking of solid ice particles in the liquid. This can be seen in many locations in the ALF502R-2 video, in some cases the ice+liquid stays in motion, and in other cases it does not move. This section examines the case where the ice adds to the liquid water film and creates a 2-phase flow. The red circle in Figure 7 (right panel) highlights an example of such motion in the ALF502R-2 video snapshot at time=0:47. This phenomenon has been seen in simulations having a concave wall representing the engine compressor case ahead of the icing site. The video instrumentation in the ALF502R-2 testing did not include a camera ahead of the EGV, so if this phenomenon took place there, it was not recorded.

Figure 7. Diagram of 2-phase flow, and video example (red oval)

The motive force for the slush movement is the airflow. Geometric features such as compressor case concave curvature acts to slow the motion. Depending on the residence time of the slush, the compressor case may be cooled, which may also have an effect on the slush movement. A concave compressor case is featured in all turbofan engines, and therefore the potential for the formation of slush and influence on the wall temperature and the slush motion are important areas of study.

The fluid dynamics and heat transfer of this 2-phase flow resembles applications such as debris flow, avalanches, and 2-phase pipeline flows in the gas industry. Whether these applications can provide insight, the 2-phase flow in the engine ice crystal icing setting needs further study. Unique aspects of the slush flow on the compressor case are (1) the apparent density and viscosity changes with axial distance, as ice particles continue to impinge on the slush layer as it moves, and (2) the slowing motion with curvature, related to density change, promoting further cooling at the wall. The composition of the slush layer may be more or less homogeneous depending on the impingement angle of the oncoming ice particles to the wall.

4.4.1 Choice of volume of interest

In order to fully capture the nature of the slush movement along the compressor wall, a volume of interest should include 2-phase mixture entering, ice particle deposition from the air and a different density 2-phase mixture exiting. The volume of interest should be chosen so that local geometry effects on fluid motion can be taken into account.

RN15 – Water and ice are present on the surface, moving as slush - Literature study of 2-phase flows and their applicability to slush in the turbofan engine, to deduce the important parameters for this 2-phase flow characterization. Component testing to study the nature of the slush flow, in particular the effects of density, wall temperature and curvature changes on motion. The ability to measure slush flow thickness and composition is vital to the understanding of its thermal effect on the accretion site. This study will depend on appropriate engine wall temperature boundary conditions – see RN14

4.5 Anchoring

It is postulated that in order for ice to build a static deposit, such as the oval at the junction of the lower vane and the endwall seen at the beginning (time=0:00) of the ALF502R-2 video, there must be freezing at the interface. Evidence supporting this idea is the eventual shedding of the oval ice deposit after it has grown slightly in size (time=0:10), as shown in Figure 8. If there were no freezing at the interface, the ice/water mixture would be driven downstream by the airflow. The apparent melting occurring at the interface of the oval with the wall to reduce the anchored area will be examined in section 4.6

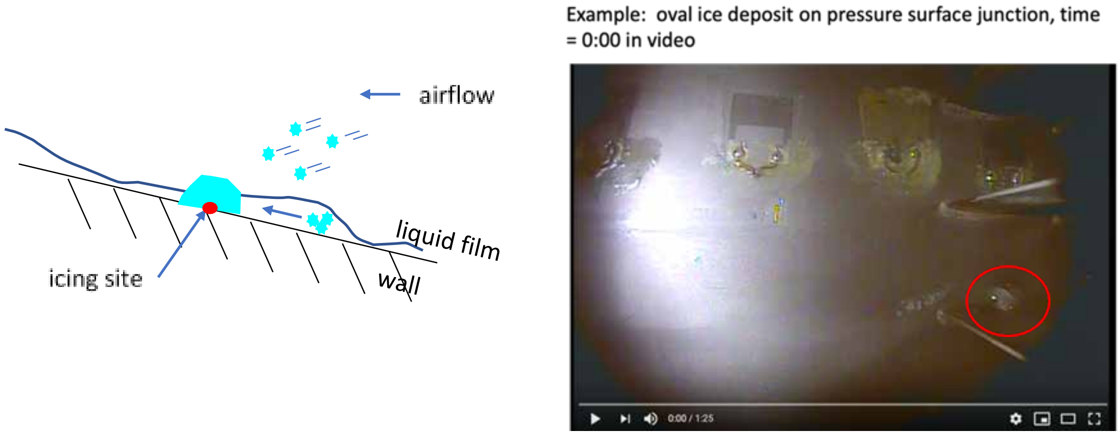

Figure 8. Diagram of anchored ice, and video example (red oval)

Examining the video, evidence of ice anchoring can be seen in many places, where the ice/liquid water mixture stagnates. These include expected locations such as at the instrumentation solder points and leading edges, but also areas with complex curvature such as the vane pressure surface junction with the endwall. The process of anchoring can be seen to be dependent on the density of the ice/liquid mass on the wall (relating to the stagnation), as well as the role of the geometry of the wall in the capture of impinging ice particles.

4.6 Ice on smooth wall, “island chain” formation

Ice anchoring is not limited to geometry, which presents an obvious stagnation area, as can be seen in the video with the formation of what may be called an “island chain” (see Figure 9). The ice formation at the junction of the pressure surface of the lower vane and the endwall creates a wake downstream, which is the mechanism by which ice aerodynamic particles entrained in the flow are deposited on the liquid film covered wall. Wakes and turbulent flow downstream of vanes are a mechanism by which the local ice impingement at the wall can be increased, such that cooling and anchoring are possible. By this mechanism ice can form on a smooth wall lacking obstructions or stagnation areas.

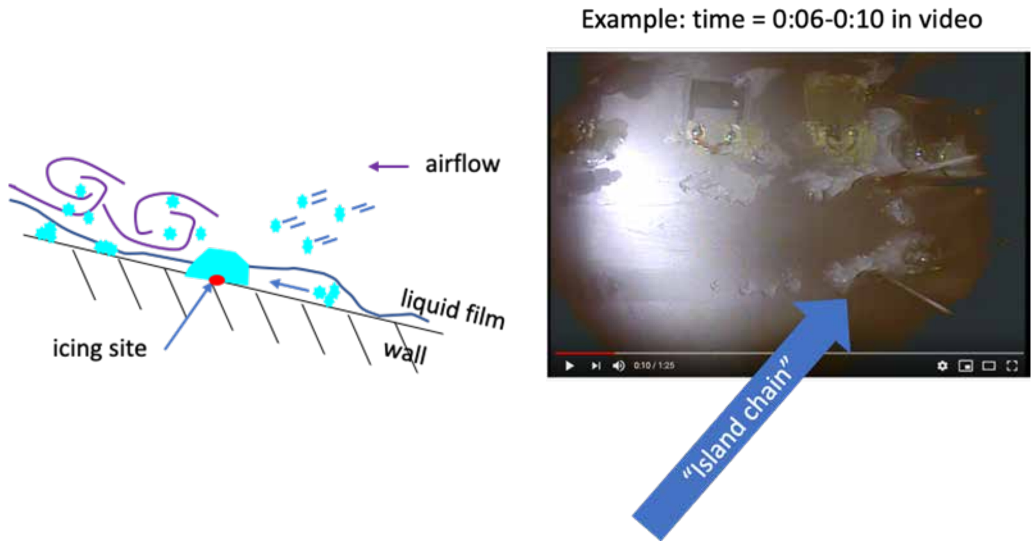

Figure 9. Diagram of ice deposit and wake, and video example of island chain

Understanding the 3-dimensional flowfield is essential to resolving this potential accretion mechanism. Much of the total mass of ice that grows in the ALF502R-2 video appears to be forming in the wake of the vanes or the wake of existing ice deposits. Other examples of ice formation in the downstream wake of a vane exist in the engine ice crystal icing event database, supporting the idea that it is an important phenomenon.

4.6.1 Coalescence

The island chain formation noted above also shows evidence of another type of growth mechanism, which is the merging of two discrete ice deposits into one as they grow. The details of this mechanism are not fully understood, and the term coalescence will be used. Since this appears to fall into the category of ice-on-ice growth, it will be covered in section 5.1

RN16 – Ice on smooth wall, "island chain" formation - Since it is complex and expensive to accurately calculate the flowfield, including wakes and boundary layers for sites at the aft end of a multi-stage compressor, some experiments to develop broad design guidance on geometric influences on ice accretion may be helpful. For example, the influence of boundary layer thickness, flow turning and turbulence intensity on ice impingement and accretion, as well as hardware influences like solidity and axial spacing of vanes.

4.7 Melting below the junction ice

Ice anchoring is a transient state as seen in the ALF502R-2 video. Soon after an ice deposit forms there is evidence of water running below the surface. This is direct evidence that the wall heat source is melting the ice at the interface.

To fully describe this phenomenon, a time-dependent accounting of heat sources and sinks at the interface between the ice and the wall, as well as mass into and out of the volume of interest, must be considered (see Figure 5). The ice deposit acts as an insulator, and the dominant source of heat is from the wall (Qdot in Figure 10). The area of anchored ice decreases with melting and, at the same time, aerodynamic forces are acting on the deposit to shear it away, while the deposit may also be growing in size due to ice-on-ice growth (section 5). In the ALF502R-2 video, the liquid appears to be in motion behind the ice indicating melting at the interface.

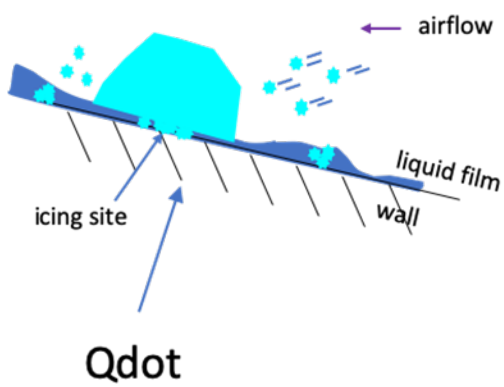

Figure 10. Diagram of process of melting below the ice deposit

Current analytical models lack: (1) a time-based accounting of the heat transfer with the wall, and (2) a volume of interest that takes into account the whole ice deposit and its adhesion at the interface with the wall, as well as the aerodynamic forces acting on it.

RN17 – Melting below the junction ice - Develop a modeling approach to take into account the heat transfer at the interface of the ice deposit and the changing volume of interest, reflecting the size of the ice deposit contact with the wall and the aerodynamic forces exerted on the ice deposit. (See Figure 4 and Figure 5.)

4.8 Harmless build/shed cycles

The formation of ice deposits and melting of the interface can lead to harmless build/shed cycles; small deposits are formed, but soon after the anchor area is reduced due to melting and they are swept away by the aerodynamic forces. The question is raised: why isn't an equilibrium reached, with harmless build and shed cycles continuing so long as the ice cloud is being ingested by the engine? The answer to this question may be the key to why ice builds up in some engines to a size that can cause damage or flameout.

In all turbofan engines encountering ice crystals, the temperature is continually increasing in the LPC. Thus, it is likely that there is some point where conditions are conducive for ice accretion, but only harmless build/shed occurs with no transition to no-shed ice growth.

4.9 Transition to no-shed ice growth – deducing the fundamental process

An example of the transition from harmless build/shed cycles to no-shed ice growth can be found in the ALF502R-2 video. Starting with time = 0:08, there is an oval ice deposit at the lower vane pressure surface junction with the endwall, and ice builds up in its wake downstream. See the right panel in Figure 8. The oval sheds shortly afterward, and the ice that was downstream of the oval (island chain ice – Figure 9 right panel) grows forward, covering the location where the oval was. This ice grows forward and circumferentially along the wall, eventually bridging the space between the two vanes. During its growth, there is water visible underneath the ice edge at the junction with the vane, suggesting that it is not anchored in that location. Prior to the ice growing all the way across the passage, it must have been held in place by an anchored area, and that area was sufficient to support the growth of the ice until the time it became large enough to bridge the passage. Again, the fundamental question raised is why the ice stays anchored long enough to bridge the passage, especially when nearby there is evidence of melting and water running at the interface? It is postulated that the answer lies in the heat balance at the wall interface, and that locally where there is anchoring in the presence of incoming heat flux from the wall, adhesion at the wall-ice interface has not collapsed because the ice mass has managed to remove the heat from the wall-ice interface.

Transition to no shed ice growth at a location appears to be because of one of three things: (1) ice accumulation at a stagnation area that cools the wall, (2) ice supported by other ice already deposited and (3) ice bridging (or support by) geometry. The latter two phenomena cannot happen until the first has happened; somewhere, ice has accumulated in a stagnation area and cooled the surface to anchor. This is the fundamental process – ice anchoring at the wall. (see also the discussion of stagnation areas in sticking efficiency, section 4.10.4.2).

The formation of the "island chain" and other ice deposits on the endwall in an area of higher ice impingement support the idea that the ice mass at the wall can (sometimes only temporarily) overcome any heat the wall may provide. This leads to the understanding of the importance of the wall backside temperature and the insight that any local area of cooler backside temperature can be more susceptible to no-shed ice growth. (See section 4.3.1: The importance of wall boundary conditions.)

4.9.1 The choice of volume of interest

The important influences on the transition to no-shed ice growth cannot be accounted for without a changing volume of interest that includes both the anchoring area and the extent of the ice growth, which may be somewhat distant, and the aerodynamic forces on the ice mass. Further, the anchoring area is a transient condition, influenced by the impingement of ice and heat from the wall, see Figure 5. (See also RN17.)

RN18 – Transition to no-shed ice growth – deducing the fundamental process - Study of the transition to no-shed ice growth, and its influences, including ice impingement rate and ice & liquid water inflow and outflow rates, wall backside heat transfer, as well as geometric influences such as concave surfaces.

4.10 Significant topics from EIWG guidance on ice crystal icing

In 2019, the EIWG published the document "Engine Icing Working Group Industry Guidance on Means of Compliance for Engine Operation in Ice Crystal Icing" to aid applicants in showing compliance to the new ice crystal icing regulations. The document has an introduction to provide context for the discussion and represents the key processes that experimenters believe are fundamental to ice crystal icing. The topics from the introduction are as follows: the significance of liquid water, percentage melt (or melt ratio), total water content (TWC), wet bulb temperature (Twb), and erosion. The information on these topics is primarily derived from experiments on an isolated geometry. Here they will be explored with reference to the processes at the wall-ice interface and later in the document, the same topics will be presented with respect to ice-on-ice growth, where ice and liquid are now impinging on an existing ice mass, rather than the wall.

4.10.1 The significance of liquid and the importance of melt ratio

The presence of both ice and liquid water on the surface for ice crystal accretion has been explored in many test settings and is well accepted. Early rig testing exploring the physics of accretion led to the development of the concept of a melt ratio plateau [29]. The melt ratio plateau defined by those authors refers to the liquid and ice present at the accretion site and is the liquid water to total water ratio favorable to the occurrence of icing. As a result of experimentation [23, 24, 29], the idea of a range of melt ratios resulting in optimum icing or a “plateau” resulted. The concept is illustrated in Figure 11. Note that term “icing severity” simply refers to ice accretion growth. At melt ratios to the left of the plateau, there is not enough liquid for the ice crystals to stick to the surfaces, and at melt ratios to the right of the plateau, there is too much liquid and the surface cannot be cooled enough for ice to freeze and stick to the surface.

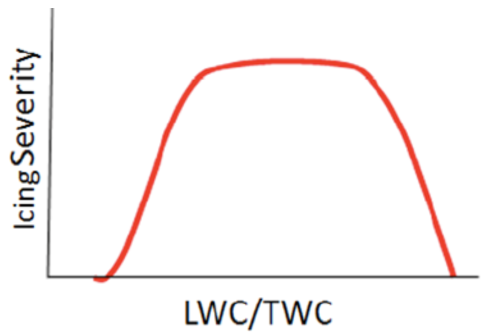

Figure 11. Hypothetical variation of icing severity with melt ratio (liquid water/total water)

Because the term melt ratio has been used in several ways, for this document, the term “comprehensive melt ratio” will be used to define the water and ice at the local accretion site, involved in the heat transfer sufficient for ice anchoring. Referring to the volume of interest suggested in section 4.9, the comprehensive melt ratio would include the water and ice running along the surface as well as entrained in the air and impinging on the surface minus any water and ice running back along the surface or splashing away. An alternate use of the term melt ratio has been in connection with rig testing of an isolated test geometry [23, 24], where all of the liquid impinging on the test geometry arrived there entrained in the airflow. The liquid was present as a fully or partly melted particle, melted by aerodynamic heating or injected liquid into the airflow. [The liquid and total water (liquid + ice) in the air could be measured by the instruments such as the Multiwire [30] and a melt ratio could be calculated.] Melt ratio numbers quoted in those works refer to only liquid and ice present in the impinging airflow and will be referred to in this plan as the “air melt ratio.” In the case of engine geometry, liquid water and ice may arrive at the accretion site after impinging on a surface and running back. In the context of this technology plan with its focus on the outer wall accretion site, care will be taken to use the term comprehensive melt ratio to refer to the local conditions at the accretion site, thereby including all water involved in the heat transfer, some of which may result from sources other than direct impingement of water-laden air. Defining the comprehensive melt ratio to refer to the water and ice involved in the heat transfer at the accretion site is complex, because as illustrated above, the water and ice involved in removing heat from the site to the point of enabling ice anchoring may not remain at that location but run back, or shed. In addition, the comprehensive melt ratio is not currently an easily calculable or measurable quantity. Integrating all the water involved in removing heat from the surface, comprehensive melt ratio more accurately captures the complex and dynamic conditions inside the engine (see also paragraph 5.2 on variation in cloud TWC and engine condition). The advantage of the concept of comprehensive melt ratio is that it provides a new viewpoint from which to consider the question of what causes ice to build-up in the engine, and to explain the behavior observed in the ALF502R-2 video.

The question of when to start the accounting of mass involved in the heat transfer that leads to anchoring, and when the transition to no shed ice occurs will need to be clarified or defined by the researchers who begin to understand the detailed processes. The comprehensive melt ratios that lead to optimum icing for ice-on-ice growth may be different than for anchoring at a wall. For ice-on-ice growth, the surface of the ice is freezing, and it may be possible to freeze more water on an iced surface, and therefore at higher melt ratios than those for anchoring at a wall.

Experimental data which led to an understanding of the air melt ratio for optimum icing have been derived from experiments where ice was formed on an isolated geometry at a constant air melt ratio [for example, reference 25]. Since these experiments did not investigate the effect of changing the air melt ratio after the ice had anchored, the information they provide is related exclusively to the air melt ratio sufficient for anchoring.

Engine manufacturers can estimate the air melt ratio at the accretion site, using a 1-D melting and evaporation calculation coupled with an engine model that calculates the average flow, pressure and temperature of each stage at the center of the flow passage. Such a calculation represents only water entrained in the air at the conditions at the center of the flow passage of the engine. For an icing site near the outer wall, this calculation does not include the mixing of wakes, boundary layers and collisions with geometries, all of which slow the transit time of an ice or water particle and could result in more melting than indicated by a 1-D calculation (RN19). In an icing tunnel, the amount of melting in the air ahead of the test geometry is calculable, as some icing tunnels have empirically substantiated analytical models of the tunnel flowfield, and the melting and evaporation of ice particles as they proceed down the tunnel. The air melt ratio is a useful way to compare test points and report results. As we improve our understanding of the detailed physics of ice crystal icing, and determine whether runback water plays a significant role (RN6, RN7, RN8), it may be helpful to carefully use the descriptive terminology introduced herein.

The idea of a band of comprehensive melt ratio (or "plateau" in the EIWG document and other sources) for optimum icing is a sensible explanation for observations of ice particle icing test points – for example, ALF502R-2 points forming a spectrum from areas having a wet appearance and light accretion to areas having a frosty and dry appearance and light accretion. Many other experiments besides the ALF502R-2 have reported these qualitative observations of the ice accreted.

There is approximately a 10 degrees Celsius difference between ALF502R-2 rollback points reported by Flegel [6]. Response of metal temperature measurements at the EGV2 and shroud show that the rate of heat removal from the surface is related to the ambient temperature at which the test point was run. Further study of these differing temperature points and the resulting comprehensive melt ratio at the accretion site is needed, particularly for ice on ice cases at the left edge of the plateau – what allows ice to continue to build up for test points which look frosty and dry?

RN19 – The importance of comprehensive melt ratio – Study of outer wall icing sites to determine what proportion of the liquid water at the icing site results from melted particles in the air impinging versus water running back. Given the runback water, does it affect the local humidity at the icing site? A comparison should be made between the predicted icing site of a 1-D melt and evaporation model and the actual engine icing site, to understand the applicability of these calculations. These studies depend on the use of a rotating rig or full engine experiment, where there are ice collisions and breakup as well as centrifuging. The results will be dependent on the engine or rig's size, number of stages, pressure and temperature rise.

4.10.2 The significance of total water content (TWC)

The hypothesis of a cloud TWC threshold above which ice accumulations begin to form in the engine flowpath has been proposed and observed in both engine and component tests[26]. This hypothesis is connected to the comprehensive melt ratio "plateau" concept (section 4.10.1), where below some TWC, there is not enough heat removal to form ice on the surface (high melt ratio). This lack of ice formation at low TWCs was also shown in the altitude test of the ALF502R-2 LF11 engine [6].

TWC is connected to comprehensive melt ratio in a complex way and questions remain, as will be illustrated by the following comparison. Consider three types of clouds that an airplane encounters, each one with a constant TWC, and assume the engine was totally dry prior to the encounter.

- Cloud 1 – low TWC: this one does not contain enough ice to cool the engine surfaces all the way down to freezing regardless of the melt ratio.
- Cloud 2 – TWC above the cloud TWC threshold: ice accretion depends on the melt ratio, enough water to act as “glue” and enough ice to cool the surface to freezing.
- Cloud 3 – twice the TWC of Cloud 2: more of both ice and water on the surface. Even if the melt ratio was exactly the same as Cloud 2, the additional water may (1) provide a thicker, slippery medium that allows the ice to runback due to aerodynamic pressure, or (2) cause faster heat removal at the surface, reducing the harmless build-shed cycles.

These examples bring up the question of whether the comprehensive melt ratio plateau width is a function of TWC.

Flegel et al. [6] documented the effect of varying TWC on time until rollback was declared for the ALF502R-2 LF11 engine. They found that with increasing TWC, rollback time decreased. This suggests the second result from the Cloud 3 encounter is more likely. Since comprehensive melt ratio is unknown, careful study of the video for these test points may shed some light on the local physics at play; general observations about the amount of melting at the icing site could be useful.

The three-cloud example above was chosen to focus specifically on the effects of TWC at the wall-ice interface. There is a lack of experimental data separating the icing-on-wall regime from the ice-on-ice regime, as well as a lack of experimental data from a test that includes centrifuging, breakup, and runback water and ice. These processes affect the comprehensive melt ratio and must be accounted for in any study of the effects of TWC. Experimental data from isolated geometries on the relationship between air melt ratio and TWC may not apply to engine outer wall icing surfaces.

Another hypothetical cloud encounter explores the interconnectedness of TWC and comprehensive melt ratio in the context of an engine and indicates another research need. An airplane is flying through a cloud and ice is accreting on an outer wall icing site, at the left edge of the comprehensive melt ratio plateau. The left edge of the plateau is where there is just enough water to form ice accretion. It is well known that there is an air temperature depression associated with flight in ICI clouds, so if subsequently the TWC is further increased, the air temperature is likewise depressed, and a reduction of melting would occur by the accretion site, lowering the comprehensive melt ratio. The result would be less accretion at the outer wall site and increased potential downstream. In summary, increasing TWC could hypothetically result in less ice accretion. An experiment to investigate this hypothesis has not yet been performed. An engine test where TWC has been increased to the point where no ice forms has not yet been conducted. However, it illustrates the possible difference between ice-on-wall versus ice-on-ice growth. The increase in TWC would occur after ice is already forming and therefore is subject to the processes of ice-on-ice growth. Understanding this phenomenon has important implications for the development of validation tests for new engines and critical point analyses.

RN20 – The importance of TWC – A study of varying TWC and its connection with comprehensive melt ratio, with a full engine test or rig. Can the accretion at an outer wall location be prevented or stopped by low comprehensive melt ratio, as the above theory suggests, or does higher TWC simply increase the ice build-up rate (as suggested by Currie [31], and seen in LF11 tests (Flegel [6])? Is comprehensive melt ratio a function of TWC? Different experiments may be needed to determine these influences for ice-on-wall and ice-on-ice regimes.

4.10.2.1 Variation in cloud total water

During the flight planning for HAIC-HIWC program, Boeing summarized event weather infrared satellite image analyses to help direct the scientists to sample clouds that were similar to those that were associated with engine events. The event analyses showed that typically the events occurred in large mesoscale convective systems with a diameter greater than 50 NM [8]. [The process of overlaying the flight track and the engine event position on the infrared satellite image also revealed that the events tended to happen at a point on the traverse of clouds that was near a local maximum of TWC [32, 33], typically associated with an updraft or source of ice being lifted from below.] The typical exposure derived from these studies would consist of long stretches (on the order of 50 NM or more) of lower total water content associated with the spreading out of ice at the equilibrium level, followed by a brief exposure to a higher total water near the maximum. Since no ice concentration data is available, the exposure distance for each of these cloud areas are somewhat arbitrary and tied to the definition of the temperature below the equilibrium level used for the infrared satellite weather analysis. An explanation for why engine events were not happening in smaller, and perhaps more intensely convective clouds was sought. One hypothesis is that the long stretch of lower total water content or "background TWC" is important for heat removal at the icing site, while it may not be sufficient for ice to accrete, as it is below the cloud TWC threshold. This precooling idea is consistent with the ideas discussed in section 4.5 that the time history of the heat transfer at the wall is important for anchoring. Several LF11 test points were conducted by the ICC to investigate this effect and are summarized in a 2016 AIAA presentation by Dischinger and Sandel [34] called the Peak Intensity Effect. They began with two exposures, one with a long low TWC and the other with a short peak TWC, neither of which would cause ice to accrete by itself. By coupling these exposures back-to-back, they produced ice accretion. This result points directly to the time history of heat transfer at the icing site being important.

RN20.1 – The fundamental research proposed in this section, RN16, 17, 18, 19 & 20 should identify the basic physical processes and how variable TWC affects the heat transfer at the engine icing site. Subsequently, tests on a full engine or rotating rig could be defined to gather validation data showing the effects of a variety of combinations of "background" and "peak" TWCs. If the same icing effect can be obtained by more than one test procedure, the result would be valuable for critical point analysis and test planning.

4.10.3 The significance of wet bulb temperature (Twb) and humidity

The amount of melting and evaporation of water entrained in moving air is connected to the wet bulb temperature of the air. Currie 2012 [24] has a very complete presentation of Twb as it relates to ice crystal icing. Twb is a function of the dry air bulb temperature, the pressure and the humidity of the air. After making several assumptions and applying a steady-state heat balance at any point on the surface, Twb is obtained by equating the heat loss by evaporation to the heat loss by air convection in deriving the temperature.

A wet bulb temperature of 0°C has been demonstrated by many researchers [23, 24] to be a boundary between well-adhered ice and ice that is loosely adhered. The icing tunnel conditions are set to achieve a desired Twb by controlling the input air humidity. In the tunnel the local wet bulb conditions at the test article are calculable. The wet bulb temperature is a convenient tool for icing tunnel test point set-up and comparing test points.

Similar to the air melt ratio, use of the wet bulb temperature to describe ice crystal icing comes from a viewpoint that focuses on the air as the main source of melted particles and evaporation as the main heat loss mechanism. At some point during an ice particle's progress through the engine toward the icing site, the water film will be so thin that these assumptions will be true. These assumptions do not apply once a thicker film has formed. The significance of water and ice arriving at an outer wall icing site from upstream still need to be established, and to the degree they are found to be important, the wet bulb temperature may be recognized as less important. When the outer-wall icing site is covered by liquid water and ice, the local processes taking place at the wall interface leading to no-shed ice growth are not driven by air wet bulb temperature.

The importance of wet bulb temperature will be revealed from a study of the film thickness along the wall upstream of the icing site, drawn from a simulation that includes the breakup, centrifuging and melting of ice particles upstream, such as a full engine or rotating rig, as covered in RN14.

Humidity is related to Twb, and in experiments is closely tied to whether ice forms or not. The effect of humidity on ice accretion is clear; the importance of the evaporative cooling heat transfer is one of the key differences between ice particle icing as opposed to supercooled droplet icing. Local humidity is not well understood at an engine outer-wall icing site during ICI conditions. Scientists have carefully determined [3] that the ambient air that is ingested in these ice crystal icing clouds is very dry (i.e. low specific humidity[2], all the moisture has been condensed and frozen out). How the humidity changes as an air parcel moves through the engine environment to the icing site is complex. The change in humidity with engine axial direction will depend on the evolution of particle size (breakup) and the ability of the small particles to melt, which depends on rotor speed, velocity, and temperature. The slowing and centrifuging of particles may result in a longer residence time for melting. This is all going on while the air is being compressed and temperature is increasing. Overall, the timescales for these processes inside the engine are extremely short (on the order of milliseconds), and depend on diffusion rates, which in turn depend on local pressure which increases with axial distance.

Once a water film has formed on the wall or on an ice deposit, evaporation from this film will play a role in the axial humidity change.

The concept of Twb collapses pressure, temperature, and humidity to a single parameter. However, when evaporation and convection are not the only primary heat transfer mechanisms, as they may not be for an outer-wall icing site, it breaks down. The final humidity at an outer wall accretion site is not yet known, and for these reasons, scientists debate what regime (Twb above or below zero) exists at the icing site in engines with events.

In order to perform accurate component tests, the humidity of the engine icing site being simulated must be known, and the tunnel air humidity matched. For full engine or rotating rig tests, the change in humidity from the engine inlet to the icing site is accurately simulated. However, in some test facilities the input air cannot be made as completely dry as the atmospheric conditions it is attempting to match, which may affect the icing within the engine.

RN21 – The importance of humidity – A study of the difference in humidity between the inlet and an engine outer wall icing site with axial distance through the engine. This may be accomplished by a parametric study under various assumptions, using a 1-D melting and evaporation model to

[2] Since relative humidity is referenced to the air temperature, and the engine air temperature is changing axially, it is best to avoid the use of the term relative humidity in this setting.

examine a set of engine boundary conditions with varying assumptions about vapor diffusion rate and particle velocity with respect to the airstream, and water film evaporation rate, in order to reveal the dominant processes and resulting specific humidity at the icing site. Evaluate changes in humidity as a function of rotor speed (particle breakup and centrifuging), in a full engine or rotating rig simulation. A study of the impact of variation of test cell humidity on the outer wall icing formations in a full engine or rotating rig test.

4.10.4 Sticking efficiency

Many scientists have been studying the important question of how much ice and water stay on a surface and contribute to ice growth. One definition of sticking efficiency [35] is as follows: “The sticking efficiency for particles is defined as the fraction of the impinging particle mass flux which remains on the surface.” It is used to describe mass in and mass out of a geometrically simple ice growth case, where liquid and ice are entrained in the incoming air and exit by erosion or bouncing. When considering the engine compressor wall icing site: there may be more water involved in the icing besides impinging particles. To fully characterize the icing at this site, all ice and liquid water impinging from the air, as well as that which is running back or shedding into and out of the icing site, should be included. Furthermore, to date scientists have been considering the sticking efficiency as a steady state value. However, from the changing volume of interest viewpoint proposed in this document, as the volume changes to include a different contour wall or additional ice deposits, the sticking efficiency would also change. In this context, a parameter that captures ice and water entering or exiting the volume may be more appropriate. Furthermore, a single sticking efficiency parameter cannot fully describe the two different regimes: ice-on-wall and ice-on-ice. One difference between these two sites is the substrate temperature. In the ice-on-ice case, there is an insulating effect of an ice deposit, so that heat transfer from the wall has little influence. The presence of an irregular and porous ice sheet may have a great deal of influence on the sticking efficiency in the ice-on-ice case.

Researchers will undoubtedly determine a parameter that best describes the physics when they are better understood. At this time, a unique sticking efficiency parameter is unable to fully describe the conditions for the ice crystal icing case at an engine compressor outer wall.

Currie’s [25] development of a sticking efficiency parameter focused on an isolated geometry with all impinging water and ice entrained in the airflow and on ice growth in the direction of the stagnation streamline. The geometry doesn’t include runback water along the wall, but the results may be applicable for ice-on-ice growth due to impinging ice/water entrained in the air. (See section 5.)

Needed research on the topic of sticking efficiency is covered in RN18, and is more generally described as ice and water inflow rate into and outflow rates from the volume of interest.

4.10.4.1 Total ice and liquid water mass involved in heat transfer

In order to fully account for the process of heat removal at the wall and ice initiation, consideration should include all ice and liquid water involved in the heat transfer. It accounts for the incoming ice and liquid mass – impinging from the air, or running in or sliding to the icing site – minus the ice leaving the site through splashing, bouncing, eroding, shedding or runback. Therefore, for the ice-on-wall regime, it should be a time-based accounting of all mass in the volume of interest encompassing the period from cooling the initially wetted wall followed by ice and water impinging and running back, and finally the point where no-shed ice occurs.

4.10.4.2 A Closer Look at Stagnation Sites

To further explore what makes ice stagnate on a surface leading to cooling of the wall, examination the ALF502R-2 video aids in understanding the local conditions that result in an icing site versus simply a wetted wall. There appear to be several conditions that result in ice stagnation points, including:

- a leading edge stagnation point
- an area of turbulent wake of an airfoil or an ice deposit or an instrument solder point
- a compound curvature region.

All engines have these kinds of features, so further research of what is happening that leads to ice anchoring at the icing site may be needed.

4.10.4.3 Leading edges vs. concave outer wall

In the case of the ALF502R-2, the ice accretion that caused the blockage and led to the engine rollback was not on the leading edges of the airfoils, but rather at the endwall between the vanes. This is true of the accretion sites of some event engines. There is ice that does grow on leading edges of the vanes in the ALF502R-2 video, but remains small and sheds, perhaps due to backside wall heat; in this case, the relatively thin vane is likely influenced by the warm airflow impinging on the ice-free pressure surface. Hence, stagnation and anchoring of ice appears to be due to a combination of geometric stagnation areas balanced with backside wall temperature effects.

4.10.5 The significance of geometry

Simply reducing engine power would move the location where the comprehensive melt ratio results in optimum icing further aft in the engine – temperature reduces and rotor speed reduces, both affecting melting, resulting in particles traveling further aft before melting. (Increasing engine power would have the opposite effect.) At this new location, the geometry may not create an ice stagnation area or a stagnation area may not be coupled with a backside wall temperature conducive to anchoring. Because the right melting conditions for optimum icing probably occur at every point within the engine at some time during its service envelope, it may be helpful to assume that all engines have conditions of optimum comprehensive melt ratio and first focus on understanding what geometry and backside wall temperature allows for ice anchoring.

4.10.6 Erosion and other mechanisms for mass leaving icing site

In the discussion of sticking efficiency, note that erosion is one of the means by which ice and liquid are removed from the surface and do not contribute to the heat transfer. Several researchers have documented the phenomenon of incoming ice particles causing erosion or preventing build up. Al-Khalil [5] documented conditions where accretions were significantly eroded or not seen on a test article and Knezevici [36, 37] has shown that large particles and high velocity are responsible for lack of accretions. In the context of this section’s focus on the wall/(ice+water interface) and the conditions for ice anchoring, the erosion mechanism is not well understood. Study in this area could lead to the understanding of conditions that define the ice-no-ice boundary, and design tools to prevent ice buildup. It has been shown that particle size and velocity are key parameters to this process. Therefore, emphasis should be placed on understanding the centrifuging and breakup occurring in the engine (RN6) and local conditions at the icing site.

4.11 Airspeed

There may be an airspeed that will not allow water and ice to remain on the surface for heat transfer to take place. For accretion conditions like the ALF502R-2, and the similar outer compressor wall accretion location example being explored in this document, the local air velocity at the accretion site may be somewhat lower than the velocity at the center of the passage (meanline) at the same axial location. It is possible that the speed of the airflow at the meanline is the reason ice does not form there. If the local flow were turbulent, such as a location in the wake of an upstream blade, then the average velocity in the axial direction would also be lower than the velocity at the mean line.

Currie 2018 [38] explains the formation of an ice ridge aft of the stagnation point on his hemispherical test article as resulting from accelerated induced freezing. In that work, Mach numbers were chosen to be representative of the air velocity at cruise conditions in turbofan engines that have had events. The acceleration of the flow over an airfoil could produce a drop in the wet bulb temperature. However, the known accretions in event engines do not occur in that location. Further study of this phenomenon is needed for compressor outer wall geometries, where local velocities may be lower, conditions may be dominated by boundary layers and wakes, and the wall may be covered with liquid water or slush. (See also 5.4.)

RN22 – The importance of airspeed - A study of the effect of airspeed on accretion should be conducted on geometries such as a stagnation area along the compressor outer flowpath, with a varying wall backside temperature.

5 Ice-on-ice growth

This section discusses the following: An ice deposit is anchored on the wall and the surface of the deposit becomes the icing site, as shown in Figure 12. This will be called ice-on-ice growth and the discussion will explore factors that cause the ice deposit to grow once anchored, as well as factors that remove ice or water from the surface, such as erosion.

Ice-on-ice growth can occur at the same time that the interface of the deposit with the wall is experiencing melting, as described in section 4.7, and the ice deposit may eventually shed.

In this section, a comparison will be made between ice-on-ice growth and the conditions described in the section 4, describing ice-on-wall growth at the wall interface, which will be referred to in this section as "initiation and anchoring at the wall."

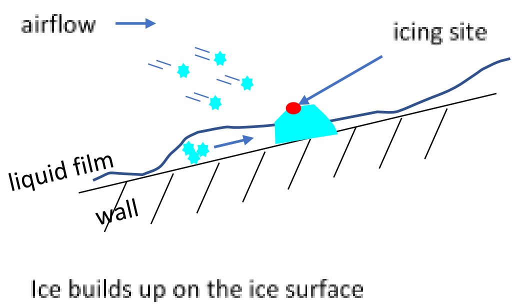

Figure 12. Diagram of ice-on-ice growth

5.1 Ice and liquid water required for ice-on-ice growth

Studies have already established the need for ice and liquid water to be present for further growth of an ice deposit. For example, when an aircraft is operated in a glaciated cloud with the cowl anti-ice system turned on, it is known from experience that the heated cowl surface could get a thin ice layer built up, but once the ice has formed, any further impinging ice particles hit a cold surface and the ice layer does not grow further. Hauk conducted a similar experiment shooting cold ice in a cold environment at a warm surface [15]. He noted ice-on-ice growth due to mechanical interlocking. Based on the cowl example above, the mechanical interlocking mechanism is not sufficient to build up an appreciable ice formation on the cowl.

Mechanical interlocking may explain the formation of small build-ups of ice on the wiper blades of aircraft flying in ice crystal icing conditions. In experiments, appreciable size buildups have always required a liquid and ice mixture, and liquid is certainly present in a warm event engine accretion location. Mechanical interlocking may be an element of the physical phenomenon that allows the incoming ice to stick on an existing ice deposit, as well as the apparent coalescence or solidification of ice particles or slush arriving from upstream.

Referring to the video description outline in section 1.4.2, insight into ice-on-ice growth can be gained by examining the “shark’s teeth” formations. Interestingly, the shark teeth tips point not to the vane trailing edge or vane wake region, but to the vane pressure surface close to the trailing edge. It indicates a build-up caused by a high particle concentration region coming off the vane pressure surface trailing edge, which traverses the vane wake region right after the vane trailing edge. In the airflow turning region inside of the vane upstream of the trailing edge one would expect that particles concentrate on the pressure side and thin out on the suction side due to their more ballistic nature. Since particles do not follow the direction of the vane camber line exactly, at the end of the turning at the trailing edge, particles deviate from the air flow direction and get carried across the vane wake. The vane wake allows the impingement of this mass on the wall.

As noted in paragraph 4.6.1, examination of the growth of the island chain in the ALF502R-2 video shows evidence of initially separate deposits coalescing into one mass. There are many unanswered questions associated with this process. Does the unconsolidated ice/liquid water adjacent to the existing deposits freeze onto them creating a bond, or is the bond created by ice/liquid water impinging from the air in the new stagnation zone adjacent to the existing mass? Perhaps water is re-freezing between the two deposits. What is the nature of the bond? Under what conditions is it able to support an ice deposit and prevent its shedding? An ice deposit or layer is not just an inert piece of ice, but a porous substance, able to absorb water and, depending on local conditions, use this ability to form a coalescing bond [39].

RN23 – Data in support of ice-on-ice growth - A study of the fundamental nature of ice-on-ice growth, its dependence on liquid, capillary freezing, mechanical interlocking, coalescence, *porosity and other processes. The boundary conditions should include ice growth on top of an ice deposit in an above-freezing airflow environment. (RN23, RN24 and RN25 are all related).*

5.2 Atmospheric variation in TWC, engine condition variation and effects on melt ratio

Ice-on-ice growth requires the presence of liquid and ice, but the proportions may vary from those required for initiation and anchoring at the wall. Ice on ice growth may be possible in a broader range of comprehensive melt ratio values than initiation and anchoring. An observation that suggests that this may be so is the formation of ice that leads to engine events despite atmospheric variation in TWC and variation in engine condition. Experimental data [23, 24] suggests that there is a narrow band of air melt ratio, which results in ice crystal accretion in fundamental studies. Yet the idea of a narrow band limiting ice growth in the engine is harder to explain when one considers the known variation of ice water content (IWC) in a single cloud and the engine condition variation (powersetting) during flight in ICI. Study of digital flight data recorder (DFDR) data after an engine event reveals that the conditions during the ice accretion are far from steady state. Consider, for example, the case of an event occurring during cruise through an ICI cloud. During cruise the autopilot/autothrottle is typically engaged and targeting a desired altitude and airspeed. Engine power setting is one of the variables used to maintain the altitude and airspeed. Flight in ICI clouds typically is associated with light to moderate turbulence [29] and there are updrafts and downdrafts ([32] figure 2). Any updraft will be compensated by a reduction in engine power (to lower the nose of the airplane), resulting in lower engine temperatures, while a downdraft will be compensated by an increase in engine power (tending to raise the nose of the airplane). Examination of the engine rotor speed during a typical cruise through an ICI cloud shows that there is variation. Rotor speed affects comprehensive melt ratio through particle breakup and temperature. Evidence of TWC variation in the cloud was obtained by the HAIC/HIWC flight campaigns (Strapp [3] figure 4.26), and also through data for the high compressor discharge temperature during flight in cloud. The variation of TWC is also quite noisy during flight in ICI clouds. Cloud TWC is directly connected to comprehensive melt ratio as noted above (section 4.10.2).

Given these two sources of variation, both of which directly influence the comprehensive melt ratio at the icing site, and given that there is a relatively narrow “plateau” (section of comprehensive melt ratio for optimum icing), how is it possible for large accretions to build up in an engine? It seems unlikely that the comprehensive melt ratio remains in the plateau region throughout a significant cloud traverse. Variation could cause the accretion to start and stop as hypothesized in section 4.10.2. It also may be that ice-on-ice growth is not as sensitive to variation as ice-on-wall initiation and anchoring (section 4), as is explored below.

Ice-on-ice growth could be dependent on different mechanisms than initiation and anchoring at the wall. First, the ice surface temperature is freezing. The ice deposit acts as an insulator from the wall heat, so wall heat transfer need not be considered. The sticking efficiency of incoming water/ice will be very different, due to ice surface roughness and amount of water on the surface. Depending on the geometric shape of the deposit, it may lack a water film. Slush from upstream may impact the existing ice and solidify. All of these elements lead to the hypothesis that the comprehensive melt ratio required for ice-on-ice growth is not the same as that for ice-on-wall initiation and anchoring, and further that the comprehensive melt ratio for optimum ice-on-ice growth may have a broader plateau than for ice-on-wall initiation and anchoring.

RN24 – Atmospheric variation in TWC and engine condition variation and effects on melt ratio - A study to explore variations in comprehensive melt ratio and TWC on ice-on-ice growth, with varying film thickness and slush impingement.

5.3 Significance of sticking efficiency

In the compressor wall icing site, ice-on-ice growth is a function of the total water and ice impinging running back or impinging on a surface. However, since the surface of the ice deposit may be some distance from the wall, and therefore from local runback water along the wall, the icing may be dominated by the water and ice impinging from the airflow. If this is the case, then the Currie [25] work on sticking efficiency, which includes erosion, may be applicable.

Even if it is found to be applicable to an ice-on-ice case some distance from the wall, Currie's approach to sticking efficiency is hard to apply in the complex flowfield of the outer wall icing site. Currie defines the change thickness, t, of the deposit in the direction of the stagnation streamline. In an outer wall icing site such as that of the ALF502R-2, the flowfield is not simple, as there are wakes and boundary layers affecting the flow. It may be unreasonable to expect a flowfield analysis to resolve these flow features, yet they are fundamental to the ice growth, and to the stagnation streamline at a point. A different formulation of sticking efficiency is needed for complicated geometries and flowfields, such as the icing site at the outer wall compressor intersection with one or more vanes.

In the outer wall icing site, there may be ice shed from upstream or slush runback encountering the ice deposit and sticking. The mechanism for consolidation/solidification of this ice/water is not understood. This mechanism for building up ice should be included when considering the ice-on-ice growth process.

RN25 – Significance of sticking efficiency – A formulation of sticking efficiency that applies to a complicated 3-d geometry, and the dynamic volume of interest as the ice grows. A study of whether a significant contribution to ice-on-ice growth is made by ice and liquid water (slush and shedding) arriving from upstream, and if so, by what mechanism does it contribute to ice-on-ice growth.

5.4 The importance of the volume of interest, and determining the total ice mass

Ice-on-ice growth may be happening simultaneously with melting the wall interface and nearby ice-on-wall initiation and anchoring. The final ice growth in one location is dependent on what is happening nearby and the shape of the nearby geometry. For these reasons, a volume of interest must be considered that includes both the anchoring area and the extent of the ice growth, which may be somewhat distant, and the aerodynamic forces on the ice mass, while accounting for the physics of ice-on-ice growth differently from ice-on-wall initiation and anchoring.

Another effect on total ice mass that must be considered is the possibility an ice deposit may constrict and accelerate the flow between vanes or even within the compressor case, thus altering the flowfield. The ice mass may create a downstream disturbance that becomes a new impingement site, but also has the potential to alter the velocity such that ice accretion conditions are no longer present (see section 4.11). RN22 should answer the question of whether there is an airflow velocity at which ice cannot form, which can then be used to estimate the ice mass that would achieve that velocity. This has implications for limits of ice growth, and therefore is useful for engine design and compliance.

RN26 – The importance of the volume of interest and determining total ice mass - An analytical calculation of the change of the flowfield velocity with a given blockage (RN23) could be coupled with an experimental validation study to investigate limits of ice size in a ducted flow.

5.5 Erosion

Section 4.10.6 referred to research experiments where erosion resulted in no ice growth on the surface as being applicable to the phenomenon of erosion at the wet wall. Knezevici and Currie [36, 37 38] saw a change in ice growth rate due to particle size and velocity, and their results would be applicable to ice-on-ice erosion.

5.6 Shedding

Shedding of an ice-on-ice growth is dependent on melting of the interface with the wall, the aerodynamic forces, the size of the ice growth, and local geometry. This topic is addressed in section 4.7.

6 Altitude scaling

This section discusses altitude scaling in the context of the challenges of matching the heat transfer at the wall in order to obtain the same accretion at sea level and altitude. Currie's work on altitude scaling emphasizes the importance of using the melt ratio as a parameter to match to obtain the same accretions at altitude and sea level. His work focused on an isolated geometry and used the air melt ratio as defined in this document.

Apply the idea of matching comprehensive melt ratio in two experiments of varying altitude to determine whether an accretion at the outer wall site can be matched. Consider two experiments with a full scale engine, one at sea level and one at altitude, where the temperature, humidity, rotor speed/breakup, and airspeed are adjusted to obtain the same comprehensive melt ratio in the two cases (so that the same mass of water and ice arrive at and leave the accretion site). Would the accretion be the same for both experiments?

Here is one possible answer: in section 4, it was proposed that the time history of the heat transfer at the wall is important for anchoring, and it is dependent on the rate of mass and heat transfer at the wall and the aerodynamic forces acting on deposits. This in turn implies that the dynamic pressure on the icing site must also be matched at the same time. In addition, to ensure that the heat transfer is identical, the wall backside heat must also be matched. These aspects of altitude scaling require a better understanding of the fundamental processes at play, already covered in this document.

RN27 – Following the fundamental icing process research described above, further experiments on altitude scaling can be designed, and will be extremely valuable to the industry for lower cost compliance data gathering. The key parameters for scaling ice initiation may be different from those for scaling ice-on-ice growth, for example comprehensive melt ratio and wet bulb temperature may be studied for ice initiation scaling, whereas dynamic pressure and backside heat may be important to scaling ice-on-ice growth and shedding.

7 Conclusions

The release of video evidence from the ice crystal icing test of the ALF502R-2 has provided an invaluable opportunity to investigate the ice crystal icing processes in a turbofan engine. In addition, it has allowed comparison with research experiments conducted so far, highlighting aspects of this complicated problem that are still not well understood.

An important aim of the document is to foster discussion within the ice crystal icing research community on the fundamental processes of ice crystal icing. Pre-publication review by ice crystal icing researchers has shown that the research community is not in complete agreement on the fundamental processes, and will not be unanimous in accepting the processes defined herein. This document should be viewed as a success if it instigates further discussion and research. It should point the reader toward experiments and simulations that more closely simulate important engine boundary conditions, and reproduce accretions that are similar to those found in turbofan engines.

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