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Ice Crystal Icing Research at NASA

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Abstract

Ice crystals found at high altitude near convective clouds are known to cause jet engine power-loss events. These events occur due to ice crystals entering a propulsion system's core flowpath and accreting ice resulting in events such as uncommanded loss of thrust (rollback), engine stall, surge, and damage due to ice shedding. As part of a community with a growing need to understand the underlying physics of ice crystal icing, NASA has been performing experimental efforts aimed at providing datasets that can be used to generate models to predict the ice accretion inside current and future engine designs. Fundamental icing physics studies on particle impacts, accretion on a single airfoil, and ice accretions observed during a rollback event inside a full-scale engine in the Propulsion Systems Laboratory are summarized. Low fidelity code development using the results from the engine tests which identify key parameters for ice accretion risk and the development of high fidelity codes are described. These activities have been conducted internal to NASA and through collaboration efforts with industry, academia, and other government agencies. The details of the research activities and progress made to date in addressing ice crystal icing research challenges are discussed.

Nomenclature

EGV	exit guide vane
HPC	high pressure compressor
ICI	ice crystal icing
IGV	inlet guide vane
IWC	ice water content
IRT	Icing Research Tunnel
LWC	liquid water content
LPC	low pressure compressor
MMD	median mass diameter
MVD	median volumetric diameter
PSL	Propulsion System Laboratory
T_{wb}	wet bulb temperature
TWC	total water content

Subscript:

t	total
s	static

Introduction

Ice crystals found at high altitude near convective clouds are known to cause jet engine power-loss events (Ref. 1). These events occur due to ice crystals entering a propulsion system's core flowpath and accreting ice resulting in events such as uncommanded loss of thrust (rollback), engine stall, surge, and damage due to ice shedding. NASA has been conducting research as part of a community with a growing need to understand the underlying physics of ice crystal icing, this community has come together through the Engine Icing Working Group (EIWG) to address the technology gaps in the current research in order to enhance the knowledge base for making recommendations to the Means of Compliance. Research efforts in the community have focused on measurement techniques (Refs. 2 and 4), fundamental accretion (Refs. 5 and 8), and particle physics (Refs. 9 and 12).

In 2011, a technical plan was developed outlining NASA's involvement with ice crystal icing (ICI) research (Ref. 13). This plan highlighted three research areas of focus in which NASA has unique capabilities, experience, and expertise:

1. Flight Characterization of the High Ice Water Content (HIWC) environment.
2. Classical Research in the area of altitude testing for engine, engine components, and fundamental studies of ice particle aero-thermodynamics.
3. Computational research to simulate engine performance, ice accretion, and engine control methods.

Since 2011, with the support from the former NASA Atmospheric Environment Safety Technologies (AEST) Project, investments have been made to perform flight characterization of the natural ice crystal environment, enhance facility capabilities, and collaborate with the community to perform fundamental ice crystal icing studies. In 2015 the engine icing research work transitioned to the Advanced Air Vehicle Program's (AAVP) Advanced Air Transport Technology (AATT) Project. Both airframe and engine icing work resides under AATT's Advanced Aircraft Icing (AAI) subproject. The goal of the AAI subproject is to develop aero-thermodynamic models and icing risk assessment tools that can assess potential icing risks for the N+2/N+3 design concepts and be available to the aviation community. Additionally, under AAVP, the Aeronautics Evaluation and Test Capability (AETC) project has invested in a 5 year effort to ensure advancement in NASA's ground based altitude icing simulation capability in the Propulsion Systems Laboratory (PSL).

The focus of NASA's research is to understand the physics of icing in an effort to build models that can predict ice accretion and inform current and future design of: key conditions susceptible to accretion, location of accretion, type of blockage occurring, shedding frequency, and identify parameters that would change accretion characteristics. This is achieved by developing a 0D/1D model, COMDES, which can identify potential inlet conditions that will lead to ice accretion in the core flowpath. Higher fidelity tools such as NASA's LEWICE3D and GlennHT codes will need to be modified to accommodate internal flow and icing physics to pinpoint the location and characteristics of the accretion site. Experimental efforts are underway to provide insight into the fundamental physics of ICI and aid in the tool and model development. Studies have focused on accretion physics, particle break-up, and accretion inside of a full scale engine. Because of the complexity and expense of testing engine designs at realistic altitude conditions, NASA is also exploring the feasibility of scaling to ground test facilities.

This paper will discuss the key technical areas at NASA, what is currently understood, and the path of future research. The paper will first discuss the flight characterization efforts to document the ice crystal icing environment. The key ground facilities used to perform the research will then be covered followed by the current and future direction of the various experimental and computational research efforts.

Flight Characterization

Documented power-loss events associated with ICI since the 1990's have been described by Mason, et al. (Ref. 1). These events are known to occur at high altitude where no liquid water is present. Efforts to characterize the ice crystal environment have been conducted through international collaborative efforts with the High Altitude Ice Crystal (HAIC) (Ref. 14) and High Ice Water Content (HIWC) (Ref. 15) projects. Two field campaigns were conducted in 2014 out of Darwin, Australia and in 2015 out of Cayenne, French Giana. The goal of these campaigns was to acquire detailed measurements on the TWC and ice particle characteristics over various temperature levels in deep convective clouds. Preliminary statistical analysis on the HAIC/HIWC flight data shows that particles MMDs were in the range of 250 to 1000 μm (Refs. 16 to 18). The data from these campaigns seem to corroborate that small ice crystals are responsible for high IWC cloud regions at high altitudes. Key trends observed were that MMDs typically decrease with increasing TWC and MMDs decrease with decreasing temperature (Ref. 18). In addition to these flight campaigns, NASA and the Federal Aviation Administration (FAA) have collaborated on Advanced Radar technology and conducted a field campaign in 2015 in Fort Lauderdale, Florida. This enabled the opportunity to collect additional data on the high altitude IWC clouds. The data from these campaigns enable a better understanding of the natural environment and conditions that need to be simulated.

Experimental Facilities

There are two NASA facilities currently being used to perform ICI studies at a fundamental and at an engine system level. The main workhorse facility for the current research is the Propulsions Systems Laboratory (PSL) which has a fairly new icing capability which is still being explored. The Ballistics Laboratory is used for the single particle ice break-up experiments. A feasibility study was recently conducted to look at the potential of using the Icing Research Tunnel (IRT) to perform sea-level ice crystal icing experiments. This section will briefly describe the facilities and the current capabilities.

Propulsion Systems Laboratory

A key focus of the AETC Project is developing a ground based altitude ice crystal icing simulation capability to conduct research on full scale engines and driven rigs. In 2010, test cell 3 in the Propulsion Systems Laboratory (PSL) was modified to enable icing research (Ref. 19). The facility, shown in Figure 1 and described in Table 1, features 12 spray bars that house 222 nozzles. Two types of nozzles are used in a fixed, alternating pattern across the spray bar. The Standard nozzles are used for higher water content conditions while the Modified 1 (Mod. 1) nozzles are typically used for lower water content sprays. The ice crystal cloud is generated by the liquid water spray exiting the nozzles into the plenum chamber. These particles freeze due to the evaporative, convective, and cooling effects as they travel through the plenum and into the contraction section. The instrumentation duct shown in Figure 1 houses a laser tomography system to monitor cloud uniformity during the tests (Ref. 20). Station 1 is the measurement plane use for cloud calibrations (Refs. 21 and 22) to characterize the humidity, water content, and particle size.

In 2013 and 2015, through a collaboration with Honeywell, ICI tests were conducted on an unmodified ALF502R-5 engine which had a known rollback issue (Refs. 23 and 26). These tests demonstrated PSL capability by replicating key flight test points including several full rollbacks. The facility showed good repeatability and also demonstrated the ability to perform peak TWC and descent simulations (Ref. 25).

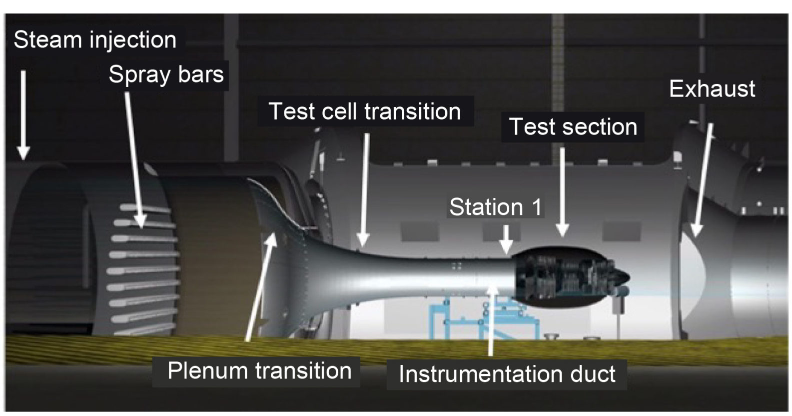

Figure 1.—PSL-3 facility layout.

TABLE 1.—PSL-3 ICING CONFIGURATION
OPERATING ENVELOPE

Specification	Min	Max
Engine/Rig Diameter, in.	24	72
Air Flow Rate, lb_m/s	10	330
Altitude, kft	4	50
Total Temperature, °F	−60	50
Mach Number	0.15	0.80
TWC, g/m^3	0.5	[a]8.0
MVD, µm	15	[b]>100

[a]Evidence that probe under-measured
[b]Particles larger than ~90 µm are NOT fully glaciated

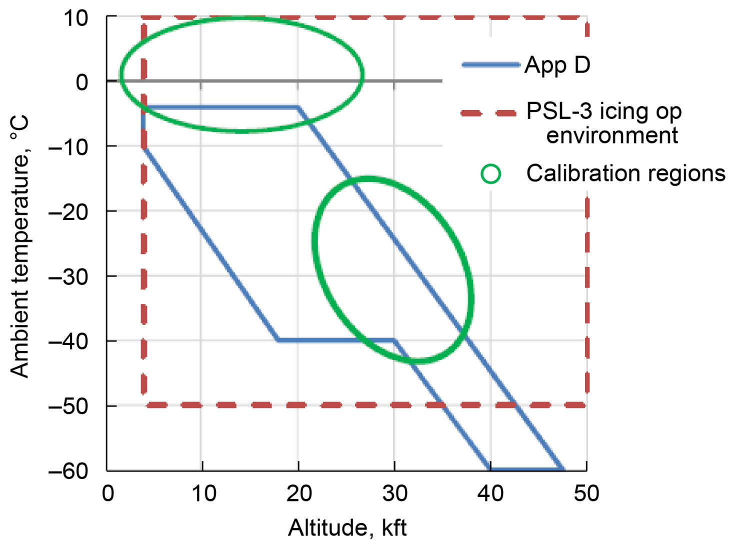

Figure 2.—PSL-3 icing operating envelope (Ref. 5).

In 2016 a fundamental ice-accretion study was performed in PSL (Ref. 27). This study looked at the feasibility of using the PSL to generate a mixed-phase condition by partially freezing the cloud. These fundamental studies seek to simulate the internal engine conditions leading to icing but in an external flow environment where measurements characterizing the accretion can be made. Parameters that are key to matching the internal environment at the accretion site of the jet engine include the (1) wet-bulb temperature, (2) particle size distribution, and (3) melted portion of incoming ice. A key objective to this fundamental test was to develop the capability in PSL to generate a prescribed mixed-phase condition at the test section for fundamental ice-crystal icing research.

As previously mentioned, the AETC project is making investments to ensure and continue to advance the PSL icing capability. As part of the original envisioned technical plan (Ref. 13), the PSL seeks to develop methods for testing engines and driven rigs for ICI susceptibility. A roadmap was created to develop the PSL capability with four goals in mind: (1) Understand the differences between the PSL Cloud and the natural environment ingested in the engine, (2) Ice Crystal Instrumentation Development and Selection, (3) Characterize the PSL Cloud, and (4) Standardize PSL Icing Test Methodology. The facility capability is largely dependent on the icing cloud produced. Since 2013 five cloud calibrations have been conducted and details of these characterization effort have been reported by Van Zante et al. (Refs. 21 and 22). The operating envelope of the facility and calibration regions are shown in Figure 2. Unlike the IRT, PSL has twelve parameters that can control the cloud conditions. Each calibration effort looks to explore and understand this parameter space. In addition, the calibration provides the opportunity to explore measurement techniques (Refs. 21 and 25).

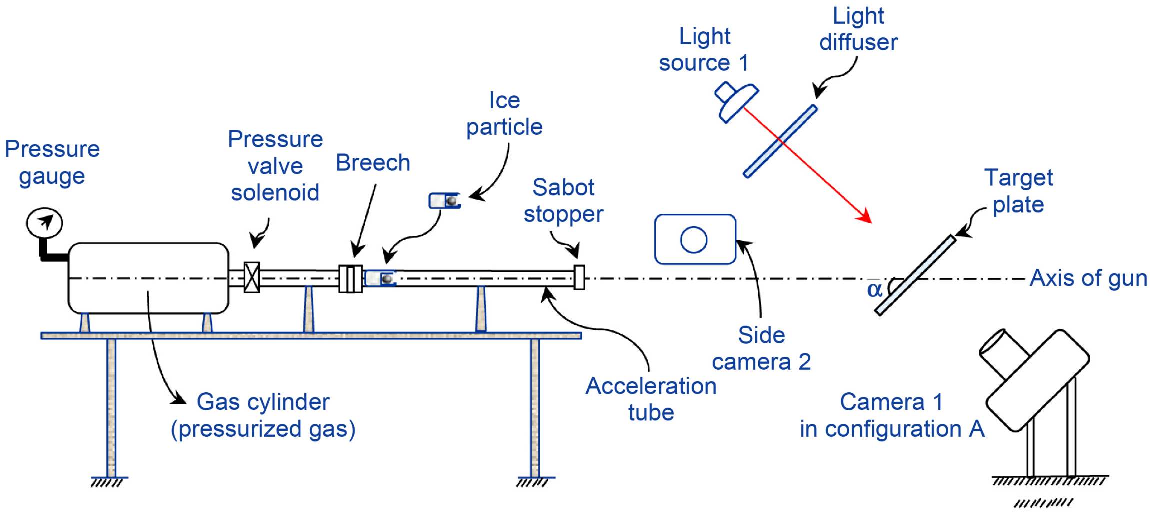

Figure 3.—Side view of the ballistics lab particle break-up test configuration.

Ballistics Impact Laboratory

The NASA Ballistics Impact Laboratory has been used for particle break-up studies on a flat plate (Ref. 28). This facility is used for impact mechanics research and technology development and features several pressurized guns offering a wide range of impact capability. The configuration for the ice particle break-up tests is comprised of several components, see Figure 3 for test set-up.

The pressurized gun that delivers the ice particles consist of a gas cylinder, barrel, solenoid valve, breech, and stopper. The particle is placed inside a sabot which is then placed inside the breech. Alternatively the particle can be placed inside the breech alone. Nitrogen gas is used to pressurize the gun and accelerate the particle. A flat target plate is used for the particle to impact on. The target is illuminated by high powered LED arrays which have shown not to heat the target area.

The ice particle shapes are generated using two methods (Ref. 28). The first method involves dropping a distilled water droplet from a calibrated pipet into liquid nitrogen. The second method ensures particles are of similar diameter by compressing an ice piece between two halves of a metallic mold. The halves are brought together to form a solid spherical particle. These particles are stored in a freezer at a temperature of –20 °C.

In Figure 3 a side camera and target camera are shown. The side camera is used to measure the velocity and diameter of the particle before impact and during the impact and breakup. To capture the post-impact fragmentation and measure the size distribution, the target cameras can be placed above or below the surface. Technical details and results of this testing will be described in the Classical Research section.

Future Direction

The Propulsion System Laboratory will continue to explore and expand its capability through future planned tests and cloud characterization studies. The next engine test is planned for 2017 and will explore cloud characterization methods aft of the fan. The AAI project plan has allocated funding for an engine or driven rig test in 2019 and 2021. However, at this time, test articles and collaborations have not been identified. A second fundamental icing test is scheduled in PSL for late 2017 which will further explore the mixed-phase capability of PSL. Two additional fundamental tests are planned between 2018 and 2021.

The Ballistics Laboratory will continue to be the facility for ice impact testing. New measurement techniques are being explored such as integrating high speed infrared cameras to obtain the particle temperature just prior to impact. The facility is also exploring ways to integrate an oven system in order to control the melt ratio of the particle.

In 2016, the IRT explored the feasibility to generate ice crystals as another option for NASA fundamental and scaling tests. The IRT could enable more frequent fundamental ice crystal tests to be conducted. This initial study found that the IRT produced much smaller particles sizes (~12 μm) which is ideal for the fundamental tests which attempt to simulate the local conditions inside the engine core flowpath. The IRT is still in the initial stages of exploring the feasibility since there are limitations on the facility that need to be understood.

Classical Research

Classical research in ICI is needed to form a basis of understanding for the ICI phenomenon and aid in the development of computational tools for engine icing analysis. NASA is focused on a range of experimental efforts both independently and collaboratively. These efforts include component level tests focused on ice accretion on a static rig or a single particle impacting on a target to help understand the fundamental physics process. Larger test efforts involving full engine testing are also being conducted which are used in the development and future validation of tools at the engine system level. Since 2011, test facilities and methods have been established and continue to be developed. The section below will describe NASA's efforts to date and provide a brief discussion on future efforts.

Fundamental Icing Physics Tests

Accretion Physics

Understanding the processes and conditions at the accretion site are a key focus of the NASA fundamental ICI physics tests. Beginning in 2010, NASA has collaborated with the National Research Council Canada (NRC) to conduct fundamental ICI studies in NRC's Research Altitude Test Facility (RATFac) (Refs. 29 to 33). These studies found that a local wet-bulb temperature near freezing plays a crucial role for the onset of accretion. The wet-bulb temperature is affected by air humidity which led to the importance of measuring and controlling the local humidity. Additionally, the local melt ratio and particle size distribution of the cloud were found to affect the accretion process. Video images of the accretions were acquired during these series of tests. A method to analyze video data in order to have quantitative measures of the leading-edge ice thickness was developed (Ref. 34). This method offered a new parameter, the growth rate of ice, to be available for icing research.

In 2013, the PSL ICI capability was developed and, in addition to full-scale engine and rig tests, NASA began examining whether this facility could be used for more fundamental component-level tests. To date, test entries related to the fundamentals of ice crystal icing took place in 2015 (Ref. 35) and 2016 (Ref. 27) where PSL was operated in a freejet configuration and a mixed-phase condition was generated by partially freezing the liquid-water droplets ejected from the spray bars. The 2015 testing was a short preliminary effort that examined some PSL facility parameters and their effect on the melt ratio of the cloud at the test section. The 2016 testing was more extensive, formally called the First Fundamental Ice Crystal Icing test at PSL (FT #1), and included a NACA 0012 test article placed at Station 1 in PSL. These tests characterized the aero-thermal conditions at the test section and explored cloud particle size distribution, water content, and uniformity. The characterization methods are described by Struk et al. (Ref. 27). The ice accretions ranged from sharp arrow-like accretions, characteristic of erosion due to ice particles, to cases with double-horn shapes, characteristic of supercooled water accretions (Ref. 27). A sample of these ice shapes are shown in Figure 4. The results include 2D ice shape profiles which are intended to help develop ice accretion models.

The results from the FT#1 show that a variety of mixed-phase conditions can be produced in the facility. Although the mixed-phase environment is not generated precisely like what is believed to occur in an engine (i.e., partial freeze-out vs. partial melting), the data are still quite valuable since it offers detailed quantitative information about the conditions which lead to a mixed-phase ice accretion (Ref. 27).

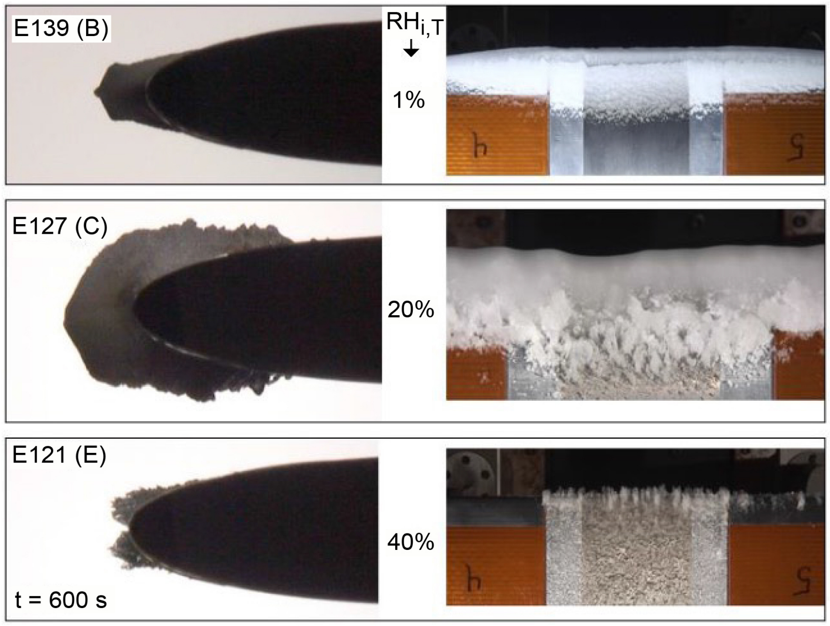

Figure 4.—Sample of ice shapes from FT#1.

The ice accretion data obtained from the FT#1 and the upcoming Second Fundamental ICI test at PSL will be compared to those from the RATFac to better understand how mixed-phase methods affect the ice accretion characteristics. The accretion shapes produced during the RATFac testing were from particles generated by grinding ice and included cases where the melt ratio was achieved with natural melting and/or introducing a liquid water spray.

Further research to demonstrate the ability to prescribe a particular ice crystal icing condition at the test section will be explored in the second PSL fundamental test in the fall of 2017. In addition, this test will aim to explore methods to better understand the erosion process. It is recognized that future efforts need to be focused on tests with more relevant geometry in an effort to generate a more representative ice accretion. This is the goal of the Third Fundamental ICI test effort. Future work also includes developing scaling laws (Refs. 36 and 37).

Particle Impact and Break-Up Physics

Understanding particle break-up of ice crystals is another area of focus for tool development. The research conducted at NASA and through collaborations is trying to identify the key parameters involved in particle break-up, understand the post impact size and velocity distribution, and understand the main qualitative features of impact fragmentation. Tests have been conducted on rotating (Ref. 38) and stationary targets (Ref. 28).

NASA partnered with Penn State University (PSU) and John Hopkins University to conduct a study in PSU's Adverse Environment Rotor Test Stand (AERTS) in 2013 (Ref. 38). This work featured a wedge installed on the leading edge of a rotor, see Figure 5. Wedges of 0°, 30°, 45°, and to 60° were used in this study. Spherical particles made from distilled water frozen in liquid nitrogen where shot at the moving wedge. High speed images captured pre- and post-impact. Sample imaging data are shown in Figure 6. This test demonstrated the ability to precisely time both a moving particle and target. The data show that particle velocities are higher at the edge of the impact cloud which is from the first ejected fragments (Ref. 38). Also at higher velocities, the impact had a lower bounce normal to the wedge compared to the motion of the fragments along the surface (Ref. 38). The researchers found that these findings compared very well to what is in the literature on hailstone impacts.

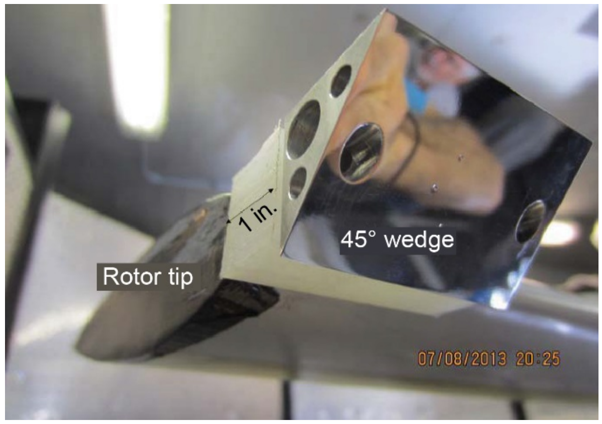

Figure 5.—45° wedge installed on a rotor tip (Ref. 38).


Figure 6.—Example of particle impact at a 30° wedge angle (Ref. 38).

In 2014 non-heated, stationary flat plate impact experiments were conducted in the NASA Ballistics Impact Laboratory (Ref. 28). Fragment size distribution (Figure 7 and Figure 8) and effect of thresholding on the imaging analysis were studied. These tests were performed on single spherical particles ranging in sizes from 1 to 3.5 mm. It is desired to study the impact of ice particles sizes that are comparable to the natural environment, around 300 μm or less. This requires improved imaging resolution and data analysis in order to measure the fragmentation size distribution, which was the focus of this work. High speed imaging was used in two configurations which are described in the Ballistics Impact Laboratory section. It was found that a high resolution and a large field of view is required to capture the smaller fragments. A parametric study of particle velocity was still needed which was acquired during the 2015 and 2017 tests. During the 2017 test, high speed infrared images of the particle were captured to determine its pre-impact temperature.

Future impact studies will investigate the ability to control the melt ratio of the particle before impact. A coupled air and particle thermal model (Ref. 39) was used to perform a feasibility analysis of this experimental set-up which showed good results. Future tests will move from a flat plate to more complex geometries including fan blade geometries.

Through a NASA Research Announcement (NRA) Cooperative Agreement, PSU conducted an experimental study on partially melted frozen droplets (Refs. 12 and 40) and mixed-phase icing wind tunnel testing (Ref. 40). This work included developing a test rig that can study the partial melting of single particles. An ultrasonic levitator was used to suspend the frozen particle which was injected with a luminescent dye (Rhodamine B) and a high-speed video would capture the melting process. A parametric study was conducted by varying the initial particle diameters (300 to 1800 μm) over four environmental temperatures (5, 15, 25, and 35 °C). This resulted in a linear relationship between the rate of melting of the frozen droplets to the inverse of the droplet diameter (Ref. 12). Follow on work by Soltis et al. sought to expand the previous research by varying the relative humidity surrounding the suspended particle from 40 to 100 percent (Ref. 40). The melting of the particle was also compared to the predictions using the NASA Glenn Coupled Air and Particle Thermal Model for Engine Icing. Transient effects due to the Rhodamine B made correlations to the model difficult since it was difficult to quantify when the particle fully melted (Ref. 40). This contributed to a higher difference between the model (64 percent) which over-predicted the melt time for the fast melting particles than the slower melting particles (13 percent difference) where the code under-predicted. A method for generating mixed-phase condition in the Penn State Icing Wind Tunnel was explored and accretion tests on a flat plate were conduted (Ref. 40). Ice accretion data were acquired over a range of duct temperatures (3.3 to 24 °C), plate temperatures (–4.5 to 7.0 °C), and wet bulb temperatures (1.0 to 7.0 °C). Boundaries between the water runoff, ice accretion, and particle bounce off were observed. The study found two types of ice accretion: opaque/rough and clear/smooth, with a transition region between the two. Data from these studies will help provide insight into the thermal model and break-up model development.

Figure 7.—Ice particle impact. The impact was captured with the Shimadzu camera and used to measure the fragments equivalent diameter distribution presented in Figure 6 (Ref. 28).

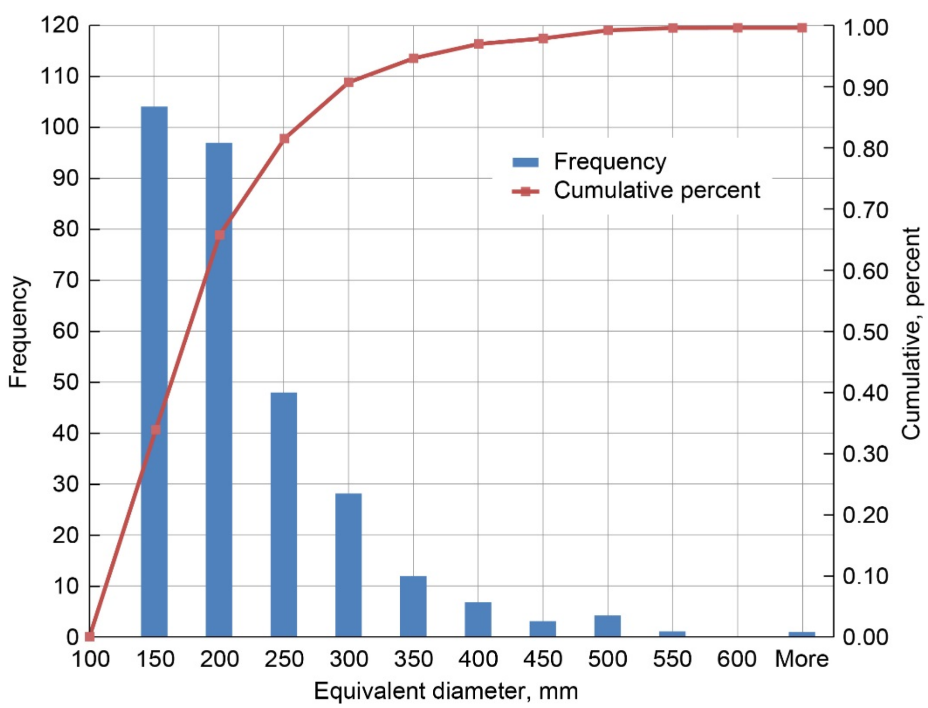

Figure 8.—Fragments equivalent diameter distribution histogram. The histogram shows the number of fragments within a given equivalent diameter range for a given bin. Bin size = 50 μm (Ref. 28).

Engine Icing Tests

Until recently no data existed in the open literature that experimentally examined the behavior and observed ice growth inside full scale engines at altitude conditions. This requires a very complex facility and instrumentation that can be run in the harsh engine environment. However, this testing is necessary to bridge the gap between the natural ice environment and ground based test facilities. Additionally, engine tests at relevant flight conditions are needed for validation of ice accretion models and analysis used for Means of Compliance. In 2012 the NASA PSL completed modifications in the facility to enable ice crystal icing research. Collaborating with Honeywell, in 2013 the inaugural engine icing test was conducted on the un-modified Lycoming ALF502R-5, LF01 flight test engine (LF01) (Ref. 23). This test demonstrated PSL's capability by simulating key flight test points including several full rollbacks which match the timescales from Honeywell's 1997 flight campaign (Refs. 24, 41, and 42). The data from this test was used to help develop the in-house 0D/1D risk analysis tool (Refs. 43 and 45). The LF01 engine featured flight test instrumentation such as metal temperature thermocouples in the exit guide vane and outer shroud region which provided limited information on the ice formation. With the success of the LF01 engine test, NASA collaborated with Honeywell again to test a heavily instrumented ALF502R-5 engine, serial number LF11 in 2015 (Ref. 25). The main objectives of this test was to:

1. Develop advanced instrumentation and use internal cameras to characterize the cloud entering the core flowpath and measure accretion characteristics.
2. Document and characterize the flow path, engine performance, and ice accretion that builds up during rollback and non-rollback events.
3. Replicate the full rollback point from the LF01 tests.
4. Duplicate key test points from the LF01 test plan and investigate sensitivities of ice build up to various engine and facility parameters.
5. Explore high and low altitude points to build a database for scaling.
6. Further develop test methodologies and PSL capability.

The LF11 engine featured standard aerodynamic test instrumentation and metal thermocouples which were placed in the same location as the LF01 engine instrumentation. Internal cameras were installed downstream of the exit guide vanes in four circumferential locations. The camera views observed the trailing edge of the guide vanes towards the outer shroud and one camera was angled downstream towards the transition duct. During the test the cameras were able to capture the ice accretion inside of the engine, see Figure 9.

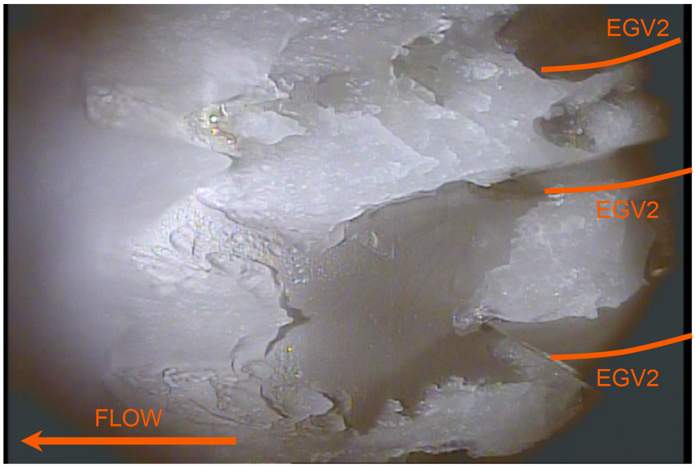

Figure 9.—LF11 ice accretion at called rollback.

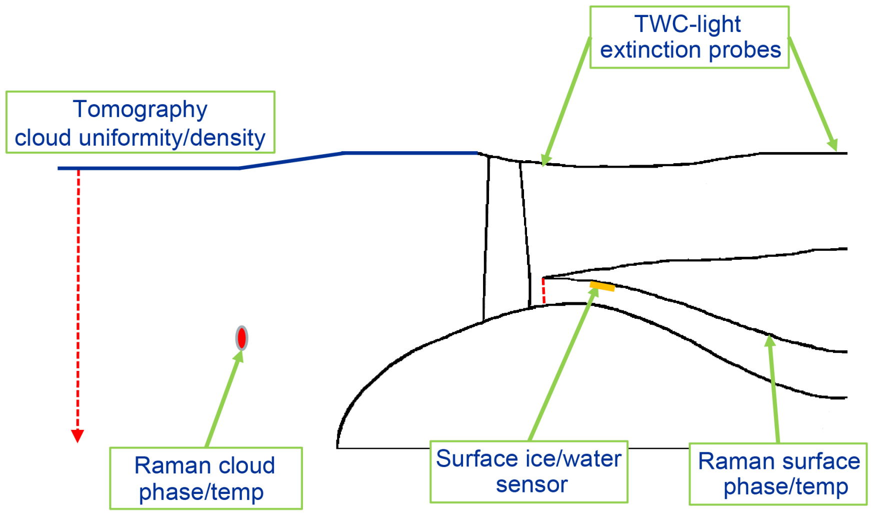

Figure 10.—Advanced instrumentation locations in LF11 engine.

To gain insight on the particle concentration and characteristics entering the core flow path, a series of developmental instrumentation were used (Figure 10). Light extinction probes were installed just aft of the fan, at the bypass inlet, core inlet, and bypass exit. The measurements acquired by the extinction probes were correlated to the inlet tomography data to show how the concentration of particles at the fan inlet were impacted by the fan. Future development includes providing insight on particle distribution and the surface conditions. This technology could also provide insight on location when melting and accretion occurs.

In an effort to detect the state of the outer shroud surfaces during icing conditions and to distinguish between liquid water from solid ice contaminations, two ice detection sensor technologies were explored. Capacitance based icing sensors developed at NASA were installed in the outer shroud region near the exit guide vane trailing edge. The cameras were able to capture all of the NASA ice sensors. During the test, the sensors detected water and ice early on but deteriorated as testing proceeded. NRC also collaborated on this test to evaluate their Ultrasound Ice Accretion Sensors (UIAS) (Ref. 26). The NRC non-intrusive sensors were installed in regions of interest close to the NASA sensors. Data from these sensors indicate ice accretion and by corroborating the data with the video, it was found that the sensors could potentially provide some indication of its severity (Ref. 26). This test enabled the development of sensors that can help pinpoint the location of accretion that is difficult to see with cameras. The NASA ice/water detection sensors have since been modified to be more robust. This concept will be explored during the next test entry.

Techniques to measure particle temperature and the particle phase through the engine are currently being sought (Ref. 22). As a first step, a Raman Scattering Surface Water probe was installed downstream, deep into the LF11 engine. The purpose of the first iteration was to see if any water could be detected on the shroud surface and the temperature measured. Limited data were available, however the probe was able to measure the temperature during some of the high water content conditions (Ref. 25). Additionally, a fluorescence technique is being explored (Ref. 22).

Kulites were installed in the each axial stage of the high pressure compressor (HPC). The purpose was to look at the HPC response due to the ingestion of the ice cloud, upstream accretion, and shedding. Preliminary results show that the HPC has some response to the ingestion of the ice cloud. Further analysis and additional testing is needed to explore the effects of various icing conditions on the HPC.

Important to note with the development of new measurements, leading into the LF11 test, the cloud calibration explored new methods of obtaining particle size measurements by using Artium's High Speed Imager (HSI) and Phase Doppler Interferometer (PDI) modular probes. Through a contracted NASA effort, Artium is developing these probes to be used in mixed-phase conditions. The HSI is more suitable for fully glaciated clouds which is the condition produced for the engine test. Sample data from the Artium probes are described in King et al. (Ref. 46) for FT#1.

All of the key objectives of the LF11 test were met. The parameter sweeps and sensitivity studies highlighted different icing regimes inside the engine from a warm, wet environment to a cold, dry environment. It was shown that the TWC had the largest effect on the onset of icing, however the other parameters had the ability to impact the rate of accretion. The video acquired for each test point reveal that when the cloud is turned on for the cases with icing leading a rollback, there is immediate water runback indicating a mixed-phase condition in the booster (LPC). The data from the two engine tests have be used to develop the in-house 0D/1D (Refs. 43 to 45, 47 and 48) and 3D tools (Refs. 49 to 51) and develop a model for active engine controls (Ref. 52). These efforts will be described later in Computational Research section.

Future engine tests will seek to understand how the fan processes the particles and what particle sizes enter the core flow path. It is thought that only very small particles are entrained in the core flowpath while the larger, more ballistic particles are thrown into the bypass by the fan. Particle size measurements would be made at the fan inlet, in the bypass, and at the core inlet. The particle sizes at the inlet would be varied to investigate if the particles entering the core remain constant. This would provide valuable insight for facility simulation capabilities. Future tests will also seek to develop measurement techniques which can help quantify the icing effects which is key for model and tool development. It is recognized that it is difficult to disseminate engine data due to the proprietary nature of engine testing. NASA is seeking opportunities to provide open ice crystal icing data on relevant engine geometries that can be used throughout the research community.

NASA Glenn Coupled Air and Particle Thermal Model for Engine Icing

In various icing facilities it has been observed that the icing cloud has an effect on the tunnel parameters, most notably temperature and humidity, when activated. In order to gain an understanding of the conditions at the test section, a one-dimensional thermodynamic model was developed to simulate the complex interaction of the cloud particles and free stream air. This numerical model derived from the conservation of mass, momentum, and energy equations, couples the thermal interaction between the ice particles, water droplets, and the flowing gas. In 2014 an initial thermal model was written to explain the observed changes seen during the NASA/NRC fundamental tests in the NRC Research Altitude Test Facility (RATFac) facility (Ref. 53). The model was able to predict the changes in gas temperature, humidity, IWC, LWC, and particle phase, size, temperature, and velocity at the test section. To accurately simulate the spray injection, the model incorporates a distribution of particles sizes (20+bins) as an initial input. These predictions were compared to the experimental measurements which showed that the model was able to account for approximately 20 percent of the water that vaporized from the cloud, and 20 percent of the gas temperature change that was measured (Ref. 53). For this initial model, it did not account for the effect the water/ice film on the tunnel wall may have on the water vapor and temperature change.

In 2015 preliminary mixed-phase icing data were acquired in the PSL facility where the nozzles are optimized to not deposit ice or water on the tunnel walls (Ref. 35). The thermal model was modified to include isentropic relations specific to the PSL facility geometry (Ref. 54). The model predictions were then compared to the experimental results. A supersaturation condition was found to have an effect on the accuracy of the predictions. A subroutine was explored that allowed for the option to control humidity so as not to exceed saturation at any point. Key findings from this work show that for every simulation there was a nearly constant but slight increase in wet-bulb temperature when the spray cloud was activated and the total wet-bulb temperature in the plenum was a large factor in determining cloud phase.

Building on this work, the thermal model was used to guide the development of the test matrix for the First Fundamental test in PSL (FT#1) and help identify the mixed-phase parameter space (Ref. 39). A new approach to simulate the supersaturated conditions more accurately was implemented, allowing an option of the vapor to condense on existing aerosol particulates. Comparisons were made on four series of tests where the relative humidity was varied. This resulted in exit cloud conditions ranging from fully liquid to fully glaciated. It was observed that there are radial variations of the cloud which cannot be accounted for in this one-dimensional code which leads to the model over predicting the aero-thermodynamic changes. For low humidity conditions, greater aero-thermodynamic changes occur in the tunnel which the model matched the trend fairly well. It was found that a range of mixed-phase clouds can be achieved in PSL by varying the tunnel humidity conditions but this range decreases when the clouds are composed of smaller particles (Ref. 39).

This model is a key tool to understanding the particle physics in the PSL facility and ensuring the tunnel is set-up appropriately to achieve the desired conditions at the test section. Future experimental efforts will be used for further development and validation of the coupled air and particle thermal model.

Icing Condition Scaling Activities

An area of research that is of interest to NASA is to understand the possible altitude effects on ice crystal accretion and identify the scaling parameters that govern the accretion process. This work tightly couples with the fundamental accretion studies and a test on a simple airfoil will be explored in a future study. In the interim the full scale engine tests have been used to explore the feasibility of condition scaling methods (Refs. 55 and 57). Recent work has focused on developing a simplified approach to altitude scaling by leveraging the 0D/1D COMES model. COMDES was utilized to determine possible scale test conditions at 5 kft altitude with similar engine icing risk potential by best matching three icing related parameters of the FLT850 full rollback reference condition. These parameters are: the local air static wet bulb temperature, the local ice crystal melt ratio of a prescribed smaller particle size at the second EGV trailing edge location, and the engine fan face total water content to air density ratio of the ice crystal cloud (Ref. 57). The internal engine video that captured the ice accretion downstream of the second EGV trailing edge was used along with other relevant air/ice crystal thermodynamic and engine performance data to qualitatively and visually assess the 5 kft engine ICI simulation results. Details of this analysis are described by Tsao (Ref. 57). This approach demonstrated the feasibility of examining accretion and icing effects on engine performance in PSL or a sea level facility. However it is recognized that improvements in facility controllability, development of test methods for scaling, and development of ice characterization methods are needed.

Computational Research

Computation research is needed to enable the investigation, understanding, and provide mitigation strategies for engine ICI. NASA has a unique capability of in-house tools that have been developed for engine performance simulations, three-dimensional gas turbine flow and convective heat transfer, and external ice accretion simulations. NASA seeks to leverage these exiting tools and utilize the experimental databases to develop icing physics models that can be integrated into the codes. A 0D/1D icing risk capability is important in the preliminary evaluation of current and future propulsion system designs. To date this tool has been used to guide the engine testing and scaling work. It is recognized that in order to fully understand the impact of engine core icing, a higher fidelity tool is needed. The section below will describe NASA’s computational efforts to date and provide a brief discussion on future efforts.

0D/1D Model Development

NASA has developed a 0D/1D tool to evaluate the risk of icing and estimate the engine performance degradation due to accretion for current and future engine designs. The tool is comprised of the Numerical Propulsion System Simulation (NPSS) (Refs. 58 to 60) thermodynamics cycle code, a compressor mean-line flow analysis code COMDES (Ref. 61), and an ice particle melt code MELT. The COMDES code also uses a fluid property model GASPLUS (Ref. 62). When an engine thermodynamic cycle is available, that can be used in place of the NPSS model.

Preliminary simulations of this mixed-fidelity tool were conducted on a representative engine over a notional flight trajectory in 2011 (Ref. 63). A conceptual LPC geometry was developed to perform the mean-line analysis. During this iteration, GlennICE was modified to include ice crystal behavior (Ref. 64) and was coupled with the NPSS code. The analysis on the notional engine demonstrated the feasibility of using the NPSS and COMDES code to identify potential locations of accretion within the engine. This work included a study that developed a method to parametrically add blockage and assess the effect of ice accretion of the compressor blade row performance (Ref. 63). The GlennICE code also identified accretion surfaces in the LPC. However, it was noted that in addition to grid refinements, further improvements were needed to better account for bouncing of ice crystal and erosion effects. This early iteration using GlennICE was later replaced by the subroutine MELT model which is derived from the LEWICE 2D (Ref. 65) code. MELT tracks the sublimation, melting, and evaporation of the particles and is coupled with COMDES so the boundary conditions at the blade leading and trailing edge is exchanged at each iteration (Ref. 66).

In 2012 further refinements to the code were made to account for the two key parameters suggested to play a crucial role ice accretion in the engine flowpath: local wet bulb temperature and melt ratio (Ref. 66). Through the collaborative fundamental tests at NRC (Ref. 29 to 31), it was recognized that the total wet bulb temperature ($T_{wb,\ Total}$) and melt ratio are two key aero-thermodynamic parameters to determine the onset of ice accretion. The COMDES mean-line compressor flow analysis code was modified to include the effects of relative humidity on the fluid properties of the air and water vapor mixture and added the calculations of T_{wb} (both total and static) and ice particle melt ratio within each blade row. If these parameters meet a specific threshold simultaneously, it is determined that there is a risk that ice will accrete within that particular blade row. The geometry section of the code was also enhanced with the addition of simple circular arc blade and vanes to improve the accuracy of computing the blade-to-blade distances and passage chord lengths. These lengths are used to estimate ice particle residence time and calculate the sublimation, melt, and evaporation rates. Details and governing equations used for this new iteration of the 0D/1D code can be found in Veres et al. (Ref. 66).

Once engine data were obtained from the LF01 engine test in the PSL facility (Ref. 23), the code was used to analyze the full rollback flight point to develop a risk criteria (Refs. 43 to 45). During this iteration, the manufacturer supplied customer deck was used as the thermodynamic cycle code in place of the NPSS model. An illustration of the boundary condition exchange between the customer deck, COMDES, and MELT are shown in Figure 11. The analysis of several accretion data points, including the

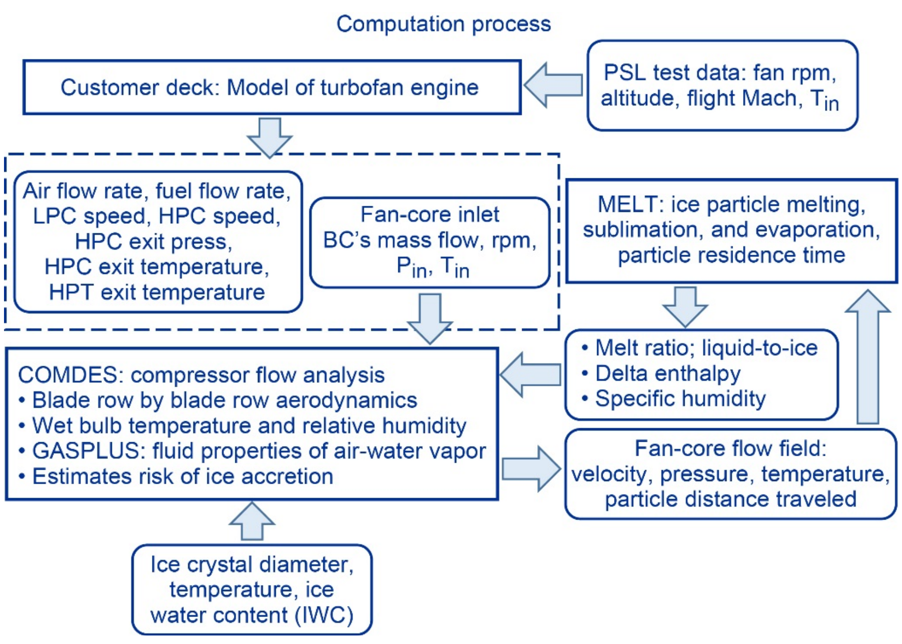

Figure 11.—Boundary exchange strategy for the fan-core and LPC (Ref. 43).

full rollback, revealed an icing criteria of a melt ratio between 2 to 21 percent with a 7 R range of T_{wbs} (Ref. 43). Sample data are shown in Figure 12. For non-accretion conditions the $T_{wb,Static}$ was well outside the 7 R range and had a zero melt ratio throughout the LPC. This tool was also used to determine low altitude conditions that would be susceptible to ice accretion. Knowing the target altitude, the engine inlet temperature was calculated based on what would produce a $T_{wb,Static}$ within the 7 R range and non-zero melt ratio. These points were run in the PSL facility and confirmed ice accretion at these predicted lower altitude data points (Ref. 43). The initial analysis identified trends in $T_{wb,Static}$ ice particle melt ratio, and engine inlet temperature as a function of altitude for predicting the risk of ice accretion in the engine due to ice crystal ingestion. Further analysis was conducted on all of LF01 test points with a focus on tracking the variations in wet bulb temperature and ice particle melt ratio through the engine core flowpath. This resulted in a refinement to the risk criteria (Ref. 39) which is described in Table 2. Further analysis using NPSS for several data points was conducted in order to understand the effect of ICI ingestion on the transient engine performance and to quantify the blockage growth rate and additional losses due to accretion (Ref. 45). The COMDES code was used to determine the values of blockage and pressure loss in the IGV and EGV required to match the overall pressure ratio and efficiency boundary conditions. These boundary conditions were provided by the NPSS model of the analyzed test points, enabling a blockage growth rate to be calculated (Ref. 45).

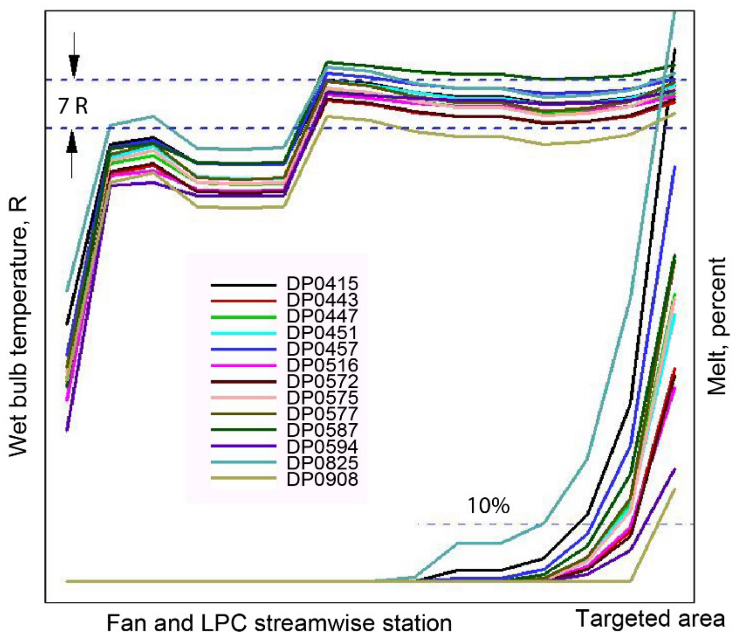

Figure 12.—Analysis of the fan-core and LPC stage for ice accretion test points (Ref. 43).

TABLE 2.—TOTAL WET BULB TEMPERATURE AND MELT RATIO VALUES RESULTING IN ICING EVENTS

Event Type	Average $T_{wb, Total}$	Range $T_{wb, Total}$	Average $T_{wb, Static}$	Range $T_{wb, Static}$	Average Melt Ratio	Range Melt Ration
Imminent (fast) Icing	13 R above freezing	7 R	2 R above freezing	9 R	12%	2 to 40%
Gradual (slow) Icing	13 R above freezing	13 R	2 R above freezing	14 R	15%	0 to 55%
No Icing	18 R above freezing	18 R	6 R above freeing	17 R	35%	0 to 45%

In 2016 the code was used to evaluate the LF11 engine test points to predict the likelihood of rollback. A spreadsheet was created that enabled a time effective way to input conditions which would execute and feed into the customer deck and COMDES code (Ref. 47). This process is illustrated in Figure 13. This pre-test analysis also guided the test matrix during the actual study and was used to formulate the altitude study test points. After the heavily instrumented LF11 engine test was complete, a post-test analysis was conducted on 24 test points (Ref. 47). This enabled further evaluation of the icing risk criteria. A new parameter coupled with the T_{wb} and melt ratio was observed to have an influence on the accretion risk. It was found that an ice-water flow to air ratio (*IWAR*) below 0.002 would not result in an engine rollback. Although video data did show that water runback and/or a non-continuous ice growth could occur. IWAR is a dimensionless parameter define by:

$$IWAR = TWC * Q/m$$

TWC = total water content
Q = volume flow rate of air
m = mass flow rate of air entering the engine

A relationship between the blockage growth rate, *IWAR*, and T_{wb} was observed and plotted, generating an "Icing Wedge", shown in Figure 14. The region under the "icing wedge" represents the conditions where there is a risk of ice accretion. Further analysis of additional data points led to a refinement of the icing wedge to a tighter region of $T_{wb,}$ see Figure 15 (Ref. 48). A parametric evaluation of the particle size was also studied. It was found that when the static T_{wb} was within the range of 492 to 498 R, the region of continuous ice accretion, the local ice particle size that would provide a non-zero melt ratio was in a range of 1 to 9.5 µm (Ref. 48).

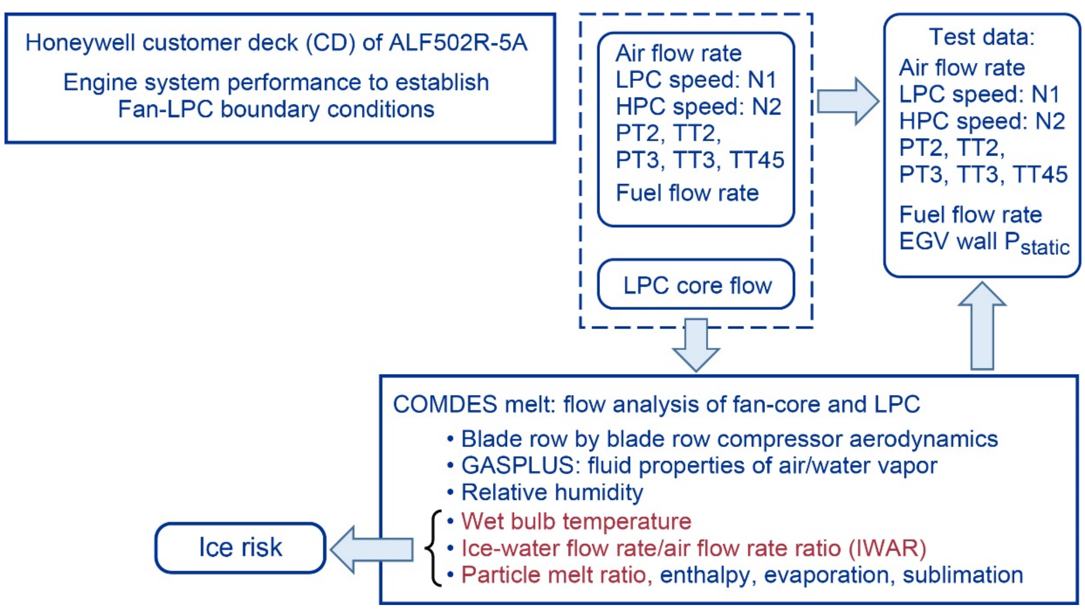

Figure 13.—0D/1D computational process (Ref. 47).

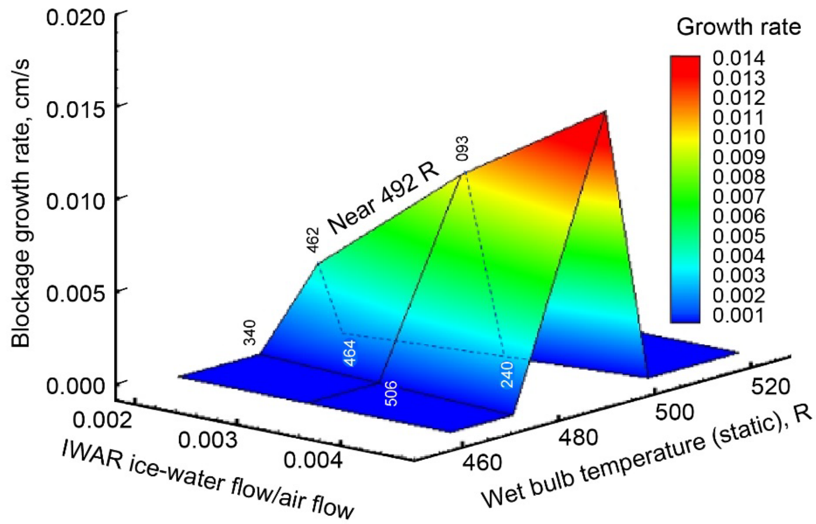

Figure 14.—Initial risk of accretion “Icing Wedge” based on 5 μm particle size (Ref. 47).

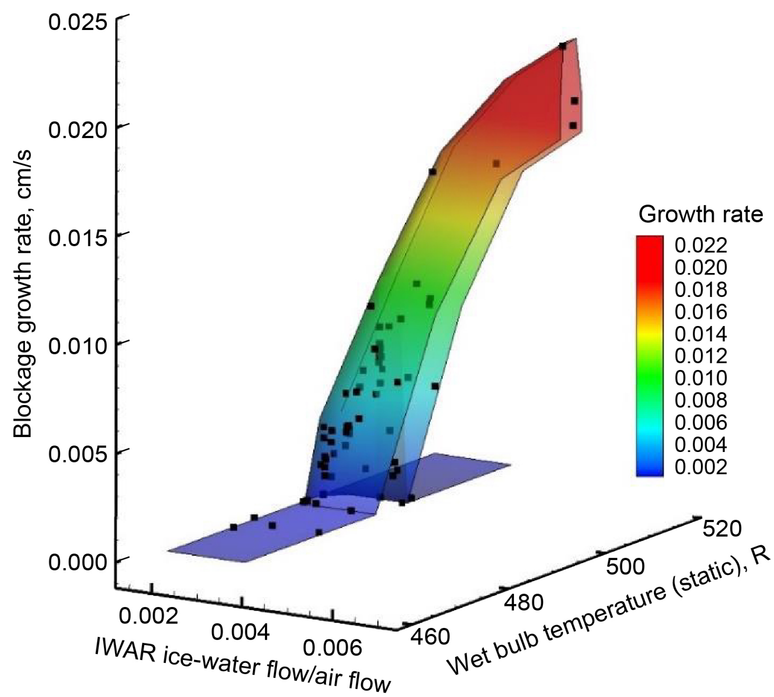

Figure 15.—Refined “Icing Wedge” based on 1-9.5 μm particle size (Ref. 48).

In order to improve the 0D/1D tool, several areas of experimental and model development are needed. Since there is not a particle break-up model in MELT, the code assumes a 5 μm particle is entrained into the LPC or in recent evaluations it was parametrically varied. Improved understanding of particle size distribution aft of the fan from experiments or higher fidelity code simulations is key to improve the low fidelity simulation techniques. Currently the code only accounts for liquid water due to the melting of the ice particle by the air. Other sources of heat (heated components, particle impacts, etc.) are not considered. Over the next 4 years, efforts will be focused to improve the code and define a clear risk criteria which can be used on any engine design.

High Fidelity Simulations

Higher fidelity icing tools are needed to simulate the accretion process in current and future engine designs, informing the user of the potential risk and impact due to ice accretion. This simulation tool will be valuable to predict the location, size, and characteristics of the accretion for a prescribed condition. This tool will also enable a more precise evaluation of the risk and potential mitigation strategies. The LEWICE3D (Ref. 67) code, has been used to calculate ice shapes on three-dimensional external surfaces for many years. Efforts are underway to modify the code to enable ice crystal icing accretion on external and internal flowpaths. Since the code has primarily been used for external flow, GlennHT (Refs. 68 and 69) is used to provide the flow analysis. These two codes use a 3D, steady mixing plane approach to analyze flow and icing in turbomachinery. In 2011 the Glenn ice particle change model was incorporated into LEWICE3D and an ice particle trajectory calculation with phase change was conducted on the E^3 engine design (Ref. 70). In 2014 an analysis was conducted on the booster section of the ALF502R-5 engine used in the PSL tests (Refs. 49 and 50). The flow analysis was generated using the GlennHT flow solver (Ref. 50) then the results were passed to LEWICE3D to perform the particle analysis (Ref. 49). This leveraged the features in the LEWICE3D V3.63 software such as the particle splash and bounce algorithm, geometry handling scheme, transformation and relative motion of input grid block, and zone to zone collection efficiencies using a mixing plane approach algorithm (Ref. 49). Two inflow conditions were used representing a test point that had an icing event (rollback) and one that did not. The only differences between the two test points were the non-icing test point had an inlet temperature 7 °C higher and a 1 g/m^3 difference in IWC. Analysis were conducted for two particles sizes, 5 and 24 μm, using a sticky impact model and SLD splash model respectively. The 5 μm particle representing the particles size used in the 0D/1D model and the 24 μm particle matching PSL cloud generated during the LF01 test. The analysis found that for the larger particles, the particle breakup resulted in a 33 percent reduction in the average particle size. A majority of the breakup and collection occurred at the spinner, fan, and splitter lip region resulting in less particles entering the core flowpath. The 5 μm particles also experienced a reduction of size through the engine, although to a much lesser extent, due to sublimation since a break-up model was not used for the 5 μm case, see Figure 16. The smaller particles produced more melting than the large particles due to the lower thermal mass. As a first step to understand the icing risk, the particle impact melt fraction and surface temperatures were analyzed. By applying the risk criteria developed during the NASA/NRC fundamental tests, the analysis revealed for the icing inflow condition using the 24 μm and SLD splash model, the surface conditions near the EGV #2 and the outer duct wall indicate ice accretion could occur. For the non-icing case the melt fraction was found to be too high which would indicating accretion would not occur. This was later verified by the videos captured during the 2015 LF11 PSL test replicating similar inflow conditions. The 3D analysis demonstrated the feasibility of using the GlennHT and LEWICE3D code for predicting icing in turbomachinery.

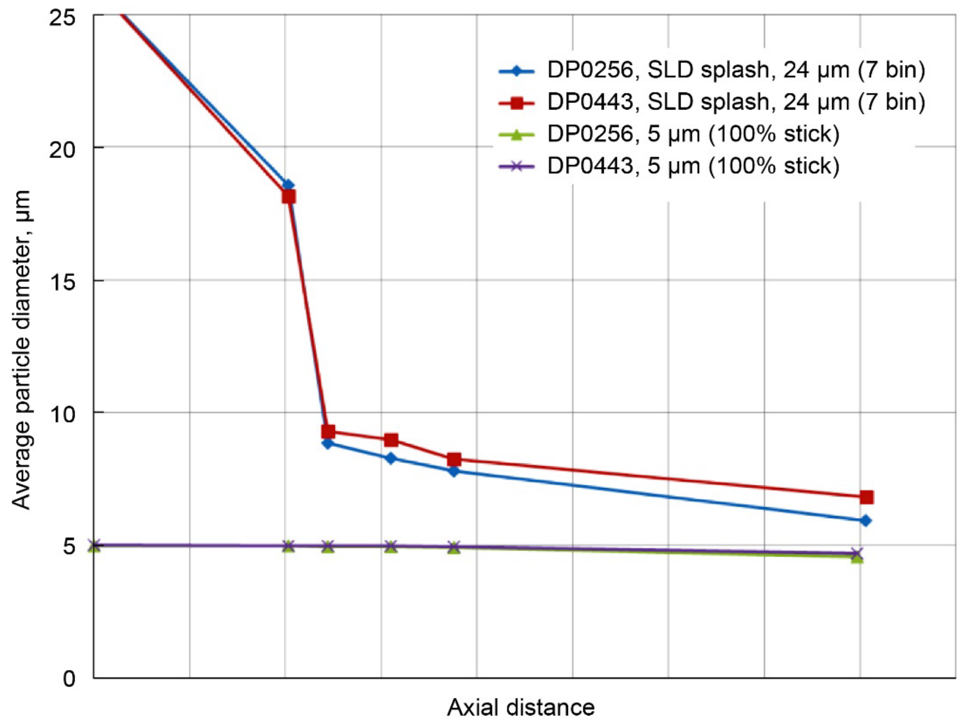

Figure 16.—Average particle size through fan inlet and compressor system (Ref. 49).

It is recognized that an ice particle impact model is needed to further improve the prediction of ice particle transport with phase change through engine flowpaths. This model needs to include the particle breakup, phase change, and surface state. As a first step towards this capability, Wright (Ref. 71) added an ice breakup and erosion model to LEWICE, a two-dimensional ice accretion software. The ice break up model is designed around four correlations. A threshold to determine when particles break-up versus bouncing is based on the work from Hauk et al. (Ref. 9) for the particles that breakup the size is determined by relationships from the supercooled large droplet regime. The direction of the particles after break-up is based on the experiments of Palacios et al. (Ref. 72). The sticking efficiency experiments performed by Currie et al. (Ref. 73) were used in the model to determine if the particles will bounce or impinge on the surface. This model was run and compared against four test cases from Struk et al. (Ref. 33) and found that LEWICE over-predicts the amount of ice accretion at the leading edge and under-predicts the amount of ice further downstream of the wedge (Ref. 71). Figure 17 shows an example simulation comparison. This discrepancy would be due to the reimpingement model used and degree of uncertainty with the experimental results.

Work continues to enable GlennHT and LEWICE3D simulations to be more tightly coupled to enable the effect of ice particles on the air flow and include effects of ice growth on air flow. GlennHT modification are still needed such as integrating an improved tip clearance model and developing a mechanism to pass heat transfer coefficient distributions to LEWICE3D. Recently, preliminary simulations were conducted using GlennHT to investigate the heat transfer coefficient distribution in the ALF502R-5 (Ref. 74). More careful studies are planned for the future, coupling air flow to ice particle flow as well as investigating appropriate turbulence models to produce accurate heat transfer prediction during the ice accretion process.

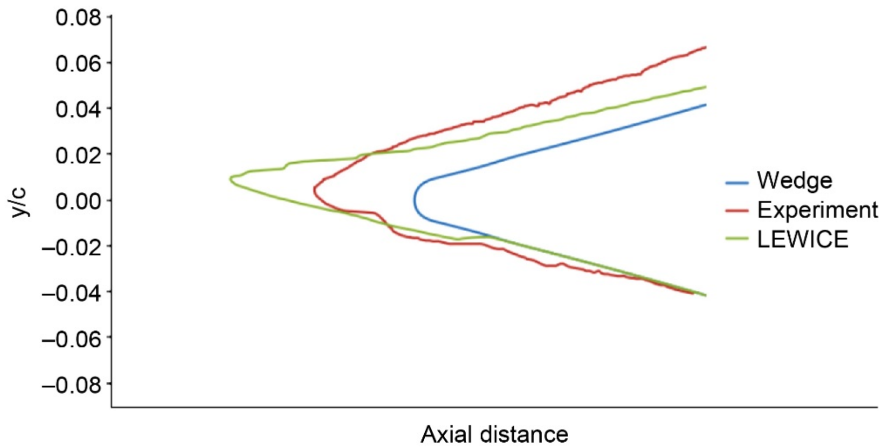

Figure 17.—Ice shape prediction for scan 996 (Ref. 71).

Conclusions

A summary of NASA's experimental and computational work for investigating ice crystal icing has been described in this paper. NASA continues to focus on experimental efforts that will provide a strong basis of understanding into the fundamental physics of ice accretion and particle behavior. As understanding improves and models are developed, the fundamental experimental work will evolve into more relevant and complex geometries to enable three-dimensional model validation. PSL full engine and rig tests are desired to continue the development of the facility's capability and computational tools. Measurement methods and techniques will continue to be a focus as well. The 0D/1D COMDES and LEWICE3D/GlennHT codes are needed to enable the assessment of the icing risk on current and future propulsion designs. Improvements and future plans of the model development have been given.

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