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NASA Analysis of Alternatives Study for Icing Research

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Contents

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Executive Summary

In 2020, NASA's Aeronautics Research Mission Directorate commissioned a study of the icing research area to provide a broad and comprehensive assessment of priority needs for NASA and enduring needs for the aviation community. Priority needs were those that supported four key focus areas for NASA Aeronautics—Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion (EAP), Small-Core Turbine Engine, and High-Rate Composite Manufacturing—as well as other priority areas, such as Advanced Air Mobility (AAM), Certification by Analysis (CbA), and Commercial Supersonic Technology (CST). Enduring needs were the additional long-term capabilities and expertise identified by the aviation community as being critical for NASA to provide. This study is called an Analysis of Alternatives because a large number of icing research needs were identified and analyzed to determine the highest priorities for NASA key focus areas and those research needs critical for NASA to provide.

A team of NASA icing subject matter experts (SMEs) was assembled from NASA's Glenn and Langley Research Centers to perform the study, which began by gathering inputs from icing stakeholders in industry, Government, and academia. Those inputs, which are summarized in this document, were used by the SMEs to identify needed icing technical elements that were grouped into four categories: (1) icing performance impacts, (2) ice accretion geometry definition, (3) ice protection and detection systems, and (4) icing weather and characterization. The technical elements were defined at a high level and were inclusive of the physical understanding, modeling capabilities, and experimental capabilities needed to

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address a given element. A multivariable analysis technique called TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) was used in conjunction with SME ratings against several potential future realities to prioritize the technical elements. The higher ranking technical elements were assembled into four work package groupings: (1) external icing, (2) engine system icing, (3) AAM icing, and (4) ice protection systems (IPSs). The specific higher ranking technical elements most applicable to NASA Aeronautics' priority areas are as follows:

- For TTBW and CbA: (1) Three-dimensional (3D) definition of ice shapes that occur on the vehicle under standard icing, freezing drizzle (FZDZ), and freezing rain (FZRN) conditions; (2) assessment of the aerodynamic performance impact of ice on the vehicle; and (3) development of IPS strategies, including icephobic material.
- For Small-Core Turbine Engine: (1) ice-shedding prediction and shed impact on performance and operability of the engine; (2) 3D ice definition in standard icing and ice crystal icing for turbomachinery systems; (3) water and ice particle concentration factors at off-body locations, such as the ingestion plane of the engine; (4) engine performance impact due to ice; and (5) establishment of a globally representative high ice water content atmospheric characterization.
- For AAM: (1) 3D ice-shape definition for ice shapes that occur on the vehicle under standard icing, FZDZ, and FZRN conditions, including rotating geometries as well as ice shedding; (2) characterization, prediction, and mitigation of ice shedding; (3) assessment of the aerodynamic performance impact of ice on the rotor/propeller performance; (4) development of IPS strategies, including using icephobic materials; (5) ice detection systems applicable to the electric vertical takeoff and landing platforms; and (6) analysis and prediction of ice buildup and mitigation on engines, inlets, and screens.

For other NASA priority areas such as EAP, High-Rate Composite Manufacturing, and CST, there are currently limited icing needs, as other technology development activities in these areas have a higher priority at this time. However, as these areas mature, icing technologies will play a crucial role in making these areas viable for industry.

The enduring needs for the aviation community are (1) for NASA to continue performing foundational icing physics studies to improve current computational and experimental capabilities and (2) for NASA to address atmospheric characterization requirements that will arise as new vehicles expand operations.

NASA will use these study findings to assist in future project planning to continue conducting high-value research in the icing area.

This report offers a detailed description of the AoA study for icing research. Section 2.0 provides background and context for the study with an overview of aircraft icing (Section 2.1), NASA's icing history (Section 2.2), and NASA's recent and current icing research (Sections 2.3 and 2.4). Section 2.5 discusses expected icing impacts on future aviation systems (airframe, propulsion, and AAM systems), and Section 2.6 provides an overview of the AoA process followed in this study. The Icing AoA study and its findings are then detailed through an account of each of the following study components:

- Stakeholder interviews, organized by segment (Section 3.0)
- Analysis and evaluation of icing research priority needs (Section 4.0)
- Results and key findings (Section 5.0)
- Recommendations (Section 6.0)
- Conclusions (Section 7.0)

Acronyms are defined in Appendix A. Members of the Icing AoA team and their affiliations are listed in Appendix B.

1.0 Introduction

In 2020, NASA's Aeronautics Research Mission Directorate (ARMD) called for crosscutting studies in three NASA skill and capability areas—combustion and emissions, acoustics, and icing—to define priorities in four key focus areas as well as across all of the work ARMD supports. This effort, cosponsored by the Transformative Aeronautics Concepts Program (TACP) Transformational Tools and Technologies (TTT) Project and the Advanced Air Vehicles Program (AAVP) Advanced Air Transport Technology (AATT) Project, involved multicenter, multidisciplinary teams. The four key focus areas, referred to as the "Fab 4," were Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion (EAP), Small-Core Turbine Engine, and High-Rate Composite Manufacturing. The studies initially sought to gather input from NASA subject matter experts (SMEs) and industry stakeholders to provide guidance and responses to the following key objectives:

1. An assessment of priority needs for each of the three skill and capability areas toward the four key subsonic transport focus areas ("Fab Four") and any other ARMD priority areas (e.g., Advanced Air Mobility (AAM) and Commercial Supersonic Technology (CST)). The time horizon for this assessment aligns with the ARMD Mid-Term Outcomes, defined as technology readiness level (TRL) 5 to 6 in the 2025 to 2035 timeframe.
2. An assessment of the enduring needs for the three skill and capability areas for the aviation community. The time horizon for this assessment aligns with the ARMD Far-Term Outcomes, defined as TRL 5 to 6 in the 2035+ timeframe.
3. A prioritized list of proposed high-value research appropriate for NASA, with rough cost estimates.
4. An assessment of any gaps remaining in the NASA skills and capabilities after addressing the needs defined in objectives 1 and 2.
5. Recommendations on how to reshape NASA capabilities to address the needs and gaps.

For the initial study, emphasis was placed on objectives 1 to 3; objectives 4 and 5 were expected to involve broader conversations with centers and ARMD at a later date and are not captured in this document. This study is called an Analysis of Alternatives (AoA) because a large number of research needs in the legacy research areas were identified and analyzed to determine the highest priorities for NASA key focus areas and those research needs critical for NASA to provide. The expected outcome of the AoA was recommendations for investments in the legacy capability areas and in newly identified capability areas based on the results of the study.

The AoA study for icing research kicked off in March 2020 with a core team from two NASA centers (Glenn and Langley Research Centers) and included multiple NASA organizations, facilities, and areas of expertise, including airframe icing, engine icing, rotorcraft and icephobics, computational icing, the Icing Research Tunnel (IRT) and Propulsion Systems Laboratory (PSL) facilities, flight research and operations, advanced materials, aviation weather, and atmospheric remote sensing. NASA center and branch affiliations were as follows:

- Glenn Research Center (GRC)
    - Propulsion Division, Icing Branch
    - Facilities: IRT and PSL, Flight Operations
- Langley Research Center (LaRC)

- ○ Advanced Materials and Processing Branch (Icephobics)
- ○ Science Directorate, Climate Science Branch (Aviation Weather)
- ○ Electromagnetics and Sensors Branch (Radar and Remote Sensing)

The core team concluded its work in March 2021, with results and recommendations presented to the ARMD at a Strategic Portfolio Management Review (SPMR) on March 10, 2021.

This report offers a detailed description of the AoA study for icing research. Section 2.0 provides background, presenting a brief icing primer and an overview of NASA's past and current icing work. Expected icing impacts on future aviation systems are discussed, and an overview of the AoA process is provided. In subsequent sections, the Icing AoA study and its findings are detailed through an account of each of the following study components:

- Stakeholder interviews (Section 3.0)
- Analysis and evaluation of icing research priority needs (Section 4.0)
- Results and key findings (Section 5.0)
- Recommendations (Section 6.0)
- Conclusions (Section 7.0)

Acronyms are defined in Appendix A. Appendix B lists members of the Icing AoA team and their affiliations.

2.0 Background

To provide context for the icing AoA study, an overview of aircraft icing is presented first, followed by a brief history of NASA's past and current icing work. Expected icing impacts on future aviation systems are discussed, including the certification challenges these systems will face under the following regulations:

- 14 Code of Federal Regulations (CFR) Part 25, Sec. 25.1419 and App. C (typical supercooled liquid icing clouds) (Ref. 1)
- 14 CFR Part 25, Sec. 25.1420 and App. O (environment with supercooled large drops (SLD) (Ref. 2)
- 14 CFR Part 33, Sec. 33.68 and App. D (ice crystal clouds) (Ref. 3)

An overview of the AoA process used to perform the study concludes this section.

2.1 Icing Overview

The formation of ice on aircraft surfaces can affect aerodynamic performance. The ability to predict ice accumulation and the resulting degradation in performance is essential for developing ice protection systems (IPSs) that enable safe operations in all but the most severe icing conditions. The consequences of underestimating icing effects can be serious; providing accurate predictions and measurements, particularly for severe icing conditions, is crucial. Similarly, when a turbine engine ingests ice crystals, it may lead to power loss events. The ability to predict if and where ice may accumulate and shed inside the core flow path is essential to understand the type of power loss event—rollback, stall, surge, flameout, or component damage—and the appropriate mitigation strategy.

Icing is a multidisciplinary competency that requires expertise in icing physics, iced aerodynamics, aircraft stability and control, computational fluid dynamics (CFD), thermal sciences, icing scaling, atmospheric characterization, and experimental methods. It is highly connected with other disciplines, including meteorology, modeling and simulation, software engineering, thermal analysis, and computational sciences.

Simulating icing on external surfaces, whether experimentally or computationally, involves two separate elements: ice accretion and iced aerodynamic performance. Both elements have their own set of additional difficulties. With ice accretion simulation, for example, there is a need to update the particle collection and subsequent ice growth, which occur at different timescales when compared with the aerodynamic flow field. With iced aerodynamics, there is a need to address complex geometries with multiple ice roughness scales that are typically not encountered in most aerodynamic simulation scenarios. Likewise, simulation of engine ice crystal icing (ICI) involves the ice accretion process and impact on engine performance.

All of these issues require collaborative research involving both computational and experimental components. Icing codes are constantly being improved to represent highly complex icing physics processes and flow fields in order to analyze the next generation of aircraft, yet the validation database for these upgrades typically comes from geometries of the previous generation. Test facilities are constantly being pushed as well—maintaining calibration, improving flow quality, accommodating new test measurement techniques, and expanding the calibrated envelope of test conditions are areas of ongoing need. In addition, there are some test conditions that still cannot be simulated by the test facilities but which, due to new missions or new regulatory requirements, are now needed.

2.2 NASA Icing History

In the 1940s and 1950s, the National Advisory Committee for Aeronautics (NACA) had a successful icing program, and by the time of the Apollo era, many veteran engineers thought the icing problem had been solved. However, as new vehicles and technologies emerged, bringing new challenges, it became clear that icing was still a critical consideration. An overview of early icing work can be found in Reference 4, which summarizes select NACA and NASA icing research from 1940 to 1962. In 1978, the Icing Branch at NASA was formed at the Lewis Research Center (now Glenn Research Center (GRC)). Originally called the Aircraft Icing Section, its goal was and still is to improve aviation safety (Ref. 5).

The Icing Research Tunnel (IRT) was constructed in 1943, with first tests conducted in 1944. The IRT underwent upgrades in the 1970s to improve airspeed, air temperature, and supercooled cloud characteristics. Further improvements were made in the 1990s, including new insulation, new fan blades, and upgrades to the spray bar system and controls. The most significant improvements were undertaken in 1999 and included a new heat exchanger, a large settling chamber, new turning vanes, and fan outlet guide vanes (Ref. 6). The most recent major facility upgrade was completed in 2011 with the construction and commissioning of a new refrigeration plant and installation of a new heat exchanger (Ref. 7).

Between 1968 and 1991, there were 14 major takeoff accidents related to ground icing. These events motivated an extensive joint test program to evaluate the effects of ground deicing and anti-icing fluids on takeoff aerodynamics (Ref. 8). Within a decade, the IRT had become a unique national asset, and it continues to be one of NASA's most heavily utilized wind tunnels.

If ground deicing was the major challenge of the 1980s, the in-flight icing encounters of commuter airplanes were the focus of the 1990s. The 1994 American Eagle Flight 4184 accident involving an ATR–72 aircraft (Ref. 9) gave a new urgency and direction to NASA's icing research. Even before this accident, questions had been raised about the acceptability of the App. C standards, and although much joint research has been conducted by NASA, the Federal Aviation Administration (FAA), Environment and Climate Change Canada (ECCC), National Research Council of Canada (NRC), and others, the effect of SLD icing remains an issue today.

NASA conducted icing flight research using a modified De Havilland Canada DHC–6 Twin Otter from 1983 to 2006. Flight research objectives included measuring natural icing cloud characteristics and associated ice shapes and understanding the aerodynamic degradations caused by ice on the wing and tail surfaces. In the mid-1990s, in response to a number of turboprop commuter accidents, NASA used the Twin Otter to study ice-contaminated tailplane stall. This research led to a broader understanding of the causes and expanded awareness among the pilot community (Ref. 10). After the 1994 Aerei da Trasporto Regionale (Regional Transport Aircraft) ATR–72 accident, NASA flew the Twin Otter in SLD icing clouds to measure the cloud characteristics (Ref. 11). The data from these flights were used with flight data from ECCC to create the FAA's Part 25, App. O SLD icing envelopes (Ref. 12). In 2015, as a consequence of these investigations into SLD, the FAA and European Aviation Safety Agency (EASA) issued new regulations (Refs. 2 and 13).

NASA used lessons learned from the icing flight research and operations to create educational videos, computer-based and web-based training, and icing flight simulation to help pilots understand the ramifications of icing and how to mitigate the hazards (Refs. 14 and 15). These widely distributed materials addressed the icing environment, flight preparedness, and strategies for avoiding icing conditions, as well as stall and loss of control due to wing or tailplane ice.

Between 1999 and 2013, NASA developed and conducted flight validation experiments of icing remote sensing systems for en route and terminal area weather information (Ref. 16). The data from these sensing suites were intended to inform pilots and dispatchers on current and near-term icing hazards and enable tactical decisions to mitigate hazards caused by icing.

From 2003 to 2005, the Engine Harmonization Working Group (EHWG) reviewed a growing database of engine power loss events that had occurred on multiple large and regional airplanes worldwide. The EHWG concluded that these events occurred as a result of flight near deep convective storms that contained high concentrations of ice crystals. The EHWG developed a technology plan that included the following tasks:

- Instrumentation development for high ice water content (HIWC)
- Flight test research to characterize HIWC environments
- Experimental testing to support ice accretion model development in HIWC conditions
- Test facilities requirements for demonstrating engine compliance with 14 CFR Part 33 and App. D requirements

This technology plan provided a roadmap for NASA and other organizations to address the newest icing threat: engine icing. NASA responded to this technology plan by collaborating with the FAA, NRC, and ECCC to develop new instrumentation to measure the harsh HIWC conditions and to further develop collaborations that would lead to flight campaigns that utilized these new instruments to characterize this environment. In parallel with these efforts, NASA developed plans to add a new icing capability to the PSL to enable fundamental and complex engine icing experiments to be performed under laboratory conditions.

NASA has continually provided icing research support to the Department of Defense (DoD). Typically, an icing concern arises for an existing or proposed vehicle, and the cognizant DoD command, along with the vehicle or subsystem contractor, reaches out to NASA for assistance. This leads to a DoD-sponsored research project that draws upon NASA expertise and NASA facilities to provide the required data for evaluation of the issue at hand. The results of these projects are reported back to the sponsoring organization and contractor. NASA has supported the U.S. Air Force in airframe icing and IPS development going back several decades. In addition, NASA has a history of collaboration in rotorcraft icing research with the U.S. Army that goes back more than 50 years.

The NASA Icing competency underwent a major downsizing between fiscal years (FYs) 2005 and 2009, losing approximately 50 percent of the civil servant workforce over this period, accompanied by reductions in contractor and procurement support. The downsizing resulted from replanning activities designed to align with the goals and objectives within a new ARMD program structure. Beginning in FY 2007, icing research was distributed among three projects in the Aviation Safety Program and one project in the Fundamental Aeronautics Program. The downsizing caused the loss or significant reduction of capability in some areas. Flight research was significantly curtailed, training and education products were discontinued, and weather product development and terminal area remote sensing began a gradual decline.

In summary, history shows that despite great progress in addressing icing issues, new challenges have continued to arise for the aviation industry. Among these challenges are accidents that occur in conditions outside the regulatory environment; such accidents have resulted in regulatory changes to which the industry is still adapting. Still other challenges emerged after environmental and economic conditions necessitated new vehicles and technologies (e.g., ground deicing in the 1970s and 1980s, turboprops in the 1990s, and high-altitude ice crystals in the 2000s). Each of these mini-revolutions required a new regulatory environment and pushed the cutting edge of existing tools and facilities.

To stay current, the Icing Branch conducts periodic assessments and sponsors workshops to guide research objectives based on feedback from industry, academia, and Government on NASA's research plan in emerging areas. The 2008 Airframe Icing Workshop (Ref. 17) was one such activity. These assessments and workshops also serve to solidify existing partnerships and identify potential future collaborations. Prior to this study, the most recent of these activities was the Icing Hazards Workshop held in January 2015.

2.3 NASA Icing Research (2012 to 2020)

In 2013, Potapczuk (Ref. 18) published a detailed and extensive history of the icing research conducted at GRC. This comprehensive article begins in the spring of 1948, when the NACA decided to consolidate all icing research at its Cleveland laboratory, and covers significant research efforts undertaken through 2011. The article discusses characterization of the icing environment; icing simulation methods (both experimental and computational); icing scaling; icing physics; IPS development; rotorcraft icing; aircraft performance characterization (including flight research and crew training); and remote sensing of icing conditions.

The following subsections summarize significant icing research efforts undertaken at GRC from 2012 to 2020 in three main areas: ice crystal engine icing, airframe icing, and rotorcraft icing. The research in these three areas was augmented by crosscutting research in icephobics and icing physics. This is not intended to be a comprehensive documentation of all research conducted, but rather provides sufficient context for the technical elements presented in Sections 3.0, 4.0, and 5.0 of this report.

2.3.1 Ice Crystal Engine Icing

As described in Section 2.2, a significant number of jet engine power loss events were identified for flights near deep convective storms that contained high concentrations of ice crystals. As a result, GRC undertook significant research activities to address ICI affecting jet engines. This research was organized into atmospheric characterization, fundamental studies of the icing physics, engine testing, and computer modeling.

The High-Altitude Ice Crystal and High Ice Water Content International Field Campaigns (Refs. 19 and 20), conducted in 2014 and 2015, acquired new atmospheric data to assess the new ice crystal regulations in CFR 14, Part 33, App. D; and EASA Certification Specification (CS) 25, Amendment 16, App. P. Those regulations became effective in 2015. NASA provided critical instrumentation and leadership in these multiagency, international, collaborative flight campaigns. Subsequently, NASA and the FAA conducted two additional HIWC flight campaigns using the NASA DC–8 to further characterize the ICI environment and develop radar-based detection methods that will allow pilots to avoid the hazardous ICI conditions (Refs. 21 and 22). The assessment of Part 33, App. D, is currently ongoing, using the atmospheric characterization data from these flight campaigns.

In 2012, NASA developed a new engine icing experimental capability by installing spray bars and nozzles into PSL Test Cell 3 (Ref. 23). This arrangement provided the ability to generate ice particles in a controlled manner through the freezing of water drops issued from the nozzles. The PSL's new ICI capability was then used in 2013 to replicate in-service power loss events with a Honeywell ALF–502 engine (Refs. 24 to 27). Subsequent engine icing tests (Ref. 28) and calibrations (Refs. 29 to 31) in ice crystal environments were conducted in the PSL, and along the way, significant advances were made in the PSL capabilities and instrumentation to position the Agency for future research in this key area (Refs. 23 and 29 to 34). In 2017, NASA published an article that summarized the ICI research efforts to date (Ref. 35).

Fundamental studies of the ICI physics were conducted in collaboration with NRC from 2010 to 2018 using NRC's Research Altitude Test Facility (RATFac). These studies found that a local wet-bulb temperature near freezing plays a crucial role for the onset of ice accretion, leading researchers to recognize the importance of measuring and controlling local humidity, which affects wet-bulb temperature. 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 testing, and a method to measure the ice shape from these videos was developed (Refs. 36 to 40).

NASA continued fundamental ICI studies using its PSL and IRT, performing fundamental accretion physics studies (Refs. 41 and 42) and several dedicated tests studying the erosion of accreted ice due to ice particle impacts (Ref. 43). This includes work in instrumentation (Refs. 44 to 48). Currently, NASA is investigating the extent to which the IRT can generate ice crystals to support the Agency's ICI research, and some limited data is presented in the previous references.

The ICI fundamental and engine studies were complemented by computational modeling efforts. Initial efforts for development of ice crystal modeling capabilities centered on modifications to the NASA ice accretion codes LEWICE and LEWICE3D. Wright (Ref. 49) modified the LEWICE code to include ice crystals in the trajectory calculations as well as including a breakup model for impact of ice crystals on engine surfaces. Rigby et al. (Ref. 50) combined the GlennHT code for computing flow in an engine passage with the LEWICE3D ice accretion code to simulate ice particle breakup and ingestion into a heavily instrumented research engine geometry. Additionally, Jorgenson and Veres (Ref. 51) modified a one-dimensional mean line flow analysis code for axial and centrifugal compressors to enable the assessment of ICI risk for turbofan engines. This code, called COMDES-MELT (for COMpressor DESign melt), has been used to assess the icing risk for engines tested in the PSL under ICI conditions (Refs. 52 and 53). Finally, there were several modeling efforts of the fundamental ICI activities (Refs. 54 to 60) as well as a simulation of the PSL facility itself to understand the complicated flow and particle behavior leading up to the engine test section (Ref. 61).

2.3.2 Airframe Icing

NASA GRC airframe icing research focuses on experimental and computational simulation of ice accretion on wings, tails, and other aircraft surfaces, along with the aerodynamic effects. NASA developed the first computer codes to predict water droplet collection, model ice buildup, and provide design tools for IPSs. LEWICE development was initiated in the early 1980s, with the first general release (Version 1.0) in 1991 (Ref. 62). Ice accretion predictions in LEWICE are two-dimensional, and the approach uses the Messinger model (Ref. 63). There have been six updates to the code: Version 1.3 in

1993, Version 1.6 in 1995, Version 2.0 in 1999, Version 2.2 in 2002, Version 3.0 in 2005, and Version 3.2 in 2006. LEWICE has been thoroughly validated for a wide range of conditions, with a database of over 3,000 ice shapes on nine different geometries. Validation has been documented in numerous papers as well as NASA reports (e.g., Refs. 64 to 66). LEWICE3D, a suite of codes developed by NASA in 1993 (Ref. 67), is widely used by industry today to determine the amount and location of ice accretion on an aircraft. It can calculate water loading on aircraft surfaces so that IPSs can be sized, and it can determine ice shapes used in failed IPS tests as well as the optimal placement of icing sensors. LEWICE3D is also used to help determine correction factors for cloud measurement instruments, such as droplet size probes or liquid water content (LWC) probes.

LEWICE remains NASA's flagship code for 2D ice accretion prediction and has been the core of the three-dimensional (3D) ice accretion tools as well. Large-scale, 3D swept wings present a particular challenge to the existing LEWICE analysis methods. Recently, NASA, the FAA, Office National d'Etudes et de Recherches Aérospatiales (ONERA), Boeing, the University of Illinois, and the University of Washington completed a collaborative research effort to address these technical challenges (Ref. 68). The effort included ice accretion experiments, iced aerodynamic experiments, and computational simulations of a baseline reference geometry that is representative of a generic state-of-the-art wide-body commercial transport. This work augmented the already extensive LEWICE3D validation database. The research was designed to fully integrate computational and experimental methods. For example, the large-scale icing test articles were designed using 3D CFD, simulating the wind tunnel walls in order to take into account blockage effects on test article performance (Ref. 69). An additional outcome of this research effort was a robust and affordable means of recording and archiving fully 3D ice accretion geometry using a commercial laser scanning system (Refs. 70 and 71). The method is now validated and available for use by researchers and outside customers in the IRT.

NASA has also collaborated with NRC on altitude scaling methods for thermal IPSs. As aircraft become more efficient, there is less power available for thermal ice protection, where the leading edge of icing surfaces are heated either electrically or with bleed air. Therefore, the system performance is often optimized during icing tunnel testing. However, there are limitations for ground-based icing tunnels, like the IRT, that do not have altitude capability. This collaboration focused on developing scaling methods to account for altitude effects in the ground-based testing of thermal IPSs.

NASA has also conducted preliminary studies into the effect of bimodal drop-size distributions that are a characteristic of SLD conditions set forth in 14 CFR Part 25, App. O. There is some limited capability in the IRT to generate monomodal and bimodal icing clouds having a median volumetric diameter (MVD) similar to the MVD defined in App. O for FZDZ. These preliminary results indicate that there may be some minor effects of the bimodal drop-size distribution that may need to be accounted for in some cases. Additionally, NASA performed testing examining the effect of Weber number on large droplets (Ref. 72).

2.3.3 Rotorcraft Icing

The simulation of rotorcraft ice accretion is a challenging multidisciplinary problem that until recently has lagged in development over its counterparts in the fixed wing community. Recently, however, several approaches for the robust coupling of a CFD code, a rotorcraft structural dynamics code, and an ice accretion code have been demonstrated (Ref. 73).

To obtain quality experimental data on ice accretion and shedding under various icing conditions, the Icing Branch collaborated with the National Rotorcraft Technology Center and the Vertical Lift Consortium to conduct a 15-day test entry of a heated rotor in the IRT. A rotating model configuration was necessary to evaluate the effects of higher speeds, centrifugal effects, and constantly changing local velocity around the azimuth. The test investigated ice accretion and the associated increase in power requirement; self-shedding; element on-times versus runback refreeze; spanwise versus chordwise shedding; evaporative anti-ice versus running wet; induced shedding and ice shard breakdown; and conditions from App. O. This was the first rotating model tested in the IRT in 20 years. Other notable IRT firsts from this test included the first production use of new 3D scanner capability, first electrothermal deicing of a rotating scale model, first capture of a rotor shed event with a high-speed camera, and the first SLD icing on a rotor blade in the IRT. The data included rotor ice shapes (tracing, photograph, and scanner), rotor performance (main balance and instrumented blades), deice and anti-ice performance (temperature), and shed ice trajectory (wall panels and high-speed video). For this effort, the High-Fidelity Icing Analysis and Validation Team won the 2014 Howard Hughes Award from the American Helicopter Society (Ref. 74).

2.3.4 Icephobics

As far back as 1969, the FAA tested icephobic coatings in the IRT. In the 1970s, NASA and the U.S. Army together conducted both ground tests and flight tests of candidate substances to reduce the adhesion force of ice on helicopter rotor blades. Research continued into the early 1990s, when NASA looked beyond traditional sources and reached out to allow amateur inventors to test their potential icephobic products in the IRT (Ref. 5).

Because of the severity and urgency of the American Eagle Flight 4184 accident in 1994, coupled with uncertainty in experimental methods, research into icephobics at NASA entered a long hiatus for many years until 2008, when GRC funded a small in-house seed fund program. From there, icephobics research grew until 2015, when it was finally integrated into the Revolutionary Vertical Lift Technology (RVLT) and AATT projects (Ref. 75). NASA's work in this area has always been highly collaborative, in particular with the rotorcraft community. NASA continues to receive inquiries from industry and academia expressing interest in both tool development and icephobic materials research. The DoD (Army, Air Force, and Navy) is also conducting its own research in the area. The FAA is another major stakeholder in the icing community.

The shortcomings of adhesion measurements were identified (Ref. 76), and NASA continues to collaborate with industry to slowly advance the quest for an icephobic coating. In order to develop effective ice-resistant coatings for aircraft, it is necessary to have a consistent, reliable method for quantifying the adhesion strength of in-flight ice. It is also necessary to characterize the behavior of candidate materials subjected to realistic environments such as rain, sand, and ultraviolet exposure.

The Icing Branch Fundamental Adhesion and Shedding Test Laboratory (FASTLab) at GRC initially included a tensile tester, an optical microscope, an infrared camera, a centrifuge, and a cold chamber. Other capabilities available to this laboratory include a scanning electron microscope, a goniometer, and an optical profilometer. In 2017, the facility was moved to a larger, dedicated space and renamed the Revolutionary Icing Materials Evaluation Laboratory (RIMELab). The facility also includes storage, 3D printing, and capabilities for examining ice grain structure.

At LaRC, research into low-ice-adhesion coatings began with exploration of the idea that controlling hydrogen bonding interactions could influence the adhesion strength of ice accreted in flight. This effort, funded by a NASA Aeronautics Research Institute award, consisted of a series of experiments with designed surface chemical constituents using single-molecular-layer functionalization of aluminum surfaces. The work transitioned to the development and evaluation of coating formulations that would exhibit low ice adhesion. Funding then transitioned to the NASA AATT project. The LaRC Advanced Materials and Processing Branch is highly qualified to investigate specialized formulations of polymeric materials for aerospace applications. Current activities at LaRC include extensive low-ice-adhesion coating design and formulation, coating durability characterization, and ice adhesion experiments.

2.3.5 Icing Physics

Fundamental studies of icing physics provide the basic understanding and databases used to develop computational models for both supercooled liquid icing and ICI. Recent research in these areas includes ice roughness characterization and convective heat transfer experiments important to the initial stages of ice growth. The newly developed capability to measure experimental ice accretion and roughness in 3D led to new methodologies to statistically analyze and quantify ice roughness (Refs. 77 to 84). This capability was later coupled with 3D printing to generate artificial ice roughness that was subsequently used to measure the convective heat transfer associated with the roughness (Refs. 85 to 88). The experimental ice roughness was generated in a series of IRT experiments, while some of the heat transfer experiments were conducted in the Vertical Icing Studies Tunnel (VIST), also located at GRC (Refs. 89 and 90). These data have been used to propose updated models that could be included in new icing simulation tools (Ref. 91).

Another example of icing physics studies considers the breakup of ice crystals and is important to the modeling of ICI. A series of experiments were carried out in collaboration with the Ballistics Lab at GRC to quantify the size and distribution of shattered ice particles impacting a flat plate at various incidence angles (Refs. 92 and 93). These data are needed to understand the potential size distribution of ice crystals inside turbofan engines.

2.4 Current NASA Work in Icing

NASA's mission for aircraft icing has been to develop the tools, methods, and databases necessary to enable U.S. industry to design and develop safe aircraft and to allow Government and regulators to evaluate those aircraft. NASA's icing prediction codes are widely used, and NASA's facilities play a key role as a means of demonstrating compliance with regulations and conducting research. The Icing Branch also develops improved instrumentation and experimental methods, supports the design and calibration of test facilities, and conducts research in icing physics and the characterization of icing weather.

As the commercial state of the art catches up, NASA retires its old tools and moves on to the next generation. The LEWICE3D code is now being rewritten from the ground up as GlennICE to take advantage of modern flow solvers, grid generators, and high-speed computer state-of-the-art capabilities that are now commercially available. The new architecture is necessary to accommodate future needs of the industry, including engine icing, airframe icing, and rotorcraft icing.

The Icing Branch continues to lead research into the fundamental physics of ICI in modern engines, which necessitates simulating complex rotating components and highly 3D geometries. NASA has developed a test article whose geometry is representative of an intercompressor duct and strut region of a turbofan engine. The Simulated Intercompressor Duct Research Model (SIDRM) will be used to provide ICI physics and validation data for development of NASA's engine icing simulation capabilities (Ref. 94).

GRC is actively upgrading capabilities in the RIMELab and the Adaptive Icing Tunnel (AIT), where low-TRL work can be conducted more economically than in larger icing facilities. The RIMELab includes a modified lap joint test capability for measuring ice adhesion, grain structure microscopy, a walk-in freezer, 3D printing, and a centrifugal test capability. The AIT is a refrigerated laboratory-scale icing wind tunnel with a 1- by 1-ft test section that will be capable of test section velocities of approximately 250 mph and temperatures down to –20 °C.

NASA leverages the Small Business and Innovation Research (SBIR) program for the incubation and demonstration of new technologies, and recently this effort has focused on the mitigation of icing hazards for AAM vehicles. NASA also supports the commercialization and infusion of advanced icing instruments and probes.

NASA is collaborating with the FAA and an international team of researchers from ECCC, the NRC, and Centro Italiano Ricerche Aerospaciali (CIRA) (Italian Aerospace Research Centre) to characterize current and emerging technology instrumentation for measurements of SLD cloud conditions and data processing methods (Ref. 95).

An Aviation Rulemaking Advisory Committee (ARAC) Ice Crystal Icing working group recommended that the FAA and NASA conduct additional HIWC flight research in regions with high aerosol content to ensure the proposed revisions to Part 33, App. D account for these conditions. GRC and the FAA are currently planning another flight campaign using NASA's DC–8 with subject matter expertise support from LaRC, Ames Research Center, and the Neil A. Armstrong Flight Research Center.

2.5 Icing Impacts and Certification Challenges for Future Systems

To develop plans to meet the objectives of the AoA study, it is necessary to consider not just the needed technologies and capabilities but also the tools, methods, and facilities that will be needed in the future. It is assumed that tool development will also include the validation databases. Tools can include engineering-level, high-fidelity codes or system-level analysis. It is also assumed that facilities will continue to be well calibrated and well maintained. Methods for measuring and simulating various aspects of icing include both experimental and computational methods. Ice detection and sensing instruments can be for both ground testing and in-flight. The AoA study included only aviation icing, with a strong focus on in-flight icing.

Figure 1 provides a visual summary of icing impacts and certification challenges. The certification environment for icing is shown in the lower right-hand corner of Figure 1. There are three different icing and ice crystal environments, commonly called Apps. C, O, and D (denoting the location in the Code of Federal Regulations (CFR) where each environment is described) (Refs. 1 to 3):

- App. C: Typical icing clouds with smaller supercooled liquid droplets, MVD from 15 to 50 μm and LWC up to nearly 3 g/m^3, can exist anywhere between the surface and 29,000 ft.
- App. O: Environment with SLD, including FZDZ, with the largest drop diameters up to 500 μm and LWC up to 0.44 g/m^3; and FZRA, with the largest drop diameters greater than 500 μm and LWC up to 0.31 g/m^3.
- App. D: Ice crystal clouds composed of a distribution of ice crystal sizes with median mass diameters of 50 to 200 μm and total water content up to 5 g/m^3. Ice crystal clouds typically exist at high altitude, up to 47,500 ft. Most events occur under Tropical Day conditions, warmer than Standard Day lapse rates.

Supercooled liquid clouds (Apps. C and O conditions) pose the greatest threat to forward-facing external airframe surfaces, including lifting surfaces, nacelles, and fan blades. The larger drops of App. O can produce ice further aft on the vehicles, causing distinct anti-icing and deicing challenges. The relative drop size ranges within and between App. C, FZDZ, and FZRA are indicated in Figure 1. Additionally, ice crystals can be ingested into the core flow path of a turbine engine, where they can cause several different types of power loss events.

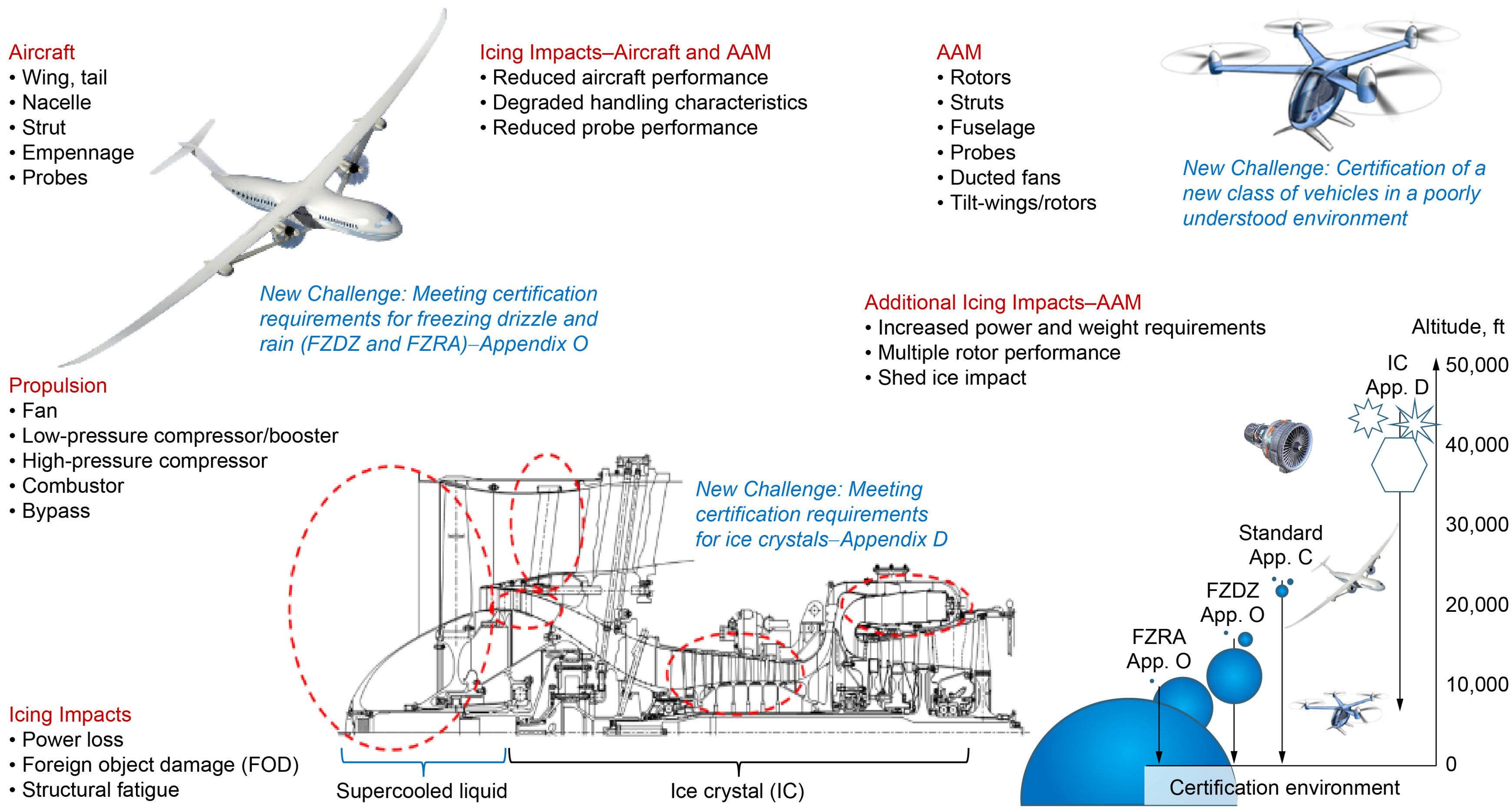

Figure 1.—Icing impacts on future aviation systems. Advanced air mobility, AAM. Low-pressure compressor, LPC; high-pressure compressor, HPC. Dashed red lines indicate areas at risk of icing in engine core. Cutaway engine image courtesy of Honeywell (used with permission).

2.5.1 Airframe Systems

Icing is commonly an issue in these areas: wing and tail, nacelle, strut, empennage, and probes. Potential icing issues for future airframe systems, as with those in the past, include reduced aircraft performance, degraded handling characteristics, and reduced probe performance.

For fixed-wing aircraft, a new challenge will be meeting the new certification requirements for FZDZ and FZRA (App. O). The App. O and App. D regulations were released relatively recently (2015), so there is still significant uncertainty as to how these icing regulations will affect new aircraft.

2.5.2 Propulsion Systems

Icing is commonly an issue in these areas: fan, low-pressure compressor/booster, high-pressure compressor, combustor, and bypass. Icing issues include power loss, foreign object damage (FOD), vibration, and structural damage.

For engines, a new challenge will be to meet the requirements for ice crystals (App. D). ICI and its impacts can occur in the core of the engine, denoted by the dashed red lines in the core region in Figure 1.

2.5.3 Advanced Air Mobility Systems

Future AAM systems face diverse challenges. In addition to the issues discussed for fixed-wing aircraft—reduced performance, degraded handling characteristics, and reduced probe performance—the icing envelope for AAM is still not well defined. AAM icing is outside the icing community's area of expertise, and validation data and experience are still lacking. Icing impacts can be expected for rotors, struts, fuselage, probes, ducted fans, tilt wings, and rotors. AAM vehicles also face icing impacts related to increased power and weight requirements, multiple-rotor performance, and shed ice impact. New icing hazard mitigation technologies and improved sense-and-avoid strategies are considerations for the emerging AAM sector.

2.6 Overview of the Analysis of Alternatives Process Used for Icing

The Icing AoA approach was initially based upon the workflow used in the 2019 to 2020 Materials, Structures and Manufacturing AoA study. The process was subsequently adapted and customized to better suit the needs of the icing study, but the general steps remained the same. Information was gathered from various stakeholders and used to conduct a quantitative ranking analysis using TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) (Ref. 96). The results of the TOPSIS analysis were used to identify the priority and enduring needs to accomplish the objectives of the icing AoA study. The details of the icing AoA workflow are depicted in the flowchart shown in Figure 2 (adapted from Ref. 97, internal report), which illustrates the key steps in the process:

- The icing AoA study team conducted 47 interviews of both internal and external stakeholders and gathered additional inputs from four NASA project areas (Section 3.0).
- This information was then used to identify and organize a list of needed technical elements in icing research (Section 4.1).
- A set of rating criteria was developed to evaluate each technical element. The rating criteria included individual stakeholder "pull" along with other criteria related to research impact, safety, and certification (Section 4.2).
- Four potential future realities were defined to investigate technical elements that may be higher ranked under different circumstances in the future of aviation (Section 4.4).

- The technical elements and evaluation criteria created a rating matrix that was provided to the icing AoA team. The SMEs completed their own ratings individually. An initial TOPSIS analysis was performed along with verification and consistency checks. In some cases, the results led to unexpected discrepancies among the SME ratings. This required a discussion among the SMEs to share knowledge and insights regarding stakeholder inputs and to refine definitions of the technical elements and evaluation criteria. After this iteration was performed, the TOPSIS analysis was repeated and yielded more consistent results (Sections 4.5 and 4.6).
- Finally, the results of the final TOPSIS analysis were used to identify priority and enduring needs in icing (Section 5.0).

The remainder of this report provides a complete description of the icing AoA process outlined here along with the key findings and recommendations for NASA icing research.

3.0 Stakeholder Interviews

The stakeholder interviews represented a significant effort to rebaseline NASA's understanding of current community challenges and opportunities. The study team sought broad coverage of industry, academia, and other Government agencies across multiple sectors. They also sought to leverage existing collaborations and ongoing feedback, such as that provided at technical working group meetings and SBIR reviews. The stakeholder input gathered through this effort represents feedback from more than 50 companies, organizations, Government agencies, and academic institutions.

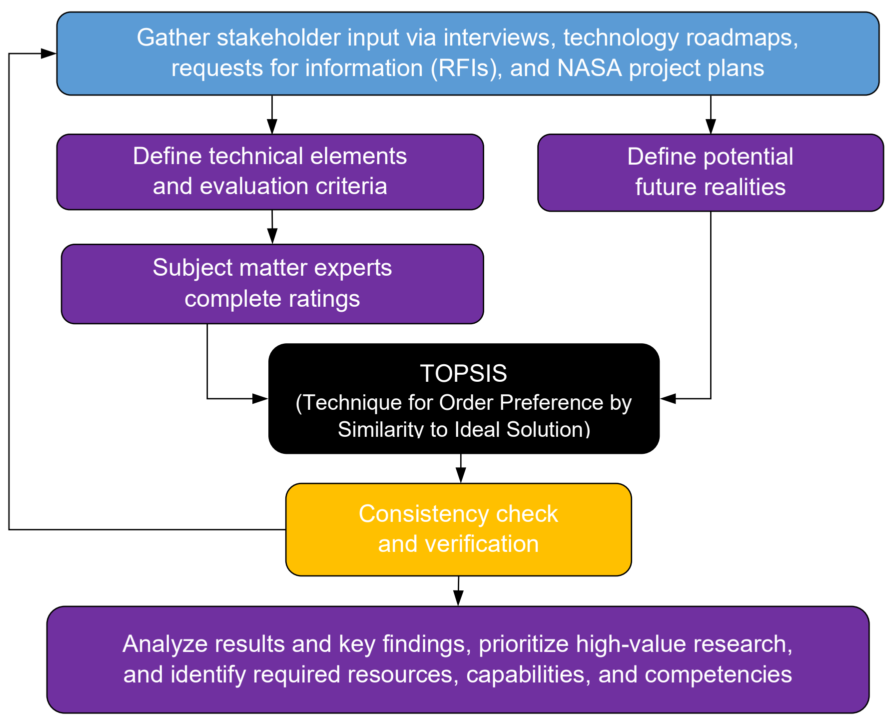

Figure 2.—Icing Analysis of Alternatives workflow (adapted from Ref. 97, Acoustics Analysis of Alternatives, internal report).

The overarching goal of the interviews was to maximize the applicability and impact of future NASA research. Specifically, the interviews sought to determine

1. Priority needs for NASA Aeronautics (TRL 5 to 6 by 2025 to 2035, with focus on the Fab Four).
2. Enduring needs for the aviation community (defined as TRL 5 to 6 by 2035 and beyond). Enduring needs are the additional long-term capabilities and expertise identified by the aviation community as being critical for NASA to provide.

3.1 Stakeholder Segments and Organizations

The interview process targeted several stakeholder segments. The external stakeholder community included original equipment manufacturers (OEMs) such as airframe, rotorcraft, and engine manufacturers as well as emerging advanced air mobility companies. Also included was the icing support industry involved in remote sensing, ice protection, instrumentation, and software development.

A number of NASA project areas and U.S. Government agencies were interviewed, and a contractor was hired to solicit input from academia.

The team ultimately identified and pursued interviews within the following broad stakeholder segments:

1. Industry/Commercial
    a. Airframe
    b. Large Rotorcraft
    c. Engines
    d. AAM (inclusive of unmanned aerial vehicles (UAVs), unmanned aircraft systems (UAS), and urban air mobility (UAM))
    e. Electric Aircraft
    f. Suppliers
    g. Software
    h. Remote Sensing
    i. Material Developers
2. Aviation Regulatory Authorities
3. NASA
4. Other Government Organizations
5. Academia

Within these segments, a total of 137 potential interviews were identified, with 47 interviews ultimately completed, most within a 2-month timeframe. Most interviews were performed via virtual meeting platforms such as Microsoft Teams and Zoom (Zoom Video Communications, Inc.). Many of the interviews involved multiple interview subjects; in total, over 80 individuals were interviewed. In addition to the formal interviews, inputs were gathered from SMEs and existing project documentation in several NASA ARMD areas and the Science Mission Directorate (SMD) Earth Science Division.

3.2 Interview Questions

The team established a general template for interviewers to follow. Questions could be tailored to the specific interview, but each interview took the same overall approach. Sample questions for industry included the following:

1. Opening statements. (Goal: to develop a rapport and provide background and context)
2. Context questions. (Goal: to understand the company's context within icing, how they operate, and what matters to their company; general questions for context that could be answered with respect to icing but do not have to be.) Sample questions:
    a. What need is driving your business?
    b. What is critical in your business to "get right"?
    c. What happens if that piece goes wrong?
    d. What do you forecast is the future of your business?
3. Needs and barriers questions. (Goal: to understand the company's needs for icing problems and barriers to advancements.) Sample question:
    a. When it comes to icing, what are some of the major needs for your company?
4. Role of NASA questions. (Goal: to understand the company's view of NASA and potential role for NASA to help address their needs) Sample questions:
    a. What is NASA's role in icing? Or what should NASA's role in icing be?
    b. Could NASA address any of the previously mentioned needs and barriers applicable to your company?

3.3 Summary of Interview Inputs by Segment

The following summary by interview segment identifies themes that emerged during the interviews and, where available and applicable, specific icing needs identified in each interview segment. Individual interviews often contributed inputs in multiple segments. Interviews were performed with the understanding that participants would not be identified in public-facing documentation.

3.3.1 Commercial Airframe Industry

Four interviews were performed. The nine interviewees represented multiple disciplines within three major commercial airframe companies.

3.3.1.1 Interview Themes

Emerging themes included the impact of new regulations; certification issues; and a need for tools for thermal IPS simulation and ice crystal evaluation.

- New regulations for Apps. C, D, and O will have large impacts on airplane design, cost, and certification:
    - Icing impacts must be captured during earlier design stages because of increased optimization, more complex integration (airplane geometry, systems, avionics, and flight controls), and to avoid "surprises" later that can adversely impact performance, efficiency, noise, and emissions.
    - The current situation relative to new regulations is that manufacturers greatly rely on similarity to existing designs, fleet history, and experience. The new regulations could limit research and development toward new and different designs. This is particularly true when using the

comparative analysis means of compliance (MOC) for EASA Certification Specification (CS) 25.1420 (Ref. 98) due to the lack of tools or testing facilities to show direct compliance for SLD.

- Predictive tools and facilities for representative flight conditions are needed to reduce performance and handling quality risks:
  - Airframers would like to reduce the amount of flight testing needed for certification. This requires the development of validated computational tools for ice growth and aerodynamics for a large range of conditions and airplane configurations. The validation range must include a path up to a flight-scale vehicle and flight test conditions. While reducing flight testing is a cost and schedule improvement overall, the major benefits of improved tools are significant reductions in risk via design exploration and improvement prior to relying on flight test discovery.
  - Improved and validated icing tools would enable more portions of the certification to be completed by analysis, spreading out the certification effort over the life of the project (as opposed to a large effort at the point of flight testing ice shapes).
  - Icing simulation tools (both computational and experimental) have only limited capability for App. O. If not addressed, this will become a problem for new airplane certifications. Such problems have the potential to manifest themselves in very conservative design approaches, limits on operational performance, and increases in development and operational costs. It should be noted that basic airplane design and performance, in many cases, can be set by flight in icing. Addressing flight-level performance and handling qualities in icing conditions is a consideration in fundamental design parameters.

3.3.1.2 Specific Icing Needs

- There is a need for improved thermal IPS simulation, including water runback and ridge ice formation, as well as ice shedding models for hybrid deicing systems. There is only minimal capability in current icing simulation tools for these applications.
- There is a need for improved capability for evaluating ice crystal concentration factors for locations of probes, antennas, and other external airframe components impacted by ice crystals.

3.3.2 Commercial Engine Industry

Five interviews were performed; a total of 12 individuals were interviewed. The interviewees were from four commercial engine companies and had expertise in a variety of areas, including icing certification, systems engineering, engine design, inclement weather, nacelles, and auxiliary power units (APUs).

3.3.2.1 Interview Themes

- New regulations for Apps. C, D, and O will have large impacts on engine design, cost, and certification:
  - Conventional icing due to supercooled water droplet accretion remains a concern due to buildup on nacelles, spinners, fan blades, and low-pressure compressor stators and rotors. Ingestion of shed ice from these components can damage downstream components and cause engine operability issues.
  - ICI particles can be ingested into the core flow path, where they partially melt and then start to accrete and shed, causing various power loss events such as blade damage, stall, surge, or flameout and rollback. App. D describes the ice crystal conditions to which the engine can be subjected and identifies the requirements that must be satisfied.

    - App. O is not considered a major safety issue in that if manufacturers can design for App. C, then SLD should be covered as well. MOCs are needed to satisfy future certification issues. Engine manufacturers do not anticipate any major certification complications due to App. O.
    - As airframe industry representatives also noted, the current situation relative to new regulations is that manufacturers rely greatly on similarity to existing designs, fleet history, and experience. The new regulations could limit research and development toward new and different designs. This should be overcome by better physical understanding, models, and tests. NASA could contribute further in each of these areas.
- Design issues included the following:
    - As with the airframe industry, icing impacts must be captured during earlier design stages to avoid "surprises" later that can adversely impact operations and potentially damage engine components.
    - Shedding is a major concern for both conventional icing and ICI. Simulation tools are needed to understand and minimize the impact of ice. Fan imbalance due to asymmetric shedding is a particular design concern, as fan ice can drive frame and bearing design. Simulation tools are needed for this as well. Investigations into the physics of ice shedding are needed to better predict this condition.
- The certification issues were similar to those noted by airframe industry representatives:
    - Engine manufacturers would like to reduce the amount of testing needed for certification (reduce cycle time and cost of certification). This requires the development of validated computational tools for ice growth. They desire to know where and how much ice will build and under what conditions. NASA could contribute by performing fundamental physics tests and developing corresponding models and algorithms that can be added to fully developed third-party codes.
    - Engine companies have been performing App. C certification tests. They have invested heavily to build test facilities to do that, and they continue to use those facilities. However, there is a business need to reduce expenses, thus there is a desire to develop flight-level predictive tools for App. C.
    - Manufacturers expect MOC to be by combination of test and analysis for the foreseeable future. As analysis improves, applicants can reduce the number of test points or eliminate some development tests, but it is not anticipated that certification will be achievable by analysis alone. Engine companies will continue to need efficient and cost-competitive test facilities for the next decade at least.
    - Icing simulation tools (both computational and experimental) currently have only limited capability for Apps. O and D. If not addressed, this will become a problem for new engine certifications.
    - NASA has the ability and the test facilities to contribute to both testing and physics model development.
- Ice ingestion into high-pressure compressors of small-core turbine engines needs to be examined.
    - It is important to understand the physics of ice ingestion in high-pressure compressors to understand the impact to the stall margin, which directly affects the operating line, efficiency, and control of the engine.
    - It is important to understand the physics of ice accretion upstream of the high-pressure compressor, which will be shed and ingested into the compressor.
    - NASA is an ideal place to do such research to build on existing icing expertise. NASA has facilities developed to perform engine icing research and to disseminate it publicly.

3.3.2.2 Specific Icing Needs

- Cheaper and more available ice testing facilities
  - Access to PSL testing is critical for ICI. Improved instrumentation for testing in the PSL is also important. It would be good for NASA to reduce the operating cost of a PSL icing test by modernizing the 50-year-old facility to increase its efficiency and reduce energy costs.
  - All of the engine manufacturer interviewees saw the PSL as a critical path for any new engine certification.
    - One engine manufacturer needs PSL to be operational and affordable for an icing certification program (fan and core) in FY 2023.
- 3D ice accretion computational tools
  - NASA's role is to develop models that are open and available. Validation data is needed to increase confidence in tools. Third-party codes are suitable for international use, have many interfaces to other discipline tools (e.g., flow and stress analysis), and have graphical user interface (GUI)/visualization capabilities that would be distracting for NASA to tackle. NASA is probably best suited to focus on fundamental testing and development of algorithms and models.
- IPS design tools
- Icephobic research
  - NASA could contribute in this area, both with the coatings themselves and to come up with an industry standard of typical commercial and business aircraft engine hardware erosion (e.g., from dust particles) against which the durability of emerging icephobic technologies could be tested.
- Ice crystal breakup and rebound models (function of crystal type, size, etc.)
  - Off of titanium compressor blades
  - Off of composite vanes
  - Off of other materials
- Ice crystal breakup and sticking efficiency models
  - For ice crystal breakup, there is, as yet, no generally accepted approach for modeling these phenomena (especially an approach that accounts for differences due to surface materials), although Hauk (Ref. 99) and AGARD Advisory Report (AR) 332 (Ref. 100) are often referenced.
  - For sticking efficiency, some preliminary models have been proposed (Refs. 101 and 102).
- Ice adhesion models for these same materials (perhaps a function of temperature, impingement rate, thickness, clean versus dirty airfoils, etc.)
- Film runback and shedding back into the airstream models
- Better understanding of reinjection of runback water into airstream
  - This is not well understood but is basic and very important for turbomachinery ICI simulation.
- Film vapor pressure as a function of temperature—could there be other factors as well?
- Combined ice crystal and LWC icing data
- Ice ingestion effects on engine operability
  - For example, measure stall margin shift of a small-core turbine engine due to ingestion of ice.
  - This could be compared against a more conventional engine.
  - Results could show some general trends for smaller core engines and ice ingestion effects on the operating line, efficiency, and control of the engine.
- Correlation of high-pressure compressor exit temperature difference to mass of ice ingested
- Examination of how each compressor stage is affected by icing during steady-state and transient (throttle movement) operations

- Investigation of accretion shapes and adhesion strength of ice that accretes upstream of the high-pressure compressor; this will directly impact what types of aerodynamic forces and thermal loading can lead to untimely shedding during throttle movement or transient operations
- Understanding of breakup of shedding ice chunks as they are ingested into the core flow path
- Data can be used to develop and/or improve engine icing accretion and ingestion modeling

3.3.3 Commercial Electric Industry

One company was interviewed in this segment and represented the emerging technology field (not a manufacturer). The company's focus at the time of the interview was on converting existing single- or twin-engine small aircraft into hybrid electrical aircraft by replacing one combustion engine with an electric motor. By 2030, there will be reliable small electric aircraft to conduct passenger operations of around 400 nmi.

3.3.3.1 Interview Themes

The challenges discussed were similar to those of electric UAS, with the primary need being development of a very low power IPS. The respondent noted that converting current IPS systems would not be efficient; new systems are required.

3.3.3.2 Specific Icing Needs

- There is a need for new, innovative, low-power IPSs that can use the higher voltage systems anticipated for electric aircraft.
- This could be a TKS®-type (freezing point depressant fluid, weeping wing) system redesigned to use the high-voltage system for pumps and controllers/indicators.

3.3.4 Rotorcraft, Electric Vertical Takeoff and Landing (eVTOL), and AAM

Eight interviews were conducted with various stakeholders in the rotary wing and eVTOL community, including representatives from Government, industry, and academia. The organizations included were three traditional rotorcraft companies; one urban air mobility company; one small aerospace supplier business; two vertical lift research centers; technical personnel in defense; and regulators in civil government. In total, 13 individuals were interviewed.

3.3.4.1 Interview Themes

From these interviews, five overarching themes emerged related to rotary-wing aircraft. The technical elements of these themes were included in the AoA tool. These themes each include a number of specific recommendations that arose as a composite review of all the interviews.

1. New vehicle concepts have complex aeropropulsive geometries. Tandem, coaxial, quad, side-by-side, and other rotor arrangements will create a highly complex vehicle flow field for collection efficiency analysis and off-body concentration calculations. A suite of icing effects test covering all the phases of transition from propeller mode through edgewise mode, perhaps including a wing or multiple-rotor arrangement, will be needed for icing tool development and validation. Little is currently known about icing on smaller rotors operating in different RPM regimes. Low-noise requirements may result in novel airfoil shapes operating at atypical Reynolds numbers. Also, future designs may use different control methods and may be constant thrust designs.

2. Certification issues. New AAM vehicles are currently entering the certification process. The short-term requirement is to certify for an inadvertent encounter of 5 min based upon visual cues for icing. Eventually, there will be a need to certify vehicles for flight into known icing. There is no good national asset for full-scale rotor icing ground testing. Documenting ice shed into downstream components is also challenging. The minimum safe speed for traditional fixed-wing aircraft does not really apply to many AAM concepts.
3. Icing tools are widely used and will continue to be used. Even if no new capabilities are added, a better interface for NASA's CFD solvers would make the entire icing analysis toolchain more useful.
    - Ice impingement behind a rotor is still not known.
    - An edgewise correlation (similar to the traditional Flemming/Lednicer correlation (Ref. 103)) for a full propeller mode parametric model, perhaps even a prop-wing, is needed.
    - Inlets on traditional rotorcraft are highly 3D and rely heavily on ground test for verification.
4. The need for coatings and surface treatments will continue in the future for low-power active hybrid systems, and possibly on otherwise unprotected surfaces. Fundamental characterization is lacking; even characteristics such as contact angle would help. The IRT is considered expensive and hard to access and so is mainly used for certification, not research. This points toward a national need for a more agile and affordable "democratized" icing tunnel. It would also be valuable if NASA's state-of-the-art physics instruments could be made available when not in use.
5. Ice detectors will need to distinguish between the various types of weather conditions, and an aircraft will need to know exactly what type of weather it is in, in real time. There will be a need for accurate localized weather and its effect on flight phase and IPS mode.

3.3.4.2 Specific Icing Needs

- 3D ice accretion on rotors and inlets
    - Multiple-time-step processing
    - Tool coupling
- 3D ice accretion on multiple-rotor vehicles
    - Aeropropulsive interactions
    - Collection efficiency
- Ice shedding from rotors
- Active, passive, and hybrid thermal IPS modeling
    - Kinetic heating
    - Deicing analysis
    - Icephobic coatings
- Iced rotor performance
- Ice detectors

3.3.5 Instrumentation

Instrumentation was the focus of three interviews with six representatives from industry. This summary includes interview results relating to (1) instrumentation for icing and ice crystal cloud characterization, (2) air data probes, and (3) ice detectors.

3.3.5.1 Interview Themes

- New regulations for Apps. D and O have prompted the need to modify, adapt, or invent new instruments, both to characterize these conditions and to detect and respond appropriately in these conditions.

- New markets and applications are driving developments in new regimes (e.g., UAV, AAM, and ground fog).
  - The smaller scale and lower power of AAM vehicles requires new onboard sensor/detector technologies. Current technologies, which have scaled from large transport to general aviation aircraft, cannot scale to AAM.
  - Lower speed, lower altitude in all weather demands improvements in cloud characterization instruments to operate in these environments, especially in ground fog (many very small droplets).

3.3.5.2 Specific Icing Needs

- Access to the IRT's realistic flight airspeeds and temperatures with a well-calibrated cloud
- Access to the PSL's realistic altitude, Mach, and temperature environment with ice crystal and supercooled liquid capability
- Collaboration with NASA SMEs, especially regarding
  - Facility operation and cloud characterization
  - Icing physics
- Validated, industry-accepted analysis tools for
  - Concentration factor, including SLD splash and ice crystal bounce/breakup/stick
  - Critical temperature calculation, especially for freezing fractions near zero
  - Thermal scaling at altitude
- Collection efficiency on total water content probe designs
- NASA funding (e.g., SBIR funding) and expertise to support new instrumentation development for Apps. O and D

3.3.6 Software Developers

The following inputs were compiled from interviews of two representatives from two companies.

3.3.6.1 Interview Themes

Integrated tools, design issues, and certification were some of the themes raised in the software developer segment interviews.

- Integrated tools are increasingly needed for complex design and certification analysis.
  - Customers desire end-to-end analysis capabilities.
  - Customers expect simulations to have a high degree of accuracy and validation.
  - Usability of their software is important. Customers want non-CFD specialists to be able to use the software and produce reasonable results.
- Design issues included the following:
  - Integrated analysis enables the IPS to be introduced earlier in the design cycle.
  - Accurate simulation of icing physics is paramount.
  - Reducing empiricism in models allows for more universal application of simulation tools.
  - Analysis of icing for geometries other than airfoils and wings is being requested by customers.
- Validation of codes for certification is desirable.
- Both supercooled water and ICI simulations are desired.

3.3.6.2 Specific Icing Needs

- Publicly available databases are critical for validation and should be expanded to cover
  - Nontraditional geometries
  - App. O and App. D
  - Collection efficiency data in general
  - Icing physics data for model development
  - Better understanding of uncertainties in computational results
- Icing physics models that can be added to their software tools
- Development of best practices information

3.3.7 Remote Sensing and Avionics Industry

AoA team members interviewed one commercial supplier in the remote sensing segment.

3.3.7.1 Interview Themes

- Icing is understood to be a significant hazard to aviation.
  - SLD and airframe ice accretion has a long history of adversely impacting aviation operations. Continued research and development is needed.
  - High ice water content clouds were more recently recognized as a threat to modern jet engines and transport operations.
    - Flow and accretion of ice within modern jet engines causes malfunctions.
  - Remote detection allows pilots and operations to avoid icing conditions, reduce long-term operating costs, and increase safety and faith of the traveling public.
- Tools utilized:
  - Airborne Doppler Weather Radar Simulation (ADWRS): NASA-developed tool that produces a time-series signal, statistically representative of radar system performance in the modeled environment. ADWRS has been successfully utilized by NASA, the FAA, and industry to assess radar performance and validation of systems to meet certification requirements.
  - Terminal Area Simulation System (TASS): NASA-developed tool that provides mesoscale modeling of synoptic weather events. TASS has been successfully utilized to model microbursts, gust fronts, wake vortices, turbulence, and now high ice particle concentrations at higher altitude associated with deep convection. TASS is fundamental in remote sensor development and validation of system certification.
  - Flight data: Simulations are only as good or as useful as the fidelity of the physics embodied. Industry has flight test capability, but it is costly, so they withhold data and results (proprietary). Flight data collected by NASA is widely distributed, producing a common basis for development and harmonization of the hazard, how it impacts aviation, how the hazard should be assessed (i.e., hazard metrics), how it should be measured (i.e., what radar observables should be produced, and how they should be filtered to produce a refined/accurate product), what are reasonable minimum operational performance standards, and how they should be tested/verified for certification.

3.3.7.2 Specific Icing Needs

- ICI remote sensing and technology certification needs:
  - Characteristics: Statistical description of the physical properties of this atmospheric condition and the surrounding environment (e.g., flight data)
  - Requirements: Hazard metric (e.g., particle concentrations and duration)
  - Algorithms: Methodology for correlating remotely sensed observables with hazard metric(s)

- Certification process: What needs to be assessed, how should it be assessed, and what is considered acceptable and unacceptable performance?

3.3.8 Icing Protection Systems and Materials

This summary includes stakeholder feedback on IPSs and ice protection materials on fixed and rotating wings, on engine nacelles and inlets, and in more “exotic” applications, such as smaller UAV bodies and nonlifting surfaces. Inputs were compiled from interviews with three companies in the IPS and/or icephobics industry. Four individuals were interviewed.

3.3.8.1 Interview Themes

- NASA is somewhat uniquely positioned to validate computational models in the IRT.
- The current drive is toward low-adhesion and/or low-power technologies.
- There is a need for improved icing physics models for rotating hardware.
- Many in industry are (still) working on durability of low-adhesion coatings or materials.

3.3.8.2 Specific Icing Needs

- Validated, industry-accepted, analysis tools are needed for
  - Particle behavior, including trajectory, impingement, SLD splash, and ice crystal bounce/breakup/stick
  - Improved 3D ice accretion
  - Ice shedding prediction, from overcoming the adhesion force (e.g., melt) to ice chunk trajectory (downstream impact)
  - Propeller icing (plus engine lip, wing, and other areas as well), including formation, runback, and performance in all icing conditions, especially freezing fractions near zero
  - Improved conjugate heat transfer models
  - Improved ice roughness models
  - Thermal scaling at altitude
- An experimental facility is needed to test
  - Rotating equipment
  - Accretion and shedding characteristics on composite materials
  - Ice adhesion

3.3.9 Icing Weather Stakeholders

Three interviews were performed; the 11 individuals interviewed included representatives from NASA’s Earth Science Division (Science Mission Directorate) and representatives from multiple National Oceanic and Atmospheric Administration (NOAA) and regulator areas. No interviews were conducted with commercial weather information providers. The need for better icing weather information tools was a primary concern for icing weather stakeholders, who also cited certification and implementation needs.

3.3.9.1 Interview Themes

- Icing weather information tools (diagnostic, nowcast/forecast) are used by aviation forecasters, dispatchers, and pilots to strategically plan where and when (or when not) to fly to minimize hazards of icing.
  - Currently, icing weather tools are good, but stakeholders require improvements to address terminal area and in-flight icing operations for current and emerging aircraft (AAM), whether

they are certified for all icing envelopes (Apps. C, O, and D) or portions thereof, or not certified for flight in icing conditions.
    - Weather information tools also inform airport operations for ground deice operations and snow removal. These tools need to be operationally available and validated.
- Development of icing weather tools includes merging new algorithms applied to observational data (satellite, radar, soundings, surface observations) and new high-resolution weather prediction models.
    - Validation of these tools is necessary prior to making them available for operational use. This process relies on the capabilities at NASA, FAA, National Center for Atmospheric Research (NCAR), NOAA, and others.
    - NASA's Earth Science Division satellite researchers develop new algorithms and work with organizations such as NCAR to help transfer these algorithms into operational tools available to the public through NOAA's Aviation Weather Center.
    - NASA's Icing Branch was often a provider of in situ icing validation data. Together these organizations were able to develop current icing weather tool capabilities.
- Due to new icing certification requirements, operations in SLD conditions will be varied based on the certification process.
    - High spatial and temporal resolution icing weather tools are needed to identify areas and altitudes and discern various forms of SLD (FZDZ: $100 < D_{max} < 500$ μm, FZRA: $D_{max} > 500$ μm).
    - Aircraft that meet only part of the current certification standards may not be approved for takeoff or landing in areas where icing conditions exceed the approved certification level. This will cause undesirable delays for the flying public and the operators.
- Most airplanes in the current fleet have not demonstrated a capability to fly in ice crystal conditions defined by Part 33, App. D. Engine power loss, engine damage, and air data anomalies may occur. FAA management has not received much push from industry for ICI weather tools. However, one major aircraft manufacturer has developed an ICI planning tool and provided it to operators who use the manufacturer's airplanes.
- Stakeholders noted the following certification and implementation issues:
    - Icing weather tools facilitate certification flight test planning and execution. Utilizing such tools reduces the amount of flight testing needed for certification.
    - The maturation process of research-based icing products to operational icing products takes time and resources and requires validation data sets. NASA's icing flight research has been essential to this process in the past and can continue to be so in the future.

3.3.9.2 Specific Icing Needs

- Streamlining the process to develop, test, and transfer research-grade icing weather products into operational tools available to the aviation industry.
- Continued advancements in observational tools (satellites, ground-based radar, automated surface observing systems, etc.), numerical weather prediction models, and high-speed computing.
- Acquisition and distribution of in situ icing cloud atmospheric conditions that are globally and nationally representative for icing weather product validation. This includes ICI and supercooled liquid icing en route on a course-scale resolution, but high temporal and spatial resolution in the terminal area (30 NM radius and up to 12,000 ft) and along low-altitude airways used by AAM systems and vehicles.

3.3.10 Aviation Regulatory Authorities

Interviews included representatives from five FAA areas: Transport Airplane Directorate (large aircraft), Technical Center, Small Airplane Directorate, Aircraft Icing, and Aviation Weather Research Program. The four interview sessions involved a total of eight interviewees.

3.3.10.1 Interview Themes

- Reliance on NASA for engineering tools, research capabilities, and technical expertise:
    - FAA strives to maintain a high level of safety, but with reduced regulatory conservatism and cost. There is currently conservatism built into the regulations because we do not have a sufficient understanding of certain aspects of the underlying basic physics. More and better understanding of these aspects could allow for some reduction in conservatism, which would make it possible to maintain equivalent or higher levels of safety with more efficient and less expensive certifications.
        - Basic physics research is specifically needed for ICI and SLD analysis tools. Manufacturers are currently relying heavily on similarity, but this will only move the industry to a certain level, relying on substantial conservatism. New and innovative designs for airframes and engines will require improved analysis tools.
    - FAA needs NASA icing research tools such as the IRT, PSL, and LEWICE, along with the expertise to use the tools properly. Some companies and other organizations do not have these capabilities, and FAA must evaluate tools and how they may be used.
    - Without NASA, FAA would have to find new partners or build its own capabilities. This would have to be built up over time by recruiting and developing SMEs and identifying capable icing facilities.
    - It could be very detrimental to U.S. industry if NASA were to scale back or cease doing icing research. The United States is still a leader in this area, and NASA could take a lead role with respect to AAM. Other countries and political systems, such as the European Union, are investing significant funds to push forward the state of current knowledge in icing technologies.
    - There is a need to update and improve weather forecasting/nowcasting models, particularly for terminal areas and for ICI conditions. However, FAA needs high-quality data to do this and has often relied upon NASA as a partner for technical support.
    - FAA is also trying to assess the weather and icing environments for AAM platforms, such as low-altitude and urban environments.
- Certification issues:
    - FAA has a mandate from Congress to incorporate AAM into the national airspace, especially for tasks such as package delivery. A big need for AAM is accurate icing detection and the ability to survive an inadvertent encounter and safely exit.
    - FAA would like improved computational analysis capability for icing in areas such as radomes. It is important to know how much ice builds up and could potentially shed and be ingested by engines downstream. FAA would also like to see more validation for ice crystal concentration factors for locating air data probes.
    - FAA would like computational analysis capability for icing of cooling inlets of electric engines. Practically all new AAM vehicles are electrically powered, and blockage of cooling inlets by ice or snow needs to be addressed even if the vehicle is not certified for icing. Cooling inlets of these vehicles are being located on or aft of 3D shapes and are influenced by rotor and propeller wash.
    - New AAM vehicles are currently entering the certification process. The short-term requirement is to certify for an inadvertent encounter in icing. Eventually, there will be a need to certify vehicles

for flight into known icing. There is no good national asset for full-scale rotor icing ground testing. Documenting ice shed into downstream components is also challenging.

- Current and future FAA research:
    - Ground icing research funding remains fairly robust and enjoys reasonable support.
    - Much FAA icing research has supported the development of MOC tools and guidance materials. Recently, however, there has been increased emphasis on innovation and innovative concepts. Research on ice prediction tools and icing facilities reflects both, as the tools and facilities are innovative and can be useful to industry in showing compliance.

3.3.10.2 Specific Icing Needs

- Ability to model ice accretion on cooling inlets of electric engines
- Improvements in analysis tools for warmer temperature runback conditions
- Ability to model ice shedding for rotating blades and multiple-rotor systems
- General icing analysis for rotating wings and propellers
- Development of ice prediction tools (or modification of existing ones) for ice prediction on AAM vehicles
- Development of icing facilities (or modification of existing ones) for testing AAM vehicles

3.3.11 Department of Defense and Supplier

Two interviews were held, one with DoD personnel and one with a military supplier; six individuals were interviewed.

3.3.11.1 Interview Themes

- There is a need for lower power, size, and weight IPSs. Lower power is the primary need, but size and weight are also concerns, particularly for AAM vehicles and rotorcraft. Other IPS considerations include icephobics and the ability to evaluate such materials quantitatively. Also, IPSs that will not interfere with radar signals are needed.
- There is a need for an in-house icing analysis capability. Currently, several DoD entities rely on NASA's icing expertise in modeling, testing, and scaling. There is a push for DoD organizations to be lead systems integrators, which would require developing an in-house icing modeling capability and associated design tools. This would reduce reliance on the OEMs for data and allow for better understanding of a vehicle's icing capability. More than one interviewee stressed the need for SLD evaluation tools in particular.
- Interviewees discussed icing qualification and certification testing needs, including the importance of access to facilities such as the IRT, the Helicopter Icing Spray System (HISS), and icing facilities available at the McKinley Climatic Laboratory and the Arnold Engineering Development Complex. The DoD uses NASA's IRT heavily and considers it "immensely valuable," and they noted a need for a lower cost SLD testing facility. A challenge with existing facilities is the ability to produce all the desired test conditions, which are not always available.

3.3.11.2 Specific Icing Needs

- Lower power, size, and weight IPSs
- IPSs that will not interfere with radar signals
- Icing analysis capabilities
- Access to icing facilities

- Lower cost SLD facilities

3.3.12 Supersonic Transport: Industry

Commercial supersonic transport efforts are currently being examined by this industry. The focus of their work is on sonic boom reduction and aircraft performance characteristics.

One interview was performed with three commercial airframe industry representatives.

3.3.12.1 Interview Themes

- Design issues:
  - There are design tradeoffs between high-speed and low-speed performance.
  - Anything that impacts this tradeoff is critical.
  - Thin wings and tailored shapes are important.
  - Design for takeoff and landing could be impacted by icing concerns.
  - IPSs were included in Concorde.
  - Cruise may be at altitudes and speeds where icing is not a concern.
- Certification issues:
  - No aircraft has been certified under current rules in Apps. C, D, or O; there is no opportunity for a "similarity to existing designs" rationale.
  - They are more concerned with noise certification currently.
  - No validation data is available for simulation tools.
  - There is no experience with testing in icing facilities for airframes or engines.

3.3.12.2 Specific Icing Need

- A computational study to determine the potential impact on vehicle performance and handling and stability would be useful.

3.3.13 NASA: Commercial Supersonic Technology (CST) Project

The CST project focuses on sonic boom reduction methods and approaches. The project's scope includes design tools for vehicles with low sonic boom and defines the necessary approaches and techniques for objectively assessing the levels of sonic boom acceptable to communities living in the vicinity of future commercial supersonic flight paths. Knowledge and data from this work will inform the efforts of both national and international regulatory organizations in the development of design standards for future supersonic commercial aircraft (Ref. 104).

Interviewees included two NASA CST project managers.

3.3.13.1 Interview Themes

- The NASA CST project focus is on sonic boom and noise.
  - Icing has not been considered, as no commercial vehicle is planned in the near term.
  - One company is planning a supersonic business jet to be available in 2026; another has no plans for the immediate future—more likely 2030s.
  - Collaborative work is driven toward a demonstrator.
  - Aircraft performance technical challenges are for the future.
- Certification issues:
  - No aircraft has been certified under current rules in Apps. C, D, or O; there is no opportunity for a "similarity to existing designs" rationale.
  - They are more concerned with noise certification currently.

3.3.13.2 Specific Icing Needs

- None identified at this time due to focus on sonic boom and noise reduction

3.3.14 NASA: Advanced Air Transport Technology (AATT) Project

Formal interviews were not performed in this segment, but the AoA study sought feedback from NASA SMEs involved with the AATT project and considered current AATT research in developing relevant AoA study inputs.

NASA's vision for advanced fixed-wing transport aircraft is revolutionary energy efficiency and environmental compatibility. AATT's overarching goal is to explore and develop technologies and concepts to enable this vision (Ref. 105). The knowledge gained from AATT research—in the form of experiments, data, system studies, and analyses—is critical for conceiving and designing cleaner, quieter, and more efficient aircraft. AATT studies are focused on the future, with an eye toward vehicles that are beyond the current state of the art that require mature technology solutions in the 2035 to 2045 timeframe.

Energy efficiency and environmental compatibility cannot come at the expense of aircraft safety. The impact of flight in icing and the ice protection requirements associated with safe flight must be evaluated during the concept and design phases to assess impact on the project goals. Certification for flight in icing is covered in 14 CFR Parts 23, 25, and 33. A description of the conditions for which certification is expected can be found in App. C of Part 25. The additions of Apps. D and O in 14 CFR Part 25 (and, to a lesser extent, Amendment 121) provide difficulty for the industry adoption and commercialization of revolutionary vehicle and engine designs. This difficulty originates from the prohibitive expense of direct compliance, primarily due to the lack of mature experimental facilities and computational analysis tools that are capable of addressing these regimes. Advances in icing-related technologies to enable direct compliance (and, by extension, industry adoption and commercialization) are necessary for AATT's vision to come to fruition.

Inputs identified for this segment centered around two primary areas with regard to icing: (1) power and propulsion (engine icing) and (2) vehicle systems integration (TTBW).

3.3.14.1 Power and Propulsion (Engine Icing)

- Challenge: Engine technology development is focused on the next entry-into-service engine with a small thermally efficient core. The technologies needed to achieve performance requirements may increase the threat of icing. Additionally, there is uncertainty as to how these new engine architectures will meet the certification requirements.
- AATT approach: Provide design and certification risk reduction on small cores. Develop a methodology for assessment of icing impact on advanced engine designs utilizing existing tools and advancing the capabilities of full 3D simulations. The objective is to provide engine designers with the ability to include the effects of icing contamination earlier in the design process and to reduce the testing needs during the certification process. This will lead to less conservative designs and reduce the cost of design and certification for icing.

3.3.14.1.1 Specific Icing Needs

- COMDES-MELT, a mean-line compressor analysis code coupled with an ice crystal thermodynamic state code, is a current low-fidelity tool that can be used for a parametric assessment of potential icing risk and evaluation of high-power-density core configuration. COMDES-MELT enables researchers and designers to determine what engine operating conditions can lead to ice growth given an input set of ICI conditions. This tool has been developed recently and is being upgraded to be a part of the Multidisciplinary Design Analysis and Optimization framework.

- GlennICE development for determination of ICI impact on high-power-density core operations as well as development of other accurate 3D engine icing simulation software. This software will be able to determine the location and amounts of ice growth in engine compressor flow path including rotors, stators, guide vanes, and casing. This tool is in the early stages of development and requires some fundamental icing physics research to develop accurate models of the ice crystal ice growth process. There is a need to implement the ice crystal and internal flow physics to assess the icing impact in an engine.
- Engine icing database: Currently, there is limited quantitative data on ICI available in the public domain. As such, there is an ongoing need for ICI experiments to develop physical models and validation data for GlennICE.

3.3.14.2 Vehicle Systems Integration: TTBW

- Challenge: The TTBW configuration has features that have not been extensively studied for impact of flight in icing conditions. As such, there is a lower level of validation in icing prediction capability, which will lead to conservatism in icing certification. Lack of similarity to previous designs for vehicles of this class will require greater dependence on simulation tools to enable certification with minimal reliance on flight testing.
- AATT approach: Provide certification risk reduction on TTBW. Provide a validated capability to determine the impact of ice accumulation on the TTBW aircraft. This capability will enable manufacturers to incorporate the effects of icing into the vehicle design with a higher degree of confidence, thus reducing conservatism while maintaining safe operation in an icing encounter. Augment this capability with development of potential materials that are both durable and icephobic, which could mitigate the impact of ice contamination on aircraft performance.

3.3.14.2.1 Specific Icing Needs

- Ice accretion prediction and validation database: A database of ice accretion shapes relevant to the TTBW aircraft, and a well-validated ice accretion simulation capability, both experimental and computational. Determination of critical ice accretion potential relevant to the TTBW aircraft.
- Impact of ice accretion on TTBW performance: Identification of the potential performance changes that can occur for the TTBW resulting from an icing encounter.
- Development of icephobic materials for mitigation: A durable ice adhesion coating that can potentially lead to reduced ice adhesion strength on nonheated surfaces and thus a reduction of the power consumption of existing deicing/anti-icing systems.

3.3.15 NASA: Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office

AETC manages, maintains, and advances the capabilities of 12 NASA wind tunnels and test facilities. Its customers include NASA missions (ARMD, Human Exploration and Operations Mission Directorate (HEOMD), SMD, and Space Technology Mission Directorate (STMD)), the U.S. Government, industry, and academia. AETC’s primary goal is to meet NASA’s test capability requirements in a timely and cost-effective manner. AETC responds to NASA’s programmatic requirements and customer feedback to define the test capability requirements and implement them through capability challenges (Ref. 106).

Two AETC representatives were interviewed.

3.3.15.1 Interview Themes

- AETC's budget is a flat $117M. This covers 500+ people (operations), facility maintenance, and capability improvements. Increasing operations costs effectively reduce the available budget by $4M/year.
- AETC places a high priority on making smart investments that reduce costs and increase return on investments.
- AETC completed a capability challenge for engine icing in 2019, and currently there are no active icing capability challenges in the AETC portfolio. Consequently, large AETC investments in icing are difficult to justify at this time.

3.3.15.2 Specific Icing Needs

- Continue to develop and validate CFD tools that model the IRT, ice accretion prediction, shedding, thermal scaling, and aeroperformance in order to reduce icing facility (IRT and PSL) test durations. As a result, there would be reduced testing costs for a given test project and more availability of the facilities for other test projects.
- Maintain the IRT and PSL icing capabilities because they are needed to support both NASA needs and to provide these one-of-a-kind test services to the Nation.

3.3.16 NASA: Electrified Aircraft Propulsion (EAP)

NASA is investing in EAP to improve the fuel efficiency, emissions, and noise levels in a variety of aircraft ranging from smaller AAM concepts to larger commercial transport aircraft. The goal is to show that viable EAP concepts exist and to advance crucial technologies related to those concepts. NASA's EAP work is performed under several different projects, including AATT's Hybrid Gas-Electric Propulsion subproject, the NASA X–57 aircraft, RVLT, and Convergent Aeronautics Solutions (CAS) (Refs. 107 and 108).

One interview was performed with a SME from NASA's EAP area.

3.3.16.1 Interview Themes

- The NASA Advanced Air Vehicles Program (AAVP) is shifting away from research and development (R&D) to technology maturation, particularly to enable the next generation of subsonic transports. Some of the lower TRL elements associated with R&D efforts, especially those cutting across several ARMD areas, could be transitioned to the Transformative Aeronautics Concepts Program (TACP).
- EAP technical activities exist across several NASA projects and are coordinated by one person. A similar individual for icing does not exist. Rather, each NASA project has a different individual coordinating the icing technical content for that specific project.
- The interviewee thinks of aircraft as "small planes, big planes, and air taxis." The Electric Powertrain Flight Demonstration project focuses on large planes with the overall objective to demonstrate a 1-MW or greater system. The CAS project works on lower TRL activities. For example, an activity under CAS characterized the requirements of a thermal IPS for three electric aircraft concepts (Ref. 109). Finally, the RVLT project and AAM Mission Integration Office focus on air taxis.

3.3.16.2 Specific Icing Needs

- New aircraft configurations (electric or otherwise) may pose new icing issues; these will need evaluation.
- IPSs for EAP will focus less on bleed air and more on electrical power. As such, there is a need to understand the impact of IPSs on electrical systems for electric aircraft.

3.3.17 NASA: Hybrid Thermally Efficient Core (HyTEC) Project

The AAVP HyTEC project seeks to accelerate the development of small turbofan engine core technologies, culminating in an advanced core demonstration in the 2026 timeframe. The goal is to demonstrate increased thermal efficiency with integrated high-power-density core engine technologies, achieving a fuel burn benefit of 5 to 10 percent (versus 2020 best in class) for early 2030s entry-into-service single-aisle aircraft (Ref. 110).

The AoA team did not conduct a formal interview for HyTEC, but a HyTEC Request for Information from September 2020 revealed the following projected icing challenges:

- Compressor operability and performance impacts due to anti-ice bleed requirements
- FOD and shedding concerns for both ice crystal and supercooled icing

3.3.17.1 Specific Icing Needs

- No specific icing needs were identified at this time due to project priorities.

3.3.18 NASA: Revolutionary Vertical Lift Technology (RVLT) Project

NASA's RVLT project is working with partners in Government, industry, and academia to develop critical technologies that enable revolutionary new air travel options, especially those associated with AAM, such as large cargo-carrying vehicles and passenger-carrying air taxis (Ref. 111).

Formal interviews were not performed, but NASA SMEs confirmed that icing needs for RVLT are consistent with the rotorcraft, eVTOL, and AAM industry needs discussed in Section 3.3.4.

3.3.19 NASA: Transformational Tools and Technologies (TTT)

NASA's TTT project develops state-of-the-art computational and experimental tools and technologies that are vital to ARMD's ability to advance the prediction of future aircraft performance in flight, such as first-of-a-kind tools that isolate the complex turbulent airflow around vehicles and within propulsion systems. TTT creates computer-based tools, models, and associated scientific knowledge that can be applied to the entire ARMD portfolio (Ref. 112). A technical challenge of TTT's Revolutionary Computational Aeroscience (RCA) research area is the ability to computationally predict maximum lift coefficient $C_{L,\max}$ and the angle of attack at which $C_{L,\max}$ occurs.

Formal interviews were not performed, but specific icing needs were identified from existing project documentation for TTT projects and from SME inputs.

3.3.19.1 Specific Icing Needs

- Benchmarking current capabilities, identifying any deficiencies, and implementing necessary improvements in both the computational prediction of the ice accretion and the subsequent computational prediction of $C_{L,\max}$ due to the presence of the ice accretion are required for
  - The analysis of current vehicle technologies subject to recent icing regulations
  - The analysis of next-generation vehicle technologies subject to all icing regulations

- An existing NASA/Boeing collaboration centered around the Common Research Model (CRM) has an icing-related focus of benchmarking the ability of RCA-based tools to predict $C_{L,\max}$ for icing regimes with limited existing public data, such as full-flight Reynolds number and high-lift configurations.

3.3.20 NASA: Icephobics

While icephobics was not designated as a specific interview focus, it emerged as a topic of discussion in 15 interviews, including those with industry, academia, NASA, and the DoD. Emerging themes fell into three general categories: need, hindrances to development, and NASA's role.

- Icephobics are needed as enabling technology for optimal IPS operation on AAM vehicles.
  - Potential to allow a vehicle to exit an icing environment and buy time to land safely
  - Reduced power and weight via a hybrid IPS that combines icephobics and traditional IPSs
- Development of an icephobic coating is hindered by
  - Durability to the vehicle operational environment—a major issue
  - Need for additional simulated impact icing testing under various environmental conditions at different facilities
  - Complicated physics and material interactions
  - Amenability to incorporation into aircraft maintenance and painting schedules
- NASA's role should be
  - Performing research by doing more unmanned-system-type application research, such as icephobics and nanomaterials for efficient IPS
  - Establishing and standardizing test metrics
  - Flight demonstrations
  - Roadmap development
  - Incorporating icephobics into composite fabrication

3.3.20.1 Specific Icing Needs

- A well-defined method for evaluating ice adhesion characteristics
- A durable icephobic material suitable for use on aircraft

3.3.21 Academia

Ten individuals from ten different universities were interviewed between Oct. 19 and Nov. 11, 2020, with four NASA researchers joining contractor Mike Bragg (Bragg and Associates) on various calls. General interview questions are provided here, followed by a summary of interview themes and specific feedback on the NASA–university relationship.

3.3.21.1 Interview Questions

1. Context questions. (Goal: to understand what needs are driving the university's research and education programs and what the future may hold)
   a. How does NASA icing research contribute to your educational mission? How should it?
   b. How does NASA icing research contribute to your research mission? How should it?
   c. What do you forecast is the future of university education and research? What are the challenges and opportunities?
   d. How is workforce development impacted without NASA icing research?

2. Technical needs and barriers
    a. When it comes to icing, what are some of the major research needs?
    b. What are barriers/technical challenges to addressing these?
    c. How do these fit the university environment?
3. NASA's role. (Goal: to understand interviewee's view on how NASA can address the icing barriers and technical needs)
    a. What is your view of NASA and its overall mission?
    b. What is NASA's role in icing? Or what should NASA's role be?
    c. Could NASA address any of the previously mentioned needs/barriers? If so, what role should universities play?
    d. How could NASA better engage universities? (Note NASA Research Announcement (NRA) process, fellowships, etc.)

3.3.21.2 Interview Themes

- Fundamental physics of ice accretion is a primary concern. Ice accretion and aerodynamics are extremely complex, and the lack of sufficiently detailed and accurate physics-based models hampers the community's ability to design, analyze, certify, and operate vehicles efficiently and safely. Research and tool development is needed in several areas:
    - Icephobics have great potential but need physics models that include impact, adhesion, erosion, basic physics, and surface chemistry.
    - Better high-altitude particle physics models are needed for engine and aircraft applications.
    - Better nonintrusive measurement techniques for ice accretion physics studies are needed.
    - Improved modeling of heat transfer, mass balance, film dynamics, and water shedding is especially needed.
    - SLD ice accretion physics modeling is still early in its development and better models are needed for droplet breakup and splashing.
    - CFD for aerodynamics is making progress but needs better physics-based turbulence models, 3D high-angle-of-attack separation modeling, and modeling of roughness effects and other complex geometry.
    - Better physics-based models of electrothermal/expulsive IPSs and residual/intercycle ice formation are needed.
- Icing analysis and protection is needed for new aircraft configurations. New vehicles present new icing challenges that old solutions are inadequate to address. Research and tool development is needed in several areas:
    - A main driver is AAM, which will demand all-weather capability.
    - Future supersonic cruise commercial aircraft may also have some challenging requirements.
    - Low-power ice protection is critical. Need to think out of the box. Current methods will not work.
    - Rapid information flow for ice avoidance will be needed and will include more data mining and data analysis.
    - Electric aircraft generate heat production, which provides an opportunity for integration into IPSs.
    - Autonomy drives a need for configuration-level and stability-and-control research.
- Improved icing computational and experimental tools for research, design, and certification are needed:
    - Companies need to drive NASA to do this research. Industry wants and needs better simulation capability with tools that are fast and robust, both physics-based and empirical.

  - Icing is a multiscale and multiphysics phenomenon; NASA needs to help integrate new methods and models into CFD.
  - Neural networks and multidisciplinary design and optimization are tools that offer to improve simulation.
  - Both 2D and 3D tools are needed.
  - Runback icing modeling and modeling to support certification are needed.
  - CFD for icing aerodynamics needs better modeling of ice shapes at high angle of attack, surface roughness, and complex aircraft geometry.
  - State-of-the-art icing facilities are needed. The IRT is a national resource critical to industry. The IRT currently has excellent research and support staff and must maintain this staffing to continue to have a world-class facility.
- The role of NASA in supporting the FAA certification and safety mission is very important. Some key points made:
  - An important goal is to reduce or eliminate FAA certification flight testing. NASA should support FAA with tools and methods to accomplish this.
  - NASA is needed to develop icing analysis tools for industry and the icing community.
  - There are serious environmental concerns that do not attract as much research as needed. For example, new solutions are needed to eliminate airport runoff of deicing fluids.

3.3.21.3 NASA–University Relationship

- NASA has a unique and important role in aircraft icing research and well beyond. Faculty expressed these thoughts:
  - NASA Icing has a responsibility to support industry and maintain U.S. leadership.
  - NASA has an important role in workforce development, especially with students at the B.S. through Ph.D. level.
  - An important role is developing and supporting roadmaps to tackle hard challenges in icing. NASA needs to identify and support icing research that is needed and provide generally accepted and validated methods and simulation tools. Long-term roadmaps and sustained, predictable funding are important.
  - NASA research is important for national and international aviation policy.
- Faculty shared the following feedback regarding universities' role and expertise:
  - Successful faculty build strong and long-term funded research programs that produce outstanding M.S. and Ph.D. graduates to help maintain U.S. leadership in aircraft icing.
  - Universities are the source of next-generation icing personnel, so adequate attention needs to be paid to workforce development, including adding this to the roadmaps.
  - Universities are best suited to address fundamental problems where they have expertise and provide innovative solutions.
  - Ice accretion code development is an opportunity—especially if it is open-source and includes multiple investigators.
  - Novel testing capabilities are a university strength.
- Feedback on NASA–university relationship opportunities included the following:
  - Partnering around new ideas, innovation, and students is most productive.
  - NASA funding is currently unreliable after moving to NRAs. Universities need relationships that are less deliverable focused and more partnership based.

    - A more ideal NASA–university relationship structure should include different grant types at different TRL levels:
        - Deliverable focused: NRA, at higher TRL
        - Team-based new idea: University Leadership Initiative, low- to mid-TRL
        - Very innovative: single principal investigator (PI) plus student(s), low TRL, funded and managed at the branch level
    - The current grant deliverable-based process limits focus on basic physics and modeling.
    - The Icing Branch needs a way to fund some research in a discretionary way.
    - NASA should actively seek to pair new PIs with more experienced icing PIs.
    - NASA should develop research roadmaps with long-term (5- to 10-year) sustainable funding.

3.4 Summary of Themes

A high-level summary of interview themes is provided here.

- When asked to describe NASA's role in icing, participants noted that NASA
    - Maintains expertise in foundational icing science
    - Provides public domain basic research
    - Provides needed icing facilities, such as the IRT and PSL
        - All of the engine manufacturer interviewees saw the PSL as a critical path for any new engine certification.
    - Is a neutral party to which industry and regulators reach out for assistance
    - Provides experimental and computational tools
    - Is the Nation's "memory" for icing research
- Many discussions centered on icing with regard to vehicle and engine design.
    - Icing issues alter the operational capabilities of the vehicle.
    - Icing must be considered during the conceptual phase of the vehicle and engine.
    - The objective for icing tests is for success on the first attempt, so proper design, analysis, and test preparation are critical.
- Certification issues were a significant concern for many interviewees.
    - New requirements will have large impacts on vehicle design, cost, and certification.
- Icing tools (codes and facilities) are widely used and will continue to be used.
- The need for icephobic coatings and surface treatments will become more important in the future.
- New concepts have complex aeropropulsive geometries for which icing impacts are not well understood.
- Ice detectors will need to distinguish between various types of weather conditions.

4.0 Analysis and Evaluation of Icing Research Priority Needs

The analysis and evaluation of icing research priority needs was conducted using methods similar to those established for the previously completed Materials, Structures and Manufacturing AoA study (unpublished). The result of the process was a numerical ranking of icing research technical elements that formed the basis of the recommendations of this study. There were six key steps:

1. Identification of icing research technical elements
2. Identification of the evaluation criteria for each element

3. Identification of data filters
4. Identification of future realities and weights
5. SME ratings
6. TOPSIS analysis

The process started with the development of a list of technical elements, ranking criteria, and data filters. Individual SMEs then rated each element against each criterion. The ratings of all SMEs were combined and used as inputs to the TOPSIS analysis, which generated a priority ranking of the elements. Additional steps included the identification of different future realities, which changed the weightings of certain criteria, and the reconciliation of individual SME inputs. Each step is described in more detail in the following subsections.

4.1 Identification of Technical Elements

Technical elements associated with priority research needs were identified directly from the interview summaries described in Section 3.0. Lists of important technical elements were then developed from the interview segments. The technical elements came primarily from industry and Government agency stakeholders and from specific NASA project needs. The academic segment provided more fundamental needs that were rolled up into the higher level technical elements. These lists of technical elements were then combined and organized into several categories. Initially, there were five categories and 36 technical elements. The original list included items such as certain icing experimental facilities and computer codes because these were repeatedly identified as common priority needs of the icing stakeholder community. After discussions with project leadership, however, a decision was made to focus the technical elements on icing technologies, inclusive of the physical understanding, modeling capabilities, and experimental capabilities. The resulting technical elements contained midlevel work efforts. Detailed, low-level work, such as physics studies on droplet splashing on wet surfaces, ice particle breakup on fan blades, or development of specialized temperature probes, was omitted to keep the information manageable. The original list was combined into 23 elements within four categories. The technical elements in each of these four categories are defined in Table I as follows:

1. Icing performance impact, Table I(a)
2. Ice accretion geometry definition, Table I(b)
3. Ice protection and detection systems, Table I(c)
4. Icing weather and characterization, Table I(d)

The four selected categories grouped the technical elements at a high level, not necessarily with equivalent work packages. The definitions in Table I were provided to the team to clarify the meaning of each element.

TABLE I.—TECHNICAL ELEMENTS

(a) Icing Performance Impact

Element no.	Technical element	Definition
1	Airframe performance prediction	Prediction of airframe performance impact during icing encounters
2	Engine performance prediction	Prediction of engine performance impact in icing encounters
3	Rotor/propeller performance prediction	Prediction of rotary wing and propeller performance impact in icing encounters

(b) Ice Accretion Geometry

Element no.	Technical element	Definition
4	Ice shedding	Failure of adhesive/cohesive bonds of ice, limiting its size and resulting in ballistic threats to other airframe and propulsion components
5	3D ice accretion—standard icing	All ice accretion on fixed-wing components in App. C icing conditions
6	3D ice accretion—ice crystals	All ice accretion in App. D icing conditions, primarily in engines
7	3D ice accretion—freezing drizzle/rain	All ice accretion on fixed-wing components in App. O icing conditions
8	3D ice accretion on rotating systems	All ice accretion on rotors (propellers, helicopter rotors, and engines) in all icing conditions
9	Thermal ice protection system (IPS)	Ice accretions resulting from resistive (electrical) or hot air (bleed air) system used to melt ice off of aircraft components
10	Mechanical IPS	Ice accretions resulting from IPS mechanically breaking ice–substrate bond (e.g., pneumatic boots and electro-expulsive)
11	Altitude scaling for thermal IPS	Ice accretions resulting from methods used to determine the appropriate test conditions in an icing wind tunnel accounting for possible altitude pressure effect on the performance of thermal IPS in various icing conditions
12	Icing condition scaling	Ice accretions resulting from methods used to determine the equivalent icing conditions available in an icing wind tunnel to generate the similar ice shapes that would be formed at flight-level conditions and full-scale geometries
13	Altitude scaling for ice crystal icing (ICI)	Ice accretions resulting from methods used to determine the appropriate test conditions to duplicate a desired ice crystal engine icing phenomenon at lower altitudes in a ground-based engine test facility

(c) Ice Protection and Detection Systems

Element no.	Technical element	Definition
14	Water/ice particle concentration factors	Determination of water or ice particle off-body concentrations for air data probe mounting location and ice protection design studies
15	Icephobics	Protective coatings that reduce bonding energy of ice or delay onset of icing
16	Low-weight and low-power IPS	Thermal or mechanical IPS suitable for use on small or high-efficiency aircraft
17	Low-radar IPS	IPS for wing and fuselage that is transparent for radar transmissions (Department of Defense applications)
18	Ice detectors	Onboard detectors that sense icing conditions in aircraft's immediate environment and alert flight crew
19	Onboard remote sensing	Remotely detects icing conditions at distances that enable flight crew to avoid or reduce icing exposure

TABLE I.—Concluded.

(d) Icing Weather and Characterization

Element no.	Technical element	Definition
20	Terminal area characterization	Collection of icing data via flight-, ground-, and space-based instruments in the terminal area (30-NM radius; up to 12,000 ft) to support validation of high-resolution icing weather tools
21	Urban area characterization	Collection of icing data via flight-, ground-, and space-based instruments along low-altitude airways used by AAM vehicles to support validation of high-resolution icing weather tools and determine if unique icing certification envelopes are needed
22	High-altitude ice crystal characterization	Collection of icing data via flight-, ground- and space-based instruments in high-altitude conditions to support validation of ICI weather tools and experimental facilities and to establish global applicability of App. D
23	Small-scale weather forecast/nowcast	Icing weather tools used by forecasters, dispatchers, pilots for flight planning to minimize risks of icing where needed due to small spatial and temporal scales

4.2 Identification of Evaluation Criteria

Having identified the icing technical elements to be ranked in the analysis, the next step was to identify the evaluation criteria for each element. A total of 21 criteria were used and were grouped into six categories as shown in Table II. Also shown in the table are the ranking scales that were used for each criterion. For all of the criteria, the individual SMEs based their ratings upon the information obtained from the stakeholder interviews along with SME knowledge and participation in community working groups, standards bodies, and other professional organizations.

The first two categories apply to the icing-related industry stakeholders and were split between OEMs and suppliers for clarity. The individual SMEs were instructed to input a “pull” rating in the form of a numerical score ranging from 0 to 5 for each technical element described in Section 4.1. NASA ARMD research priorities were included in the pull criteria as shown in Table II. Individual SMEs input their ratings based upon knowledge of current research plans in each of the Fab 4 areas described in the introduction (Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion (EAP), Small-Core Turbine Engine, and High-Rate Composite Manufacturing) as well as within the RVLT project. The project ratings were not intended to capture any perceived pull but were limited to current project plans. As such, criteria such as EAP and High-Rate Composite Manufacturing pulls had ratings of 0 pull or No pull for all icing technical elements.

Other Government research priorities were included for the DoD and the FAA as shown in Table II.

The next set of criteria were labeled “Safety and Certification” to capture the criteria listed in Table II. These criteria all had the same rating scale in terms of the benefit applied to each technical element. SMEs rated the Safety Improvement that could be achieved from conducting work in each technical element. For example, improved forecasting/nowcasting capabilities for FZDZ and FZRA conditions could result in a significant safety benefit. The Conservatism Reduction criterion referred to work in the technical elements toward satisfying certification requirements or improving performance and/or efficiency. For example, significant advancement in the ice shedding technical element may lead to reduced conservatism along with associated gains in performance and efficiency. Certifiability Improvement accounted for benefits to the certification process. For example, a validated 3D icing simulation capability for App. O conditions would establish a new MOC to meet certification requirements. Each of these three criteria was evaluated based upon the overall change for the aeronautics community. A large benefit to a small portion of the community and a small benefit to the whole community would thus each receive a score of 3—Moderate pull.

TABLE II.—EVALUATION CRITERIA AND RANKING SCALE

Category	Criterion	Ranking scale
Industry pull—Original equipment manufacturers	Airframe Industry	0 – No pull 1 – Low pull 2 – Moderately low pull 3 – Moderate pull 4 – Moderately strong pull 5 – Strong pull
	Engine Industry	
	Rotorcraft Industry	
	AAM Industry	
Industry pull—Suppliers	Instrumentation and Ice Detection	
	Ice Protection Systems and Materials	
	Remote Sensing Systems	
	Icing Analysis Software	
NASA project pull	Fab 4: Transonic Truss-Braced Wing	
	Fab 4: Small Core	
	Fab 4: Electrified Aircraft Propulsion	
	Fab 4: High-Rate Composite Manufacturing	
	Revolutionary Vertical Lift Technology Project	
Other Government pull	Department of Defense	
	Federal Aviation Administration/Regulator	
Safety and certification	Safety Improvement	Benefit = 0 – None; 1 – Low; 2 – Moderately Low; 3 – Moderate; 4 – Moderately Strong; 5 – Strong
	Conservatism Reduction	
	Certifiability Improvement	
Other	Disruptibility	0 – None; 1 – Low (small evolutionary step); 2 – Moderately Low; 3 – Moderate; 4 – Moderately Strong; 5 – Major (revolutionary advance)
	Technology Risk	Likelihood of Success = 1 – 99%; 2 – 90%; 3 – 80%; 4 – 50%; 5 – 20%
	NASA Involvement	1 – Research and development (R&D) activities will advance industry/academia at a sufficient pace without NASA 2 – R&D activities will need small NASA contributions of expertise or funding 3 – R&D activities will benefit from moderate NASA contributions of expertise or funding 4 – R&D activities will require significant NASA expertise and funding 5 – R&D activities will only advance with NASA expertise and funding

The Disruptibility criterion was used to capture the extent of future improvement associated with each technical element. Disruption is the extent to which future improvement was expected to change the overall aeronautics community, with a 5 being as large a shift as any icing technology could produce. For example, a perfect icephobic material could be rated a 5—Major disruption. Disruptibility is not relative to each technical element; for example, a 10-percent improvement in IPS efficiency would be huge for that area, but it would not be very disruptive to the overall industry—IPS would still take about the same amount of weight and power and require similar considerations, they would just be about 10 percent cheaper overall. This would not fundamentally change the way business is done, even though that is a huge improvement relative to that technical element. By comparison, a very good mechanical or thermal deicer (>50 percent increase in efficiency) may be more disruptive by comparison, allowing deicing on much smaller aircraft than is currently possible.

The Technology Risk criterion was used to capture the global measure of risk for the technical element's success. SMEs rated the likelihood of success for each technical element based upon current and historical levels of research investment. For this criterion, a value of 1 in the ranking scale implies the lowest risk.

The last criterion captured the level of NASA involvement required to advance the state of the art for each technical element. In some cases, NASA may have the only skillset or experimental capability to address certain elements, whereas other elements may be better addressed by other organizations.

4.3 Identification of Data Filters

In addition to the rating criteria described in Section 4.2, a set of data filters was also developed. In this context, a filter is a screening tool that can be used to isolate selected technical elements for analysis. As shown in Table III, a total of 40 filters were grouped into four categories. As with the evaluation criteria, knowledgeable SMEs were asked to answer each filter question based upon the information obtained from the stakeholder interviews along with the SMEs' knowledge and participation in community working groups, standards bodies, and other professional organizations.

The first category was Technology Readiness Level (TRL). SMEs were asked to assess the current TRL of each technical element along with the time required for the technical element to reach TRL 6.

The second category had a number of filters related to NASA ARMD. The first of these sought to determine the most appropriate role for ARMD for each of the technical elements. If more than one role seemed appropriate, the primary role was selected. The roles were defined as follows:

- Lead: NASA personnel and/or facilities are the leader in this area for the United States
- Leverage: NASA can leverage this element through areas like SBIR and NRA
- Collaborate: NASA can work with others to achieve this technical element (could be a coleader but not an exclusive leader)

The next series of ARMD filters asked if each technical element was included in current plans to address the Fab 4 or in other ARMD projects. The last series of ARMD filters asked if each technical element *should* be included in current plans to address the Fab 4 or in other ARMD projects.

The third category contained questions related to workforce readiness and strategic planning. In evaluating the resource investment required for each technical element, SMEs considered the resources needed to reach TRL 6, with the following guidelines:

- Low: Existing people and experimental capability
- Medium: (One of the following) One to two new people, existing IRT capability, or existing flight test capability
- High: (One or more of the following) More than two new people, existing PSL capability, and/or new experimental capability

TABLE III.—DATA FILTERS

Filter category	Filter	Response menu
Technology readiness level (TRL)	Current TRL	Low (TRL 1 to 2); Medium (TRL 3 to 4); or High (TRL 5 to 6)
	Time required to reach TRL 6	Near (2025 to 2030); Mid (2030 to 2035); Far (beyond 2035)
Aeronautics Research Mission Directorate (ARMD)	ARMD role	Lead; Leverage; Collaborate
	Is element in Fab 4 – Transonic Truss-Braced Wing (TTBW)?	Yes; No
	Is element in Fab 4 – Small Core?	
	Is element in Fab 4 – Electrified Aircraft Propulsion (EAP)?	
	Is element in Fab 4 – High-Rate Composite Manufacturing?	
	Is element in Revolutionary Vertical Lift Technology (RVLT)?	
	Is element in Aeroscience Evaluation and Test Capabilities (AETC)?	
	Is element in Commercial Supersonic Technology (CST)?	
	Should element be in Fab 4 – TTBW?	
	Should element be in Fab 4 – Small Core?	
	Should element be in Fab 4 – EAP?	
	Should element be in Fab 4 – High-Rate Composite Manufacturing?	
	Should element be in Fab 4 – RVLT?	
	Should element be in Fab 4 – AETC?	
	Should element be in Fab 4 – CST?	
Workforce, resources, and execution	In-house workforce readiness (level and skillset)	None; Marginal; Acceptable; Exceeds
	Resource investment required	Low; Medium; High
	Execution approach	AATT; Transformational Tools and Technology; RVLT; AETC; Other
	Strategic partnerships	Other Government; Companies; Academia
Experimental facilities needs and capabilities	Icing Research Tunnel (IRT) needed?	Yes; No
	Propulsion Systems Laboratory (PSL) needed?	
	PSL with drive system needed?	
	Adaptive Icing Tunnel (AIT) needed?	
	Revolutionary Icing Materials Evaluation Laboratory (RIMELab) needed?	
	Vertical Icing Studies Tunnel (VIST) needed?	
	DC–8 needed?	
	Twin Otter needed?	
	Laboratory for Adhesion Mitigation Projects (LAMP) needed?	
	IRT capability?	None; Marginal; Acceptable; Exceeds
	PSL capability?	
	PSL with drive system capability?	
	AIT capability?	
	RIMELab capability?	
	VIST capability?	
	DC–8 capability?	
	Twin Otter capability?	
	LAMP capability?	

For execution approach, a number of NASA ARMD projects were listed, and SMEs selected the best choice for each technical element. SMEs also selected the primary strategic partner. Priority was given to the entity that could make the largest technical contribution. For example, while FAA may be a strategic partner in terms of supplying resources to an academic institution, "Academia" would be selected for this exercise because they would make the primary technical contribution. Other Government partnerships included foreign organizations that have partnered with NASA in the past, such as ONERA (France) and the NRC (Canada).

The fourth category was evaluation of existing experimental facilities and capabilities. SMEs determined the experimental facilities required to address each of the technical elements. SMEs also evaluated the current level of facility capability for each technical element.

These filters were used to understand certain attributes of the technical elements and implication of the ranking process. For example, using the ARMD category of filters, it was possible to rank technical elements based upon which of the elements should be captured in ARMD research areas or projects versus which of the elements were already included. The difference in these rankings was used to confirm that the top priorities were included in current ARMD research plans. An additional example utilized the experimental facilities categories to determine how many technical elements required use of the NASA IRT and whether the existing IRT capability was adequate.

4.4 Identification of Future Realities and Weights

An important part of this study was the identification of different possible future realities. The TOPSIS analysis was conducted for future realities to show which of the icing technical elements may be ranked highly under different sets of possible future circumstances. This approach provided insights into icing research alternatives that could be viable over future investment areas rather than being limited to the current state of aeronautics. This section describes the four future realities considered in this study. Three of the four future realities focused primarily on commercial-transport-type airplanes and propulsion systems for civil aviation. These airframes and propulsion systems are the main focus of ARMD's Fab 4 technology areas and the AATT project that was a cosponsor of this study. The fourth future reality focused on AAM vehicles, a priority area for ARMD research portfolios and an important emerging market in civil aviation. After the four future realities were developed, a set of weights was assigned to each of the evaluation criteria described in Section 4.2. The weights were additional inputs to the TOPSIS analysis. This section describes the four future realities and the weights associated with each. The near/mid term is considered to be 2025 to 2035; the far term is considered to be 2035+.

4.4.1 Future Reality 1: Delayed Return to Growth Due to COVID–19

The first future reality was a near-term delayed return to growth in aviation as a result of COVID–19 (coronavirus disease 2019), where current technology was assumed to be adequate for large commercial transports. Under this future reality, the amount of technical research investment by the engine and airframe OEMs is limited, in part because airline operators are not buying new products due to the decreased demand for air travel. Airframe and engine OEMs are focused on derivative products with certain enhancements to improve efficiency and performance. Growth in the AAM and supersonics areas is also slowed due to the significantly reduced demand for air travel. The large rotorcraft industry is much less impacted due to the offsetting demand for military vehicles. In terms of icing research for this future reality, the current analysis tools, technologies, and environment definitions have sufficient maturity for commercial aircraft certification.

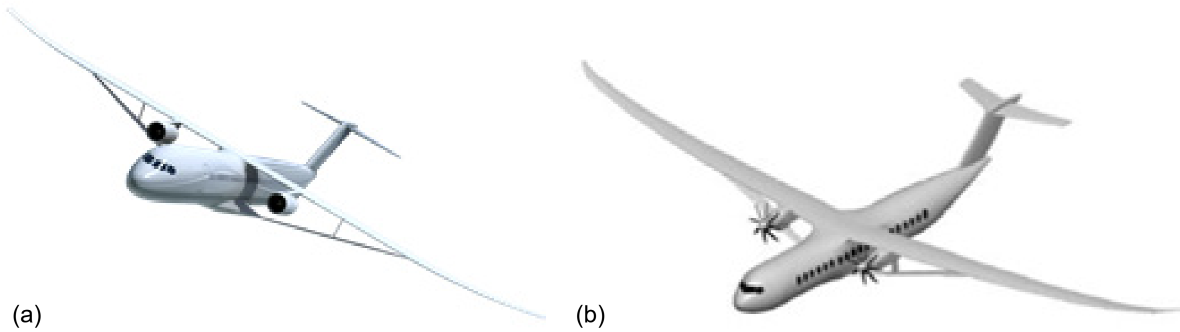
(a) (b)

Figure 3.—Transonic truss-braced wing airplane concepts. (a) With ducted fan. (b) With unducted fan.

4.4.2 Future Reality 2: Return to Growth With Reduced Carbon Emissions

The second future reality was a near-term return to growth with an emphasis on reduced carbon emissions. This future reality represents the current focus of ARMD research priorities in the Fab 4 technology areas, with the associated goals of improving efficiency while reducing carbon emissions and noise for commercial transport airplanes. In order to achieve these goals, new and unconventional airframes and propulsion systems are required. These concepts include the high-aspect-ratio TTBW airframe (Figure 3) combined with high-propulsive-efficiency systems like hybrid–electric, unducted fans, and small-core turbine engine technologies. In terms of icing research for this future reality, there are significant constraints related to new regulations in Apps. O and D certifications. Airframe and engine OEMs of both subsonic and supersonic aircraft may not be able to rely on similarity approaches to satisfy certification requirements due to the lack of relevant service history in icing conditions. In addition to this problem, current icing analysis tools may lack the capability to be used for design and optimization of these airframe and propulsion systems. These limitations also apply to the AAM vehicle sector, where these vehicles may not be certified to operate in icing conditions owing to the lack of icing analysis tools and facilities to address certification requirements. An additional concern for highly thermal-efficient small-core turbine engine technology is the App. D requirements for flight into clouds that contain high levels of total water content in high-altitude ice crystals. New atmospheric characterization research is needed to determine if App. D represents the global characteristics of ice crystal clouds. These factors could slow the development, and thus delay the entry into service, of advanced airplanes needed to address the global climate challenges for aviation.

4.4.3 Future Reality 3: Ultra-Efficient and Quiet Aircraft

The third reality was a far-term future targeting an ultra-efficient and quiet aircraft. The significant gains in fuel efficiency and noise reduction will demand more advanced configurations such as the hybrid wing body shown in Figure 4. The hybrid wing body airframe must also be coupled with all-electric propulsion or boundary-layer ingesting air-breathing engines with high propulsive efficiency. In terms of icing research, these concepts are not practically achievable with the current state of icing technologies, and thus investment is needed for (1) new capabilities for fully 3D simulation and (2) experimental capabilities for Apps. O and D. As the longest term reality, this also helped serve to capture enduring needs for icing.

4.4.4 Future Reality 4: Emerging Market for AAM Vehicles

The fourth future reality was Emerging Market for AAM Vehicles. This sector includes hybrid–electric and eVTOL vehicle types equipped with multiple rotors, tilt rotors, and tilt-wing configurations. Three example concepts are shown in Figure 5. In this future reality, there is a strong emerging market for weather-tolerant, on-demand aviation of this type. In terms of icing research, the current tools, technologies, and environment definitions are inadequate to address the design and certification challenges for these vehicles. This will limit the growth of this emerging market because operations in icing conditions will not be possible.

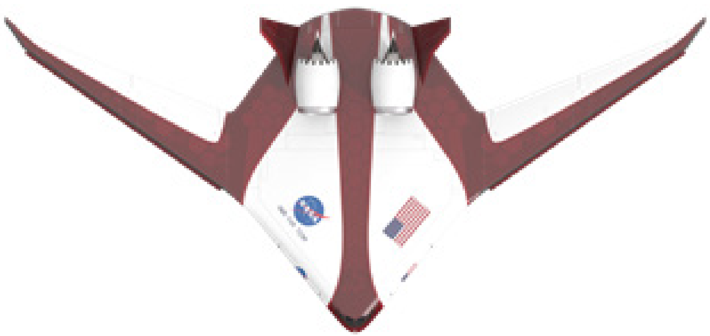

Figure 4.—NASA hybrid wing body concept airplane.

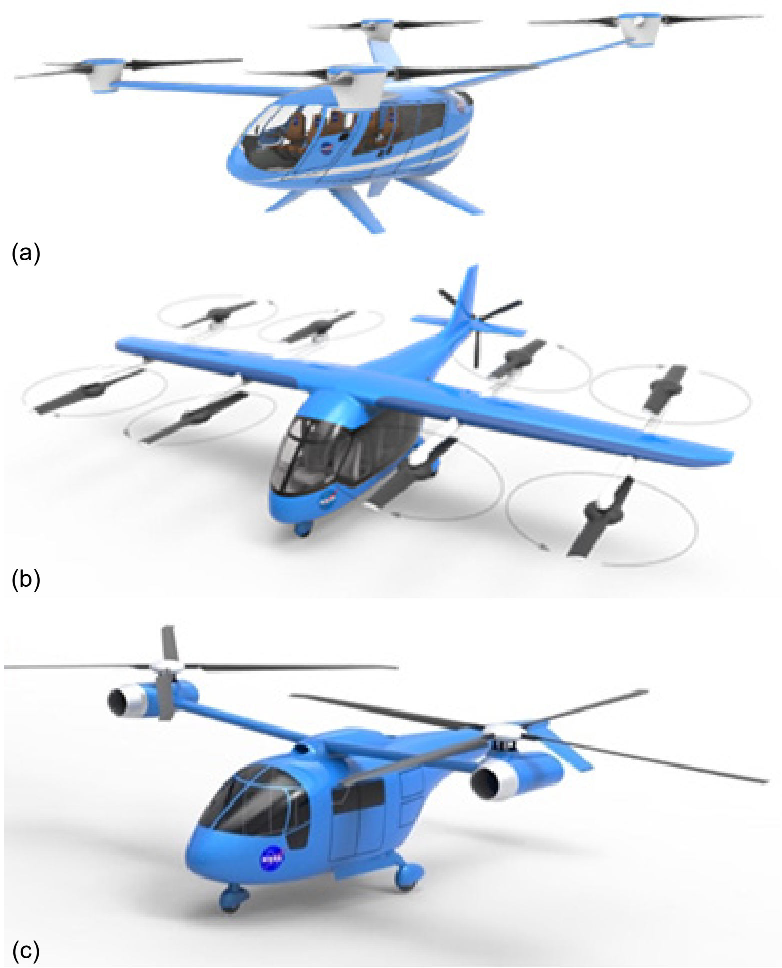

Figure 5.—NASA Revolutionary Vertical Lift Technology (RVLT) project concept vehicles. (a) Multiple rotors. (b) Lift plus cruise. (c) Side by side with hybrid propulsion.

4.4.5 Identification of Weights for Evaluation Criteria

Weights for each of the evaluation criteria described in Section 4.2 were identified to capture the four future realities in the TOPSIS analysis. An absolute scale from 0 to 5 was used, where 0 was "no weight" and 5 was the maximum weight possible. The SMEs were organized into smaller teams to develop the weights for each future reality, with the combined results being reviewed by the entire team. The final set of weights for each of the evaluation criteria is shown in Table IV. The relative weight is also indicated by the color of each cell, with higher weight being a darker shade of blue. A good example for weight selection is found in the first row criterion, Airframe Industry pull. In general, the airframe industry pull would have the highest weight for both the second and third future realities, Return to Growth With Reduced Carbon Emissions and Ultra-Efficient and Quiet Aircraft. In contrast, the airframe industry pull would have the lowest weight for the fourth future reality, Emerging Market for AAM Vehicles. These weights were used as inputs to the TOPSIS analysis described in Section 4.6.

TABLE IV.—FUTURE REALITY WEIGHTS FOR EVALUATION CRITERIA

High	Medium	Low

Category	Criterion	Future reality weight			
		Delayed Return to Growth	Return to Growth/ Reduced Carbon	Ultra-Efficient and Quiet Aircraft	Advanced Air Mobility (AAM)
Industry pull – Original equipment manufacturers	Airframe Industry	2	5	5	1
	Engine Industry	2	5	4	1
	Rotorcraft Industry	5	1	1	5
	AAM Industry	1	1	1	5
Industry pull – Suppliers	Instrumentation and Ice Detection	2	4	3	5
	Ice Protection Systems and Materials	2	4	4	4
	Remote Sensing Systems	2	2	3	3
	Icing Analysis Software	4	4	4	4
NASA project pull	Fab 4: Transonic Truss-Braced Wing	5	5	1	1
	Fab 4: Small Core	5	5	3	0
	Fab 4: Electrified Aircraft Propulsion	2	3	5	2
	Fab 4: High-Rate Composite Manufacturing	2	2	2	1
	Revolutionary Vertical Lift Technology Project	5	4	1	5
Other Government pull	Department of Defense	3	0	0	4
	FAA	3	3	4	5
Safety and certification	Safety Improvement	2	1	4	4
	Conservatism Reduction	2	5	3	4
	Certifiability Improvement	2	3	3	5
Other	Disruptibility	4	2	4	5
	Technology Risk	0	2	3	3
	NASA Involvement	5	5	5	5

4.5 SME Ratings

A spreadsheet was created by combining the technical elements described in Section 4.1 with the criteria and filters described in Sections 4.2 and 4.3, respectively. This spreadsheet was provided to each of the 12 SMEs, who input their ratings using drop-down menu selections for each cell. The SMEs assigned ratings in areas that were consistent with their expertise and familiarity with the stakeholder interviews. SMEs were instructed to leave answers blank for subjects outside their realm of expertise.

After the SMEs completed their individual ratings, the answers for each SME were grouped by criterion and filter, such that for each criterion or filter the number of responses, average response, and response standard deviation were shown next to individual responses. Responses were then analyzed for disagreement. Answers that were more than 2 points away from the average for fields with a standard deviation above 1 were reviewed. Reviews were conducted in small groups, typically consisting of four to five SMEs, and included at least one study lead, one of the SMEs focusing on analysis, and the SME with the disparate answers. A minimum of three SMEs were always present for the review of criteria results. Filters were reviewed in the same fashion, but with as few as two SMEs. This process was useful in identifying areas where definitions were ambiguous. As a result, definitions were updated and reviewed with the group. During these discussions, a review of stakeholder interview notes was often performed to better clarify and understand stakeholder needs as well as the corresponding NASA project point of view.

Completion of the SME ratings and reconciliation process provided the inputs needed for the TOPSIS analysis.

4.6 Multivariable Analysis: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS was applied to the results to obtain a set of scores useful for prioritizing the technical elements in each future reality. The TOPSIS algorithm's weighting was modified as described in this section to provide more consistent results. Finally, sensitivity studies were performed on the TOPSIS results to assist in determining the certainty of the results.

TOPSIS is a multicriteria decision analysis method used to rank the technical elements using the criteria. This method ranks the technical elements with short distances to the positive ideal solution (PIS) and long distances to the negative ideal solution (NIS) being favorable. The term "solution" is used in the original TOPSIS documentation and is equivalent to the term "element." PIS and NIS will be defined later. Weights can be applied to criteria.

A decision matrix is created with each row (or column) associated with an element and each column (or row) associated with the element's criteria score. The process for implementing TOPSIS is as follows:

1. Normalizing the decision matrix
2. Applying normalized weights to the decision matrix
3. Determining PIS and NIS
4. Calculating distance from PIS and NIS
5. Calculating closeness (similarity) of elements to NIS

The standard TOPSIS method described (Ref. 96) uses ℓ_2 normalization on the decision matrix, uses ℓ_1 normalization on the weight matrix, and calculates distances as an ℓ_2 norm. The ℓ_1 norm, also known as the taxicab norm, is defined as the sum of the magnitudes of vectors in a space. The ℓ_2 norm, also known as the Euclidean norm, is defined as the square root of the sum of the squares of magnitudes of vectors in a space.

PIS and NIS for each criterion are the best and worst (respective) score for each criterion. The closeness s of each element is calculated as

$$s = \frac{d_w}{d_w + d_b} \tag{1}$$

where d_w is the distance of the element's criteria score to the NIS and d_b is the distance to the PIS.

In practice, a few modifications were made to this method for the Icing AoA study. The decision matrix was normalized to an absolute scale of [0,5]. PIS and NIS were chosen to be the maximum and minimum possible score for each criterion. The ℓ_2 norm was still used to calculate distances. These modifications maintain relative distances between criteria scores for each particular criterion. They also force absolute PIS and NIS values. For this to be accurate, it is assumed that, unweighted, each criterion holds equal value with identical scaled scoring. Final scores are presented scaled from [0,1] for ease of interpretation. As such, the scores do not indicate direct closeness to the ideal score, but rather a closeness to the best and worst available scores.

Monte Carlo simulations were conducted to investigate the stability of SME inputs and weights. To analyze the SME inputs, a series of 1,000 trials were run using the standard deviation of the SME inputs per technical element for each criterion. A beta distribution was used to define the trial inputs.

The probability distribution function for the beta distribution on the domain $x \in [0,1]$ can be written as

$$f(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1} \tag{2}$$

where α and β are real, non-negative shape parameters. The expected value of the distribution is

$$E_0[X] = \frac{\alpha}{\alpha+\beta} \tag{3}$$

and the variance (the square of the standard deviation) is

$$\mathrm{var}[X] = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \tag{4}$$

For some pairs of expected values and variances, the shape parameters α and β can be solved for in closed form. For other pairs of expected values and variances, a reduced expected value and reduced variance must be used. These reduction factors can be solved for iteratively.

Final results (unscaled) of this analysis, using a baseline scenario with equal weights, are presented in Figure 6, where red lines represent the median score, the blue box represents the 25 to 75 percent quartiles, and the bars represent the full range (excluding outliers). The technical elements are presented from least close to closest to the ideal solution from the TOPSIS analysis.

There was concern over certainty of each element due to the significant overlap in ranges from this analysis. In response, the SME ratings were analyzed for disagreement, as described in Section 4.5. The TOPSIS inputs were updated with the reconciled SME inputs and reviewed with the entire team. Figure 6 used the original data set, and the remainder of the results used the reconciled data set. The updated scores are shown in Figure 7.

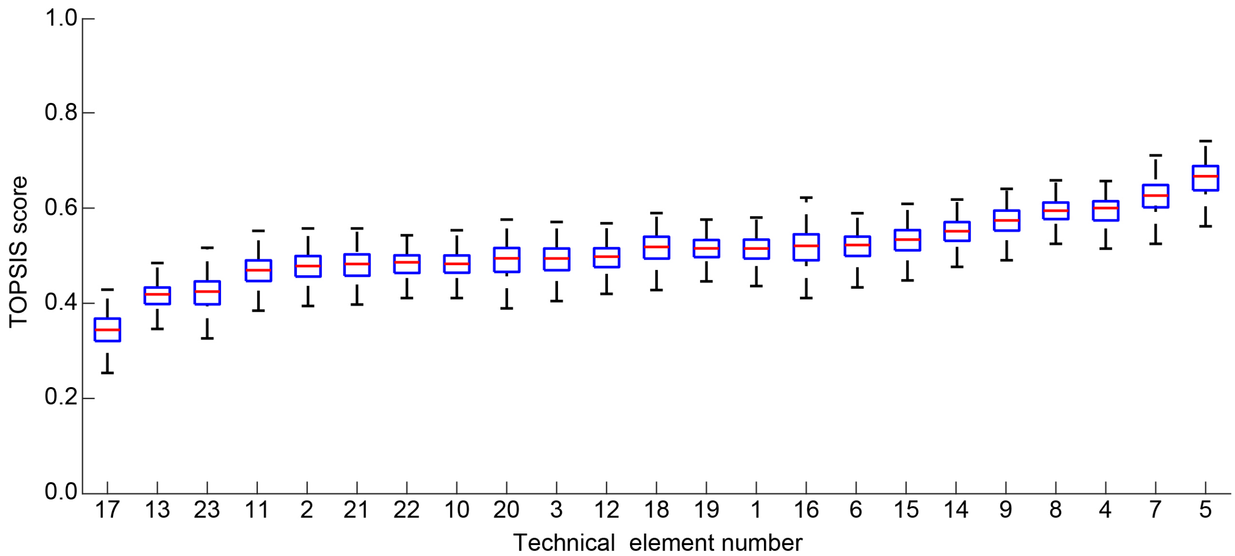

Figure 6.—Original technology rankings with uncertainty bars.

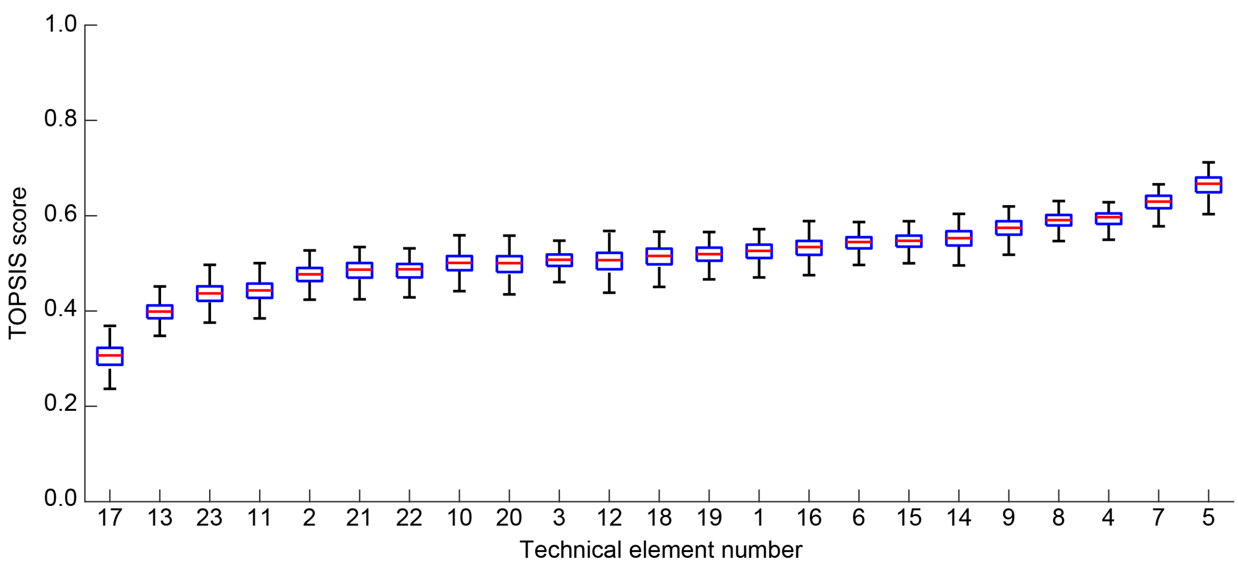

Figure 7.—Reconciled technology element rankings with uncertainty bars.

Results show that the top-ranking technology elements were stable with regard to SME inputs. While some of the top five ranking elements swapped positions, the top five elements remained otherwise unchanged. Uncertainty bars increase in size with lower ranked elements. The lowest ranked elements, however, were stable in their ranking.

The SME rating reconciliation process effectively verified or updated the definitions for all elements and criteria and significantly decreased scatter. The average original interquartile range (top of the blue box to the bottom of the blue box) was 0.0425 and decreased to 0.0285, a 33 percent reduction. The relative scores decreased, but the range of median scores increased by 14 percent as a result of the reconciliation process, producing significantly enhanced resolution of the TOPSIS results. Notably, the distribution for the top-scoring elements was significantly reduced, but still overlapped—the interquartile range for the top five elements decreased by 38, 48, 43, 43, and 34 percent, respectively.

Monte Carlo simulations to investigate the uncertainty around criteria weights were conducted using a method developed by the Acoustics AoA study group (Ref. 97, internal report). This method also runs a series of 1,000 trials but utilizes a truncated standard distribution on the weights instead of the beta distribution used for the SME input Monte Carlo simulation. The probability distribution function for this truncated standard distribution has a closed-form formulation and does not require iteration. However, the standard deviations of the distributions are not always as closely matched to the desired standard deviations. The selected standard deviation for the criteria weights was 0.5, or 10 percent of the 0 to 5 scale. For details on this analysis, refer to Reference 97. The results of this analysis are presented in Figure 8.

Figure 8 shows that for technology elements ranking near the top, the uncertainty bars are all typically small for all future realities. In these plots, the horizontal axis corresponds to the rank of each technology element, not the technical element number as in Figure 6 and Figure 7. These results give confidence in the stability of the future reality weights for the top-ranked elements. Future realities 1 and 3, Delayed Return to Growth Due to COVID–19 and Ultra-Efficient and Quiet Aircraft, generally have slightly larger uncertainty bars. However, for elements in the top five, there is confidence that the elements do indeed belong in the top five. Uncertainty bars increase with lower ranked elements.

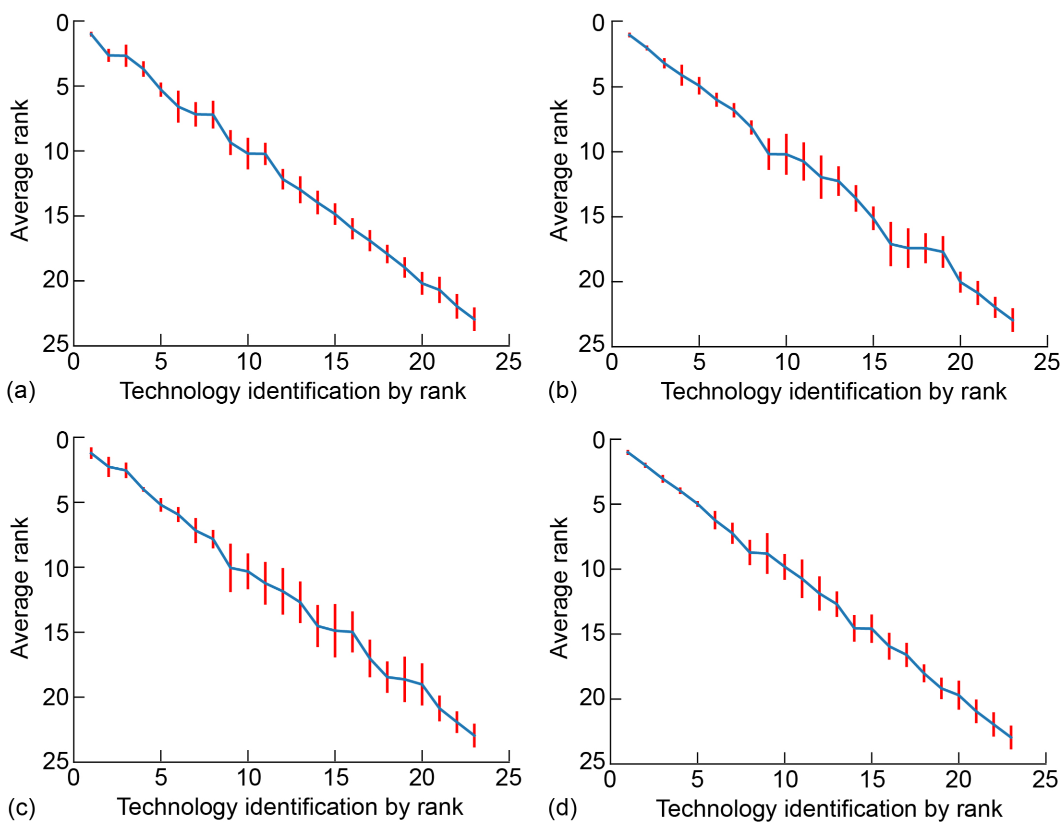

Figure 8.—Average technology rankings with uncertainty bars for each future reality (modified from Ref. 97; original figure by Cliff Brown). (a) Delayed Return to Growth Due to COVID–19. (b) Return to Growth With Reduced Carbon Emissions. (c) Ultra-Efficient and Quiet Aircraft. (d) Emerging Market for Advanced Air Mobility (AAM) Vehicles.

The comprehensive interview process was critical in the AoA, and TOPSIS inputs relied on discussions with stakeholders and among the SME team members. In the end, TOPSIS provided a framework to determine what information needed to be gathered and quantified. TOPSIS alone was not a turnkey toolkit to conduct the icing AoA study. Meeting the overarching objectives required significant discussion and engineering judgment from the SMEs, fortified with stakeholder inputs.

5.0 Discussion of Results: Key Findings and Priority Needs for ARMD

This section presents key findings from the Icing AOA study. The overall technical element rankings based on the TOPSIS analysis are presented in Section 5.1. The higher ranking elements were subsequently grouped into icing work package areas to address current ARMD priority needs; these are described in Section 5.2. Section 5.3 discusses emerging ARMD areas where icing work will be needed in the future as well as crosscutting icing technologies that are beneficial to several ARMD projects. Section 5.3 concludes with a discussion of enduring icing needs for the aviation community.

5.1 Results

Table V shows the ranking of the 23 technical elements based on the TOPSIS analysis for the four future realities considered. The table includes the 23 technical elements from the 4 categories. The rankings changed based on the future reality considered. The value shown is the TOPSIS score normalized by the highest ranking element for each future reality. The technical elements receiving scores greater than 0.6 were considered high ranking and are shaded in dark blue. Technical elements scoring greater than 0.4 but less than 0.6 were considered medium ranked and are shaded in a lighter blue. Elements scoring below 0.4 were considered lower ranked and are shaded in a very light blue.

Several technical elements ranked highly across most of the realities, demonstrating their crosscutting need for the future as well as for the various segments. It should be emphasized that each of these technical elements was important to at least one of the icing stakeholders. Those that ranked highest did so because they had application (or pull) across numerous criteria, which resulted in an overall higher ranking. In other words, lower ranking does not translate to lower importance, just fewer segments needing that technical element.

5.2 ARMD Priority Needs

Using the higher ranking technical elements from the study, four work package groupings were developed that were most applicable to the Fab 4 and other ARMD priority areas:

1. External Icing
2. Engine System Icing
3. AAM Icing
4. IPSs

Table VI shows these groupings together with the applicable ARMD areas. The rankings were based on Future Reality 2: Return to Growth With Reduced Carbon Emissions and Future Reality 4: Emerging Market for AAM Vehicles. The highest ranking elements and some medium-ranking elements were used to build these groupings. The medium-ranked elements were deemed important for the specific ARMD application or NASA was uniquely positioned to work that specific element. Note that some technical elements appear in more than one grouping. These elements have crosscutting aspects (i.e., learning in one grouping is applicable to the other), although each element has its own area-specific needs as well. For example, ice shedding appears in both the Engine System Icing and AAM Icing areas. The general physics describing ice shedding will have similarities in both areas, although the specific geometries and operating conditions are unique to the applications.

TABLE V.—TECHNICAL ELEMENT RANKINGS ACROSS FUTURE REALITIES

High	**Medium**	**Low**

Category	Element no.	Technical elements	Future reality ranking			
			Delayed Return to Growth	Return to Growth With Reduced Carbon	Ultra-Efficient and Quiet Aircraft	Advanced Air Mobility
Icing Performance Impact	1	Airframe performance prediction	0.67	0.55	0.49	0.58
	2	Engine performance prediction	0.50	0.54	0.57	0.32
	3	Rotor/propeller performance prediction	0.60	0.40	0.41	0.63
Ice Geometry Definition	4	Ice shedding	0.83	0.78	0.81	0.77
	5	3D ice accretion—standard icing	1.00	1.00	1.00	1.00
	6	3D ice accretion—ice crystals	0.58	0.76	0.96	0.49
	7	3D ice accretion—FZDZ/FZRA	0.83	0.85	0.94	0.93
	8	3D ice accretion on rotating systems	0.80	0.72	0.77	0.75
	9	Thermal ice protection system (IPS)	0.69	0.68	0.74	0.80
	10	Mechanical IPS	0.46	0.49	0.56	0.51
	11	Altitude scaling for thermal IPS	0.24	0.42	0.46	0.27
	12	Icing condition scaling	0.54	0.52	0.44	0.48
	13	Altitude scaling for ice crystal icing	0.12	0.32	0.35	0.20
Ice Protection and Detection System Technology	14	Water/ice particle concentration factors	0.66	0.68	0.65	0.68
	15	Icephobics	0.69	0.61	0.50	0.63
	16	Low-weight and low-power IPS	0.63	0.53	0.48	0.65
	17	Low-radar IPS	0.00	0.00	0.00	0.00
	18	Ice detectors	0.43	0.44	0.49	0.62
	19	Onboard remote sensing	0.40	0.40	0.52	0.61
Icing Weather and Characterization	20	Terminal area characterization	0.36	0.40	0.54	0.53
	21	Urban area characterization	0.38	0.33	0.39	0.57
	22	High-altitude ice crystal characterization	0.31	0.56	0.68	0.34
	23	Small-scale weather forecast/nowcast	0.27	0.20	0.27	0.40

TABLE VI.—ICING WORK PACKAGE GROUPINGS BUILT AROUND ARMD AREAS

Work package	ARMD area	Technical elements
External Icing	Transonic Truss-Braced Wing (TTBW), Certification by Analysis (CbA)	3D ice accretion—standard icing 3D ice accretion—freezing drizzle/rain Water/ice particle concentration factors Icephobics Airframe performance prediction
Engine System Icing	Small-Core Turbine Engine	Ice shedding 3D ice accretion—ice crystals 3D ice accretion on rotating systems High-altitude ice crystal characterization
Advanced Air Mobility (AAM) Icing	AAM	Ice shedding 3D ice accretion on rotation systems Rotor/propeller performance prediction Icephobics Ice detectors
Ice Protection Systems (IPSs)	TTBW, AAM	Thermal IPS Water/ice particle concentration factors Icephobics Low-weight, low-power IPS Ice detectors

The next sections present the work package groupings together with the icing-related challenges for specific areas of the Fab 4 and AAM. The challenges relevant to each ARMD area come from the stakeholder interviews and SME knowledge. The priority needs to address those challenges come from the technical elements captured in the work package groupings.

5.2.1 Key Study Findings for TTBW

This section discusses the icing-related challenges facing the TTBW (Figure 9) and the priority needs for addressing those challenges. The priority needs are cross-referenced to the applicable work package groupings and associated technical elements discussed in Sections 5.2 and 5.1, respectively.

5.2.1.1 Challenges

Conversations with aircraft manufacturers revealed that icing certification requirements can compromise the larger efficiency goals for an aircraft. For certification, the aircraft must show compliance with the airplane performance and handling requirements in icing conditions. Typically, this involves using the most critical ice accretion on unprotected surfaces as well as any ice accretion on the protected surfaces as part of the normal IPS operation (e.g., residual ice). Part of the performance includes maintaining an adequate margin above stall speed. This margin must be maintained even with ice on the aircraft. To maintain such margins often requires the aircraft designer to increase the demands of the IPS or change the aircraft geometry to ensure safe flight in icing. Those design changes can result in less efficient aerodynamics or increased energy usage to operate anti-icing and deicing systems. For a thinner wing aircraft like the TTBW, the impacts of ice accretions might be more significant, as seen in Figure 10.

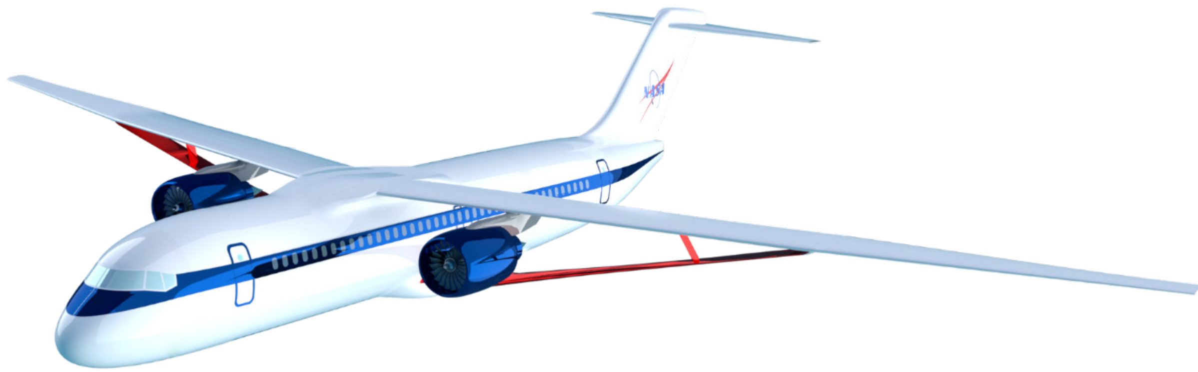

Figure 9.—Transonic truss-braced wing aircraft concept.

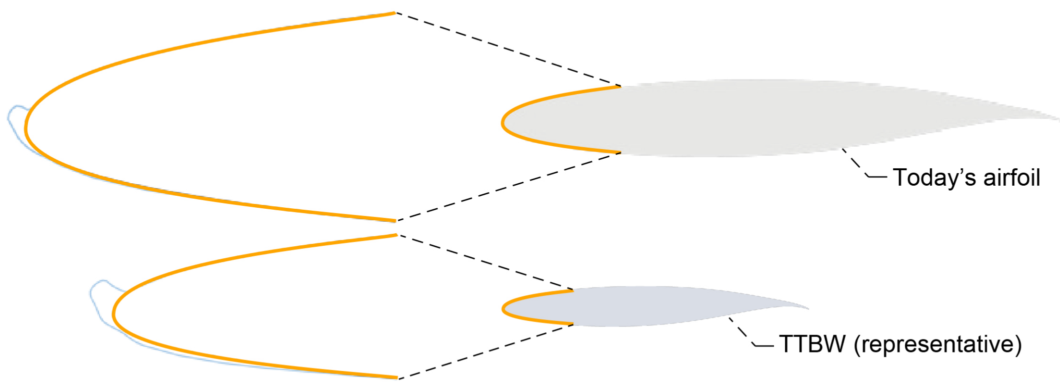

Figure 10.—Two-dimensional ice predictions using LEWICE code showing larger ice shape relative to airfoil size (28 percent of cross-sectional area) for representative transonic truss-braced wing airfoil nearer wing root during 30-min icing exposure under nominal temperature, liquid water content, and median volumetric diameter.

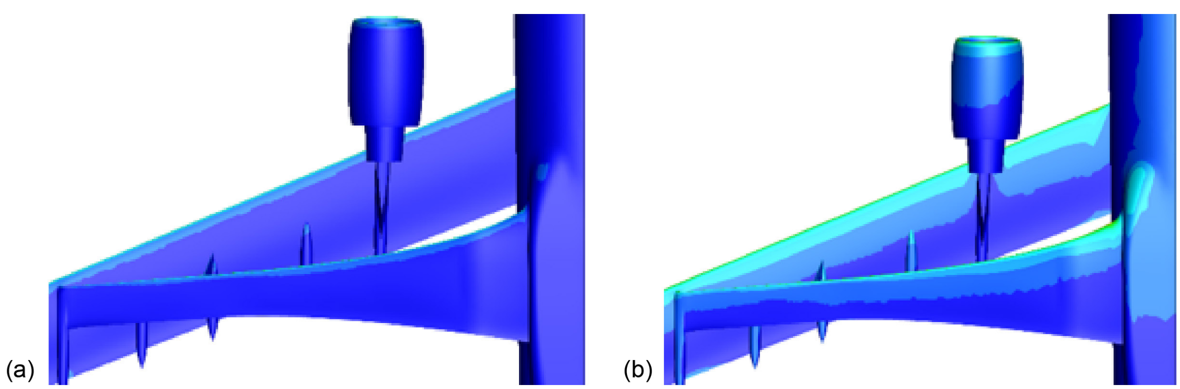

Figure 11.—Comparison of icing challenges on transonic truss-braced wing (bottom-up view). Lighter blue denotes higher water impingement. (a) Standard icing, 20-µm cloud. (b) Freezing rain, >40-µm cloud, maximum drop diameter D_{max} > 500 µm.

Maintaining safety of flight in icing without compromising efficiency goals is a major concern for the successful introduction of the TTBW into the fleet of any airline. The TTBW currently has goals of reduced fuel burn that need to be met to justify the adoption of this technology. The IPS can negatively impact those goals by excessive weight and power requirements that are connected to the coverage needed to maintain safe flight. Additionally, the thin wing design can impose challenges on the IPS due to volume requirements for the equipment within the relatively small volume available within the wing. Accurate assessment of the necessary coverage of the wing and truss are thus critical for the design of the TTBW.

Any new concept aircraft with advanced configurations like the TTBW cannot rely solely on similarity for icing certification. With derivative vehicles, manufacturers can satisfy icing certification requirements by showing similarity to a previous design with a long service history. As a brand-new vehicle with no service history, the TTBW design and certification efforts will depend upon computational and experimental simulation as well as flight testing. The costs associated with the introduction of new vehicle concepts go up as the requirements move from computational simulation to wind tunnel testing and finally to flight testing. Manufacturers of such a vehicle will thus base much of the design, with respect to icing concerns, on the ability to accurately predict where icing will occur and how much ice will accumulate for various phases of flight. Reduction of uncertainty in icing simulation will lead to less conservatism in the design and thus help to maintain the desired efficiency and environmental goals for the vehicle. Reductions in uncertainty are obtained by validation efforts for the simulation tools with representative models in relevant icing environments.

Current icing simulation tools are not validated for aspects of new aircraft configurations and regulatory environments. While there is general confidence in the prediction of 2D ice accretions for modern airfoils in App. C conditions, as seen in Figure 10, ice accretions around 3D features such as strut/wing interfaces and high-lift devices still require significant capability improvement and validation. Furthermore, the newer App. O certification requirements, which have limited testing facilities available currently, need further development. Figure 11 shows a recent analysis performed on the TTBW geometry that indicates larger impingement limits for FZRA conditions of App. O. However, these results require validation from a ground-based experimental facility or from actual flight testing.

Finally, there may be significant challenges for IPSs in thin-wing, high-aspect-ratio designs. The thin wing offers less cross-sectional area, which may pose challenges for integration of IPS hardware. In addition, a high-aspect-ratio wing has a larger frontal area that may require more ice protection compared with today's aircraft.

In summary, the icing challenges for the TTBW are as follows:

- Certification requirements may compromise efficiency goals.
- Comparative analysis cannot be relied upon for icing certification.
- Current icing simulation tools are not fully validated for relevant icing certification.
- Thin-wing, high-aspect-ratio designs pose challenges for ice protection integration.

5.2.1.2 Priority Needs

Based on the study analysis, the following priority needs were identified for TTBW:

- Definition of the 3D ice shapes that occur on the vehicle under standard icing and for FZDZ and FZRA. This includes both unprotected and protected surfaces (residual ice) for all airfoils and components of the vehicle.
- Assessment of the aerodynamic performance impact of ice on the vehicle once the ice shapes are understood. The assessment of ice shapes on aircraft aerodynamics is performed to understand which areas of the wing are critical for placement of IPSs.
- Development of IPS strategies, which will likely require new low-weight and low-power approaches, including potentially icephobic material.

5.2.2 Key Study Findings for AAM

AAM vehicles, eVTOL vehicles, and advanced rotorcraft are poised to revolutionize the transportation of people and goods. Market studies continue to strongly indicate that public acceptance of AAM depends on overcoming the barriers of community noise and safety. The icing discipline is particularly suited to address the issue of safety. During an in-flight encounter with icing conditions, ice can build up on unprotected aircraft, rotorcraft, and engine components. IPSs are necessary to mitigate this threat; otherwise, the vehicle will be unsafe or unavailable for the mission. NASA seeks to develop and maintain a capability to evaluate new technologies, to simulate the next generation of IPSs, and to demonstrate compliance with regulatory requirements.

The design and evaluation of these future vehicles will require ice prediction tools (both high fidelity and system level, plus validation data) and new experimental methods, which only NASA is currently situated to develop.

5.2.2.1 Challenges

Many aspects of future rotorcraft and air mobility vehicle designs lie outside the current design space, both in aeropropulsive arrangement and rotor designs. Future vehicles may have new capabilities and new requirements that cannot be met by current IPSs.

AAM vehicles with distributed electric propulsion pose particular challenges to the prediction of ice accretion, whether due to rotation speeds, Reynolds number, or low-noise airfoil designs. The operation and mission in a future highly mobile airspace may be quite different from current fleets. Still, a robust weather capability and icing certification will be required.

IPSs to enable these vehicles require revolutionary advances, especially in power use and performance capability. Coatings and blade treatments must withstand a harsh environment, including rain and sand, while maintaining low adhesion shear strengths.

A number of competing metrics go into designing a rotor blade IPS, such as minimizing overall power consumption, managing peak power, maintaining rotor balance, minimizing runback refreezing to unprotected areas, reliably getting power to the blades, and controlling the blade heater in order to avoid blade damage. Typically, the IPS is constrained by the blade geometry, not the other way around. There may not be a closed set of constraints that can be applied to the outer mold line geometry for blade design optimization.

The icing challenges for AAM vehicles (Figure 12) are summarized as follows:

- In the near future, AAM vehicles will be expected to have weather-tolerant capabilities to fly in conditions such as icing.
- AAM vehicles such as eVTOLs have very limited power and weight available for icing mitigation.
- Ice detection systems currently in use on larger aircraft are inadequate for AAM vehicles.
- Current icing simulation tools do not exist or have limited capability for rotating systems, and especially for multiple-rotor configurations.

5.2.2.2 Priority Needs

There are a number of issues that need to be addressed when designing a rotor IPS. These include chordwise extent of icing on both the upper and lower surfaces, ice accretion prediction (the rate at which ice will accrete, the form of the ice, and the resulting aerodynamic degradation), the power density and temperature required in various heated areas, the sequencing of individual elements and heater on-off times if applicable, and the structural blade design that allows the reliable and consistent integration and repair of heating elements and controls.

Figure 12.—Icing-related challenges facing advanced air mobility vehicles.

Shedding is a complex process that requires determining the width of the heater zone, the thickness of the ice, the adhesive strength of the ice attached to the blade (which may also be affected by torsion and flapping loads), and the shape and amount of ice that is shed. Accounting for shed and ingested ice is a requirement that currently exists but is made more challenging by any novel multiple rotor arrangement.

A key component of these novel IPSs is likely to be icephobic coatings or materials, which may be necessary to meet the vehicles' power and weight requirements. NASA can play a key role in understanding and developing these systems.

The other enabling technology envisioned and required for eVTOL and future vertical lift is detection and sensing of vehicle weather and condition. This is especially important for autonomous vehicles, but in general will be necessary for any mission with robust all-weather requirements.

Based on the study analysis, the following priority needs were identified for AAM:

- Definition of the 3D ice shapes that occur on the vehicle for standard icing and for FZDZ and FZRA on both fixed and rotating geometries
- Characterization, prediction, and mitigation of ice shedding
- Assessment of the aerodynamic performance impact of ice on the rotor/propeller performance
- Development of IPS strategies for AAM vehicles, including using icephobic materials
- Ice detection systems applicable to the eVTOL platforms
- Analysis and prediction of ice buildup and mitigation on engines, inlets, and screens

5.2.3 Key Study Findings for Small-Core Turbine Engine

Icing challenges for engines occur both from impacts of supercooled liquid water droplets and from the ingestion of ice crystals. Figure 13 illustrates some of those icing challenges, including images of actual icing observations as well as some of the consequences of icing. Supercooled water icing on the fan and spinner can lead to performance losses as well as ice shedding into the engine. Ice crystals entering the engine can partially melt, accumulate, and refreeze in the regions around the low-pressure compressor and can lead to performance and operability issues as well as the potential for damage from shed ice (Ref. 113).

ICI remains a concern for the engine community, and there is a concern that shrinking the engine core may increase the risk of an ICI issue. For example, ICI led to engine rollback, or uncommanded loss of thrust, in a smaller turbofan engine (the ALF502R) (Refs. 26, 113, and 114). Extensive research and testing determined that ice accretion in the area of the exit guide vanes was leading to blockage in the core flow path and ultimately rollback. None of the other larger engines with known ICI events have experienced rollback. It is thought that ice cannot bridge across the stator passages in larger engines as it had in the ALF502R (Ref. 115).

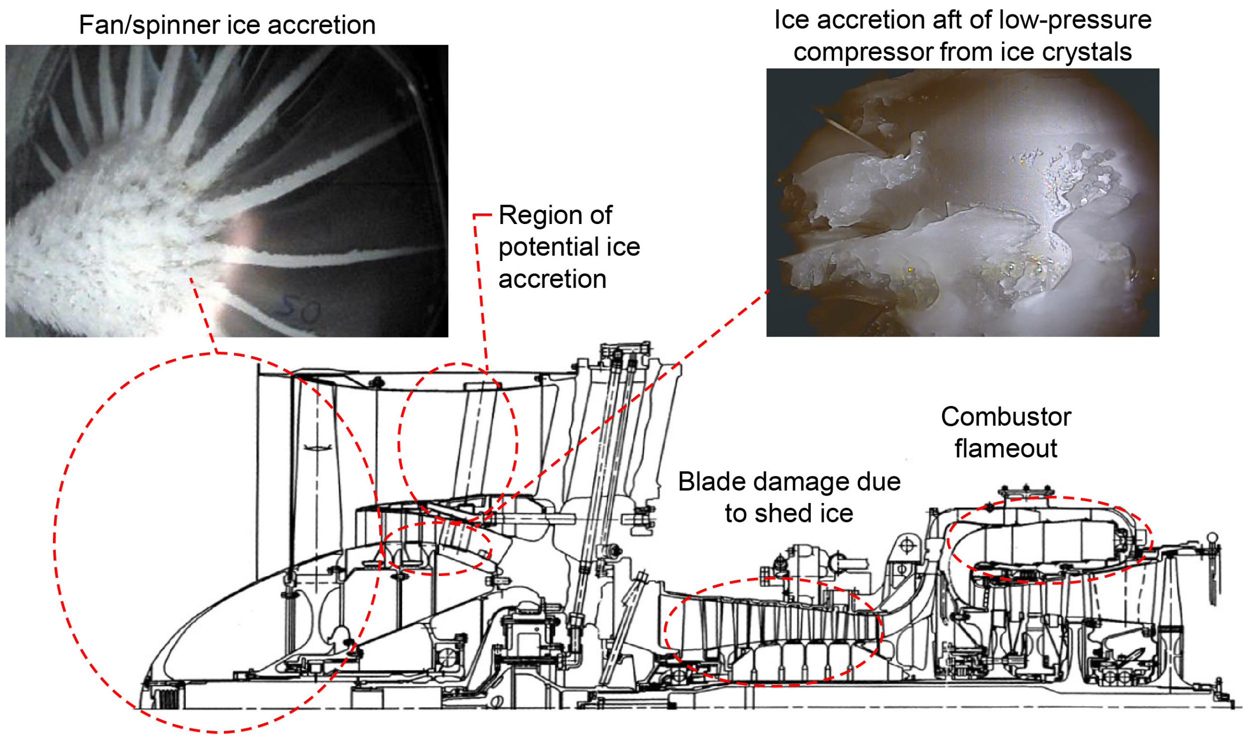

Figure 13.—Icing-related challenges for turbine engines. (Fan/spinner icing image and engine cutaway schematic courtesy of Honeywell, Inc.)

Fixing the issue in the ALF502R required redesign, testing, and recertification. Specifically, anti-ice heat was required to keep the metal temperatures in the vicinity of the exit guide vane above freezing. Flight testing was required to demonstrate that the redesign was successful. This was accomplished by outfitting an aircraft with both modified and unmodified engines and seeking out ICI conditions (Ref. 26). The additional anti-icing heat required to modify the ALF502R likely reduced engine efficiency as it increased bleed-air requirements. Bleed air is a common method used by engine manufacturers for anti-icing of critical engine (as well as aircraft) components.

The ICI issue with the ALF502R was not discovered until after the engine was in service. It was an example of a "surprise" that adversely impacted operations. As a result of this and the hundreds of other identified ICI events (Refs. 116 and 117), the FAA in 2015 updated the airworthiness standards for aircraft engines in 14 CFR Part 33, Section 33.68 and App. D, which prescribed engine operation requirements in an ICI environment. However, there is uncertainty in the engine community regarding how to address these new rules, and MOCs need to be established. Currently, manufacturers rely on similarity to existing designs, fleet history, and experience to help satisfy regulatory requirements. Consequently, the new regulations could limit the introduction of new and different designs until acceptable MOCs for new designs are established. It is anticipated that new engines will rely heavily on icing simulation tools for their design and certification, including MOCs.

According to the industry, current simulation tools have limited capability and lack validation not only for ICI, but even for standard icing conditions in an engine environment. In 2020, the FAA published an Engine Ice Crystal Icing Technology Plan With Research Needs (Ref. 115), which identifies technology gaps and research needs in this area. Although substantial progress has been made toward an understanding of the physics of ICI accretion in engines, with over 80 research papers published, the document re-baselines the research needs based on the recent ALF502R testing at the NASA PSL facility.

In summary, the icing challenges for the small-core turbine engine are as follows:

- Shrinking the core may increase the icing threat.
- Addressing this icing threat may require a compromise to the efficiency goals of the small-core turbine engine design.
- There is uncertainty as to how new engine architectures will meet icing certification requirements, particularly in ICI (App. D), since this is in new regulatory territory.
- Current icing simulation tools have limited capability and lack validation in an engine environment not only for ICI, but even for standard icing conditions.

5.2.3.1 Priority Needs

- Ice shedding prediction and impact of shed ice on performance and operability of the engine, including mitigation such as icephobics
- 3D ice definition in standard icing and ICI for turbomachinery systems
- Water and ice particle concentration factors at off-body locations, such as the ingestion plane of the engine
- Engine performance impact of ice geometries
- Globally representative ICI atmospheric characterization
    - The current regulations are based on theoretical maximums, and recent flight tests showed significantly lower concentrations in the atmosphere. However, the atmospheric sampling did not include areas of high aerosol concentrations where higher ice water content is believed to occur. This needs to be resolved so the engine community understands what conditions they need to certify against.

5.3 Other Key Study Findings

This section discusses key findings regarding NASA project areas other than the TTBW, AAM, and Small-Core Turbine Engine. In addition, separate subsections discuss crosscutting icing technologies across the current ARMD portfolio and enduring needs for the external icing community.

5.3.1 Other ARMD Areas: EAP, High-Rate Composite Manufacturing, and CST

Analysis of results revealed a strong pull for icing from the stakeholder community for TTBW, AAM, and small-core gas turbine engines. For other areas like EAP, High-Rate Composite Manufacturing, and CST, there are currently limited icing needs; other technology development activities have a higher priority at this time. However, icing technologies will be required as these areas mature to make them viable for industry. In other words, investments made now in TTBW, AAM, and Small-Core Turbine Engine will help EAP, High-Rate Composite Manufacturing, and CST in the future.

5.3.2 Crosscutting Icing Technologies

Several icing technologies identified in the analysis are crosscutting. Table VI shows technical elements that appear under multiple work package groupings. This includes (1) 3D ice accretion from the Ice Geometry Definition category, (2) airframe/rotor performance prediction from the Icing Performance Impact category, and (3) icephobics from the Ice Protection and Detection System Technology category. The crosscutting aspects of these technical elements are discussed in this subsection.

Ubiquitous to all new concept flying vehicles is the technology to define the ice accretions and evaluate the performance impact of that ice on that vehicle. Such technology is needed to advance the

TTBW and will be needed as AAM vehicles look to operate in icing conditions. Furthermore, technology to define ice accretions and associated performance impacts are also crosscutting with Certification by Analysis (CbA), which is a thrust by the aviation community to reduce and/or eliminate expensive flight testing for design and/or certification of various components. Advances and validation of both computational and experimental analysis tools are required to achieve these goals. Currently, NASA has scoped its CbA efforts to focus on the ability to predict $C_{L,max}$. Advances in computational and/or experimental icing analysis tools will enable icing considerations to be accounted for earlier in the design process, resulting in safer and more efficient vehicles. These advances will also enable earlier adoption of revolutionary vehicle designs and concepts by reducing the burden required to assess vehicle behavior for certification.

Ice shedding can occur from any element of the aircraft that has ice buildup. Most frequently, this occurs from rotating components such as propellers, rotors, fan blades, and spinners. Ice shedding occurs when the external forces on the ice, centripetal or aerodynamic, overcome the adhesive forces maintaining the ice on the surface or the cohesive forces keeping the ice together. The shedding event is not well understood, and available data has typically been inconsistent. This has prevented the creation of reliable models that could be introduced into ice accretion codes. More research is needed in the physics of ice shedding, and better standards are needed for the measurement methods currently used to accumulate that data.

The relationship between ice accretion, adhesion, and shedding is complex and still poorly understood. Historically, published results tend to exhibit more data scatter than desired. The current generation of mostly empirical codes account only for temperature, but it is known that substrate properties and formation mechanism affect adhesion, as do test parameters such as strain rate. Many experimental methods are available to measure adhesion, but additional comparative studies are needed to explain the disagreements. Research indicates that the various methods (lap joint, centrifugal, blister, cantilever, etc.) do not measure the same quantities. In situ and ex situ methods may not give comparable results, either. It is necessary to improve ice adhesion testing to minimize the influence of unintended mechanical and thermal stresses.

The durability of a potential ice-adhesion-reduction coating to the commercial aircraft environment will continue to be an area of research. Coating adhesion and durability are assessed using a variety of techniques (e.g., cross-hatch adhesion, hardness, mandrel-bend flexibility, and impact testing) prior to and after exposure to thermal cycling, accelerated weathering, abrasion resistance, and solvent soak (including water, jet fuel, hydraulic fluid, and deicing fluid). These test capabilities, which are consolidated into the Laboratory for Adhesion Mitigation Projects (LAMP), located in LaRC’s Advanced Materials and Processing Branch, continue to be needed. Other characterization instrumentation is also used, including optical and contact profilometers to determine surface roughness and contact angle goniometry to assess wettability of the coating surface.

With the continuing search for new coatings and materials, it will be beneficial to design chemical and surface properties for both ice mitigation and erosion resistance. Improved adhesion models can help in the design and certification of new IPSs. Coatings with controlled surface morphology can help with developing a validated macro-scale model, which can then be integrated with the atomistic simulations to guide the development of future materials to improve IPS performance.

Finally, low-weight, low-power IPSs are an area of particular importance in future realities where a low carbon footprint and electric propulsion are prominent. IPSs have a number of requirements that must be taken into account, whether making a new design or incremental improvement. Sometimes these requirements can be conflicting. An IPS must be capable of removing ice for varying icing conditions, as described in 14 CFR Parts 25 and 29 App. C. An IPS must be resistant to corrosion and erosion (sand and rain). It must provide an acceptable aerodynamic penalty when actuated and a negligible penalty when it is not. It must be capable of operating reliably after many repeated actuations. Power consumption and distribution can also be a major design constraint for an IPS. A system must operate over a broad temperature range. It must be durable and able to withstand ultraviolet (UV) exposure, solvents, handling, etc. Other factors include system complexity, reliability, repairability, cost, and weight.

Historically, NASA has not developed IPSs in-house but rather has focused on development of the tools, methods, and capabilities (instruments and facilities) that support the development of these technologies. NASA does have the mission of simulating IPS performance to the highest level of fidelity necessary for design and certification, particularly for the civil aviation market. This simulation includes both ground-based test facilities and computational tools.

5.3.3 Enduring Needs

NASA's mission in icing has been to provide U.S. industry with the tools, methods, and databases it needs to develop and certify vehicles for safe flight in icing conditions defined by FAA regulations. NASA conducts periodic assessments (such as this study) and workshops to guide research objectives; to receive feedback from industry, academia, and Government on NASA's research plan in emerging areas; to solidify existing partnerships; and to identify potential future collaborations.

Beyond identifying the near- to mid-term priority needs for icing for NASA Aeronautics (particularly for the Fab Four), this AoA study sought to determine the enduring needs for icing—the long-term capabilities and expertise identified by the aviation community as being critical for NASA to provide. The study revealed two clear enduring needs in icing that external stakeholders are looking to NASA to meet: (1) the capability to conduct fundamental icing studies in the public domain and (2) the capability to address atmospheric characterization requirements.

A NASA capability to conduct fundamental icing physics studies in the public domain to improve both computational and experimental capabilities is a clear desire of the icing stakeholder community. This is especially needed in newer areas such as SLD (FZDZ and FZRA) and ICI. Implicit in this need is the capability to experimentally generate relevant and well-characterized icing conditions in wind tunnels and other facilities. It is important that NASA's facilities be well calibrated and capable of covering the entire envelope envisioned for current and future vehicles. NASA's computational tools must be robust and validated enough to support the next generation of vehicles. NASA wants to provide these capabilities at a reasonable cost to a broad community of industry, academia, and Government users.

In addition, NASA is needed to address atmospheric characterization requirements that will arise as new vehicles expand operations. This includes the characterization of ice crystal clouds at high altitude for the engine community as well as the icing environment near the surface for the emerging AAM market. Atmospheric characterization is also needed to validate forecasting and nowcasting tools that the aviation community requires to operate safely in an icing environment.

6.0 Recommendations

Upon initial review of the AoA study and its preliminary results, ARMD management directed the team to further prioritize the study results by generating a list of priorities, ranked in order from 1 to *n*, to assist the various projects in future planning activities. This section is restricted to NASA readers.

6.1 Recommended Priority Needs

Table VII shows a prioritized list of icing work packages and specific technical elements. Icing priorities 1 to 4 and 6 reflect activities that were already in various stages of planning as of March 2021.

The initial priorities were established based on whether the work was planned in an established Technical Challenge (TC) or Emerging Technical Challenge (eTC), with a TC receiving a high priority. As of May 2021, only the TTBW icing work is part of an established TC. The other priorities follow the rankings from the study. Priority 5 reflects the study finding from the engine community that supercooled water icing and subsequent ice shedding from the front end of the engine are of a high concern.

The leftmost column of Table VII shows the priority order from 1 to 6 and reflects the results of the AoA study. The next columns show the work package grouping and AoA technical elements to be addressed. "Work package grouping" is used rather than "work packages" because not all highly ranked technical elements are fully addressed with the Fab 4 focusing. A superscript "1" beside a listed AoA technical element indicates that only limited work is planned using current capabilities (footnote 1). For example, FZDZ and FZRA would use only the available capabilities in our codes and facilities, which are limited. The fourth, fifth, and sixth columns show the ARMD area along with the targeted projects, notional deliverables, and collaborations, including existing agreements that could be leveraged (footnote 2) and potential new collaborations (footnote 3). Notional facility usage is depicted in the seventh column. The arrow in the final subcolumn indicates that IRT or PSL usage for the Engine System Icing work package is projected to occur beyond FY 2024.

Priority 1 was the highest priority and has a TTBW focus. This was due to the AoA rankings of the technical elements that make up this work package grouping and because it is being planned as part of the TTBW Technical Challenge. By leveraging current capabilities in icing, we can make the earliest impact to the Fab 4 by assessing the icing impacts for TTBW and identifying gaps in our icing knowledge. Currently, there is also some work planned with the icephobics group.

Priority 2 has an AAM focus. This is an emerging area in which icing will certainly play a role. However, icing challenges are further out on the AAM roadmap, and the current level of investment reflects that timeline. This also aligns with FAA focusing icing efforts toward AAM. The deliverables here would be a rotor test capability for icing, a key early step in this process.

Priority 3 has a Small Core focus and is looking to reduce the design and certification risks of the next entry-into-service small-core turbine engine. Right now, the focus is on testing of a simulated compressor geometry under ICI conditions, which addresses the third priority technical element in the Engine System Icing work package grouping. FY 2022 planning will begin transitioning the primary focus of the engine icing work to the higher priority elements identified in this study, specifically in the area of ice shedding and 3D rotational icing, which is identified as Priority 5.

Priority 4 is in the area of Certification by Analysis (CbA). This area is growing and is synergistic with Priority 1, the External Icing work package grouping. Plans are currently underway for icing to be part of the Common Research Model (CRM) CbA activities with notional FY 2025 deliverables that baselines the icing CFD capabilities under flight Reynolds numbers and a high-lift configuration.

Moving down to Priority 5, again, this is part of the Engine System Icing work package grouping and looks to move into ice shedding research and into 3D Rotating System icing starting in the FY 2023 timeframe, as described previously. In addition, some early learning in ice shedding can be leveraged from the crosscutting work done in Priority 2 for AAM icing.

Priority 6 is the High Ice Water Content Flight Campaign, which is a medium priority in the Engine System Icing work package grouping. However, the FAA is asking NASA to lead the research efforts due to our unique flight research expertise, and there is significant cost sharing available.

TABLE VII.—PLANNING PRIORITIZED BASED ON ANALYSIS OF ALTERNATIVES (AS OF MARCH 2021)
[Acronyms are defined in Appendix A.]

Priority	Work package grouping	Technical elements	ARMD area (Targeted project)	Deliverables	Collaborations	Facility usage (notional)			
						FY22	FY23	FY24	FY25
1	External Icing	• 3D ice accretion • FZDZ/FZRA[1] • Off-body concentrations[1] • Icephobics[1] • Performance prediction	TTBW (AATT VSI)	• TTBW icing impact assessment and gaps (FY25) with current FZDZ capability • Candidate icephobic materials	Boeing, Ansys[2]	LAMP	IRT LAMP		
2	AAM Icing	• 3D icing rotating systems • Ice shedding[1] • Icephobics[1]	AAM (RVLT)	• Rotor test capability (FY22) • Rotor ice shedding database (FY25) • Test methods for ice adhesion (FY25)	SBIR NRC[3], FAA[3]	IRT ERB	IRT ERB	IRT ERB	IRT ERB
3	Engine System Icing	• 3D icing ice crystals	Small Core (AATT P&P)	• Static component testing: Icing dataset (FY23), building block for engine assessment capability (Priority 5)	ONERA MUSIC-haic, Ansys[2], FAA[3]	IRT	IRT		
4	External Icing	• 3D ice accretion • FZDZ/FZRA[1] • Performance prediction	CbA (TTT/AETC)	• Aeronautics database on iced CRM at flight Reynolds number and high lift (FY23) • Baseline iced CFD at Re,C_{lmax} (FY25) (learning here relevant for TTBW)	Boeing, Ansys[2] FAA[3], NRC[3], ONERA[3]	0.3M TCT	NTF Q5 (QinetiQ)	IRT	
5	Engine System Icing	• Ice shedding • 3D icing rotating systems • 3D icing ice crystals	Small Core (AATT P&P)	• Rotating rig test database (FY25) • Capability to assess icing impacts and shedding on engines (~FY30)	NRC[3], Industry[3]				IRT or PSL →
6	Engine System Icing	• HIWC atmospheric characterization	Small Core (AATT P&P)	• Update to atmospheric envelope for design and certification (FY25)	FAA[3], Honeywell[3], Collins Aerospace	DC–8			

[1]Limited activity in this technical area.
[2]Existing agreement that could be leveraged.
[3]Potential new collaboration.

6.2 Icing Options

The combined results of this study yielded several additional icing research activities that may be considered for future investment beyond the priority needs discussed in the previous section. Six options for potential investment are presented in Table VIII. These options address enduring needs and crosscutting needs in icing identified during stakeholder interviews. While the associated technical elements were medium to highly ranked in the TOPSIS analysis, they were not necessarily captured in the priority needs because they represent lower TRL activities with resources that exceed current project plans.

The first option, Foundational Icing Physics Studies, is considered an enduring need and affects all work packages. This research captures the need to conduct small-scale fundamental icing physics studies to improve both computational and experimental capabilities. These studies are needed to make significant improvements in our capabilities, but these come at a higher risk. Examples of such fundamental areas in icing include physics studies like ice particle breakup characterization, physical model development, and heat transfer augmentation caused by icing roughness. In the past, this type of work was captured under larger projects such as AATT but were sometimes harder to justify due to the low TRL and lack of direct connection to higher TRL milestones. Therefore, this work may be better suited for the TTT project since the work there is generally lower TRL, but the knowledge gained is crosscutting.

The second option, Freezing Drizzle (FZDZ) and Freezing Rain (FZRA), reflects the need for expanded experimental capabilities to address the icing challenges associated with these environments. NASA has studied the possibility of replacing the IRT with a large vertical flow facility to include FZDZ and FZRA clouds. The estimated cost in 2015 was $70M, but this was not pursued because it was not needed to address ARMD research priorities. Since that time, other facilities such as the RailTec Arsenal in Vienna, Austria, and the Altitude Icing Wind Tunnel in Ottawa, Canada, have added capacities to generate FZDZ and FZRA clouds that may be able to reproduce the App. O certification environment. Research conducted under this second option would assess the current experimental capabilities worldwide against NASA in-house capabilities. This assessment would be used to determine if there remains a need for NASA to consider major facility investments.

There is a closely related fundamental and crosscutting research element under this second option. Once a suitable experimental capability for FZDZ and FZRA is identified and established, it must be utilized to acquire collection efficiency data that are greatly needed to validate computational icing simulation tools. After calculating the flow field surrounding the external airframe, the first step in an icing simulation is to determine where the water drops strike the surface. The amount of water that strikes the surface is referred to as “collection efficiency.” This is an important validation step because this amount of water directly affects the resulting ice growth that is the second step of the simulation. There is a significant lack of experimental collection efficiency data for FZDZ and FZRA conditions. Furthermore, the previous methods of measuring collection efficiency may not be valid for large drops, where splashing and re-impingement are known to be important. This second research option reflects the need to investigate and develop methods to measure collection efficiency to validate computational icing simulation tools.

TABLE VIII.—ICING OPTIONS BASED ON ANALYSIS OF ALTERNATIVES
[Acronyms are defined in Appendix A.]

Options	Work package grouping	AoA technical elements	Potential ARMD area	Notional deliverables	Potential collaborations
1 Enduring Need	All work packages	Foundational icing physics studies to improve capabilities	TTT	• Foundational Icing Physics Studies that are crosscutting across all work packages.	FAA, Academia
2	External Icing	• Freezing drizzle (FZDZ) and freezing rain (FZRA)	AATT, AETC, RVLT, AAM	• Strategy Study: Explore current experimental capability options for FZDZ/FZRA. Goal: Develop options and strategic partnerships.	FAA, RTA, DoD–McKinley
				• Collection Efficiency Validation: Develop experimental method to measure collection efficiency.	FAA
3	AAM and IPS	• 3D ice accretion on rotating systems • Ice shedding and icephobics • Rotor/propeller performance prediction • Thermal IPS • Low-weight, low-power IPS	RVLT, AAM	• AAM Icing Capability: Follow 2019 RVLT roadmap to develop an experimental and computational icing simulation capability for AAM vehicles.	FAA, Industry
4	External and Engine System Icing	• Icephobics • Off-body concentrations • 3D accretion—ice crystals • HIWC atmospheric characterization	AATT	• HIWC Flight Piggyback Tests: Explore and develop small-scale piggyback test(s) for FY23 flight campaign. Possibilities include icephobic erosion durability, off-body concentrations, etc.	TBD
5	IPS	• Thermal IPS • Icephobics	AATT	• TTBW IPS Strategy: Develop strategy to ice protect TTBW (FY25+) based on learning from vehicle analysis.	Industry
6	AAM and IPS	• Thermal IPS • Icephobics • Low-weight, low-power IPS • Ice detectors	RVLT, AAM	• AAM IPS Demo: Fund Phase 3 SBIR with most promising AAM proposals.	TBD

The technical elements associated with the third option are similar to the AAM Icing work package grouping described in Section 5.3. They are included here as optional work that is needed to accelerate the pace of AAM icing research and develop experimental and computation simulation capabilities. Work in this area is captured as a priority need described in Section 6.1. The current funding level allows for steady and incremental progress and reflects the situation where icing capability is not an immediate requirement for the AAM industry. However, as these vehicles enter service and the operations become more common, weather-tolerant operations will be expected. Unlike the fixed-wing airframe industry, the eVTOL and rotorcraft industries do not have computational tools readily available for icing design and certification. The industry relies heavily on expensive experiments, conservative assumptions, experience, and engineering judgment. The technical elements listed under the third option are an opportunity for expanded work to grow the needed computational and experimental tools to more rapidly advance the AAM market. The technical elements related to IPSs in the third option reflect the need for new, state-of-the-art systems that can meet the power and weight requirements for eVTOL AAM vehicles. The ice protection challenges for these vehicles are new and unique because of the multiple-rotor, tilt-rotor, and tilt-wing designs. The research conducted under this option would involve a range of scales, from small-scale IRT-like experiments up to a full-scale vehicle icing test such as in the McKinley Climatic Laboratory chamber. Large-scale testing of this nature would require support from other organizations, such as the FAA or DoD.

The fourth option is an augmentation to Priority Need 6: HIWC Atmospheric Characterization, described in Section 6.1. The flight campaign provides an opportunity to conduct some added research in the areas of icephobic coatings and off-body ice particle concentrations. More data about the durability of icephobic materials in real ice crystal environments are needed to determine the overall feasibility of the coatings in harsh environments. More data are needed to better define how ice particles may concentrate in certain areas around an airframe. These data are important to the validation of computer codes used to identify the locations of air data and other flight probes. Data for these two areas could be obtained by adding sensors to the airplane in strategic locations. This represents a research opportunity to provide significant data for a relatively low additional cost.

The fifth option envisions future work needed to address the high-efficiency challenges of ice protection on the TTBW. The current work planned under Priority Need 1, described in Section 6.1, will determine the extent of the ice protection needs for the TTBW airframe along with some potential icephobic materials that can meet durability requirements. Research under this option would continue this development through the next steps of building and testing new IPSs that incorporate icephobic materials and limited amounts of thermal energy as needed. This work would then provide potential solutions to the TTBW ice protection challenges.

The sixth option also addresses IPS needs for AAM vehicles, but with a different approach than envisioned under the fifth option. NASA has not typically developed IPSs in-house, instead opting to fund the private sector through programs like SBIR. This sixth option provides for continued investment in the private sector with suitable oversight and NASA involvement. Similar approaches have been used successfully in other areas.

These additional icing research options reflect current and future needs of both NASA and external stakeholders. Investment in any of these areas will provide for greater return on the priority needs described in the previous section because of the fundamental and crosscutting nature of these options.

6.3 Remaining Technical Elements

Table IX lists technical elements with limited activity identified in the priority needs—activity that is not sufficient to fully develop that element as understood from the stakeholder interviews. For example, the technical element 3D ice accretion—freezing drizzle/rain would only utilize existing capabilities, whether they be simulation tools or facilities, to look at impacts to the TTBW. It would not include developing a more robust capability, which is what icing stakeholders desire. Similarly, the work in ice shedding currently planned for AAM would not lead to a comprehensive capability for industry to evaluate whether ice shedding is an issue for their vehicle. However, the work does include some preliminary steps toward that end. Additional work in these technical elements is proposed in Section 6.2 and cross-referenced in Table IX. The shading represents the technical element rankings as previously defined in Table V.

Several technical elements were not captured in either the priority or enduring needs discussed in Section 6.1 or the icing options discussed in Section 6.2. These remaining elements are captured in Table X. The shading represents the technical element rankings as previously defined in Table V. While these technical elements were identified during the stakeholder interviews, they ranked medium to low relative to other technical elements for the near-term or AAM future realities, with one exception. Onboard remote sensing ranked high for the AAM future, but there was no NASA project with a priority need for this technology at the time of this study. Future potential stakeholders were identified for this and the other remaining technical elements, as shown in Table X. These stakeholders may elect to pursue these technical elements at some point in future.

TABLE IX.—LIMITED ACTIVITY IDENTIFIED IN PRIORITY NEEDS

High	Medium

Technical elements	Near term	AAM	Limited work areas
3D ice accretion—freezing drizzle/rain	0.85	0.93	[a]Priority 1, Option 2
Ice shedding	0.78	0.77	[a]Priority 2 and Priority 5, Option 3
Thermal ice protection systems (IPSs)	0.68	0.80	Options 3, 5, and 6
Off-body concentration	0.68	0.68	[a]Priority 1, Option 4
Icephobics	0.61	0.63	[a]Priority 1 and [a]Priority 2, Options 3, 5, and 6
Low-weight, low- power IPSs	0.53	0.65	Options 3 and 6
Ice detectors	0.44	0.62	Option 6
Rotor/propeller performance prediction	0.40	0.63	Option 3

[a]Denotes limited activity in proposed work, not fully addressed (or pick options).

TABLE X.—REMAINING TECHNICAL ELEMENTS

High	Medium	Low

Technical elements	Near term	AAM	Future stakeholders
Onboard remote sensing	0.40	0.61	LaRC, Industry, GRC
Icing condition scaling	0.52	0.48	GRC, FAA, Industry
Mechanical ice protection systems (IPSs)	0.49	0.51	Industry, FAA
Terminal area characterization	0.40	0.53	FAA, GRC
Urban area characterization	0.33	0.57	FAA, GRC
Engine performance prediction	0.54	0.32	GRC, Industry, FAA
Altitude scaling for thermal IPS	0.42	0.27	GRC, Industry, FAA
Small-scale weather forecast/nowcast	0.20	0.40	LaRC, FAA
Altitude scaling for ice crystal icing	0.32	0.20	GRC, Industry, FAA
Low-radar IPS	0.00	0.00	Department of Defense

7.0 Conclusions

In 2020, NASA's Aeronautics Research Mission Directorate (ARMD) commissioned a study to provide a broad and comprehensive assessment of priority needs for NASA and enduring needs for the aviation community in the icing research area. A team of NASA icing subject matter experts (SMEs) was assembled from Glenn and Langley Research Centers to perform the study. The team included multiple NASA organizations, facilities, and areas of expertise, such as airframe icing, engine icing, rotorcraft and icephobics, computational icing, Icing Research Tunnel (IRT), Propulsion Systems Laboratory (PSL), flight operations, advanced materials, aviation weather, and atmospheric remote sensing.

Through dedicated interviews, the team collected technology barriers and needs from a broad section of the icing stakeholder community, which included original equipment manufacturers such as airframe, rotorcraft, and engine manufacturers; emerging urban air mobility companies; and the icing support industry for remote sensing, ice protection, instrumentation, and software development. The team also interviewed representatives from several NASA projects, NASA technical areas, and U.S. Government agencies, and a contractor was hired to solicit input from academia. The interview results were summarized by segments (nine industry segments, seven NASA areas, three segments from other Government agencies, and the academia segment).

A list of 23 icing technical elements were identified from the stakeholder interviews and grouped into four categories: (1) icing performance impacts, (2) ice accretion geometry definition, (3) ice protection and detection systems, and (4) icing weather and characterization. The technical elements were defined at a high level and were inclusive of the physical understanding, modeling, and experimental capabilities needed to address a given element. Subsequently, the technical elements were rated by the SMEs using a variety of evaluation criteria such as industry pull, NASA project pull, other Government pull, and safety and certifiability improvement.

A multivariable analysis technique called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was applied to the SME ratings to produce a set of scores useful for prioritizing the technical elements. The analysis was conducted for four potential future realities to show which of the icing technical elements ranked highly under different sets of possible future circumstances. Those potential future realities were (1) Delayed Return to Growth Due to COVID–19, (2) Return to Growth With Reduced Carbon Emissions, (3) Ultra-Efficient and Quiet Aircraft, and (4) an Emerging Market for Advanced Air Mobility (AAM) Vehicles. Under each scenario, various weights appropriate for that potential future were applied to the evaluation criteria. Sensitivity studies were performed on the TOPSIS results to assist in determining the certainty of the results.

The NASA icing priority needs came from the higher ranked, and in some cases medium-ranked, technical elements for the Reduced Carbon and AAM future realities. Using these technical elements, the team assembled four work package groupings most applicable to the four key ARMD focus areas, or "Fab Four" (Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion (EAP), Small-Core Turbine Engine, and High-Rate Composite Manufacturing), and other ARMD priority areas. The four work package groupings were (1) External Icing, (2) Engine System Icing, (3) AAM Icing, and (4) Ice Protection Systems (IPSs). Several icing technical elements appeared in more than one grouping, indicating that they are crosscutting, which implies that learning from one grouping can be leveraged in another. Using these groupings, the specific icing challenges were described as they relate to current NASA priorities such as the TTBW, Small-Core Turbine Engine, and AAM. Those challenges are summarized as follows:

- For the TTBW and Certification by Analysis (CbA) areas (e.g., External Icing and IPS work package grouping), the specific technical elements or priority needs are (1) 3D ice-shape definition for ice shapes that occur on the vehicle under standard icing and freezing drizzle (FZDZ) and freezing rain (FZRA), (2) assessment of the aerodynamic performance impact of ice on the vehicle, and (3) development of IPS strategies, including icephobic material.

- For the Small-Core Turbine Engine (Engine System Icing work package grouping), the priority needs are (1) ice shedding prediction and shed impact on performance and operability of the engine, (2) 3D ice definition in standard icing and ice crystal icing (ICI) for turbomachinery systems, (3) water and ice particle concentration factors at off-body locations such as the ingestion plane of the engine, (4) engine performance impact due to ice, and (5) establishment of a globally representative high ice water content atmospheric characterization.
- For AAM (AAM and IPS work packages), the priority needs are (1) 3D ice-shape definition for ice shapes that occur on the vehicle under standard icing and FZDZ and FZRA—this is similar to the TTBW need but also includes rotating geometries as well as ice shedding; (2) assessment of the aerodynamic performance impact of ice on the rotor/propeller performance; (3) development of low-power and low-weight IPS strategies, including using icephobic materials; and (4) ice detection systems applicable to the electric vertical takeoff and landing (eVTOL) platforms.

For other NASA priority areas such as EAP, High-Rate Composite Manufacturing, and Commercial Supersonic Technology (CST), there are currently limited icing needs, as other technology development activities have a higher priority at this time. However, as these areas mature, icing technologies will play a crucial role in making these areas viable for industry. The enduring needs for the aviation community are (1) for NASA to continue performing foundational icing physics studies to improve current computational and experimental capabilities and (2) for NASA to address atmospheric characterization requirements that will arise as new vehicles expand operations.

NASA will use these study findings to assist in future project planning toward efforts to conduct high-value research in the icing area. NASA projects will consider including the higher ranked technical elements for inclusion in their portfolios starting in the timeframe of fiscal years 2022 and 2023. Several other technical elements were identified as needs for the icing community, but given the criteria used in this study, they ranked medium to low. The AoA team identified potential stakeholder organizations that could pursue these remaining technical elements at some point in the future.

Appendix A.—Acronyms

3D	three-dimensional
AAM	Advanced Air Mobility
AATT	Advanced Air Transport Technology
AAVP	Advanced Air Vehicles Program
ADWRS	Airborne Doppler Weather Radar Simulation
AETC	Aerosciences Evaluation and Test Capabilities
AIT	Adaptive Icing Tunnel
AoA	Analysis of Alternatives
APU	auxiliary power unit
ARAC	Aviation Rulemaking Advisory Committee
ARMD	Aeronautics Research Mission Directorate
CAS	Convergent Aeronautics Solutions
CbA	Certification by Analysis
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CIRA	Centro Italiano Ricerche Aerospaciali (Italian Aerospace Research Centre)
COVID–19	coronavirus disease 2019
CRM	Common Research Model
CS	Certification Specification
CST	Commercial Supersonic Technology
DoD	Department of Defense
EAP	electrified aircraft propulsion
EASA	European Aviation Safety Agency
ECCC	Environment and Climate Change Canada
EHWG	Engine Harmonization Working Group
ERB	Engine Research Building
eTC	Emerging Technical Challenge
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
FASTLab	Fundamental Adhesion and Shedding Test Laboratory
FOD	foreign object damage
FY	fiscal year
FZDZ	freezing drizzle
FZRA	freezing rain
GRC	Glenn Research Center
GUI	graphical user interface
HEOMD	Human Exploration and Operations Mission Directorate
HISS	Helicopter Icing Spray System
HIWC	high ice water content
HPC	high-pressure compressor
HyTEC	Hybrid Thermally Efficient Core
IC	ice crystal
ICI	ice crystal icing
IPS	ice protection system

IRT	Icing Research Tunnel
LAMP	Laboratory for Adhesion Mitigation Projects
LaRC	Langley Research Center
LPC	low-pressure compressor
LWC	liquid water content
MOC	means of compliance
MUSIC-haic	3D MUltidisciplinary tools for the Simulation of In-flight iCing due to High Altitude Ice Crystals
MVD	median volumetric diameter
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NCAR	National Center for Atmospheric Research
NIS	negative ideal solution
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NRC	National Research Council of Canada
NTF	National Transonic Facility
OEM	original equipment manufacturer
ONERA	Office National d'Etudes et de Recherches Aérospatiales
P&P	Power and Propulsion
PI	principal investigator
PIS	positive ideal solution
PSL	Propulsion Systems Laboratory
R&D	research and development
RATFac	Research Altitude Test Facility
RCA	Revolutionary Computational Aeroscience
RFI	request for information
RIMELab	Revolutionary Icing Materials Evaluation Laboratory
RVLT	Revolutionary Vertical Lift Technology
SBIR	Small Business Innovation Research
SIDRM	Simulated Intercompressor Duct Research Model
SLD	supercooled large drops
SMD	Science Mission Directorate
SME	subject matter expert
SPMR	Strategic Portfolio Management Review
STMD	Space Technology Mission Directorate
TACP	Transformative Aeronautics Concepts Program
TASS	Terminal Area Simulation System
TC	Technical Challenge
TCT	Transonic Cryogenic Tunnel
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
TRL	technology readiness level
TTBW	transonic truss-braced wing
TTT	Transformational Tools and Technologies
UAM	urban air mobility

UAS	unmanned aircraft system/s
UAV	unmanned aerial vehicle
UV	ultraviolet
VIST	Vertical Icing Studies Tunnel
VSI	Vehicle Systems Integration

Appendix B.—Icing AoA Team

Study role and affiliation	Name	Job description
Core team member and subject matter expert (SME), Glenn Research Center (GRC)	Peter Struk	Chief, Icing Branch/Propulsion Division
	Andy Broeren	Research Aerospace Engineer, Icing Branch/Propulsion Division
	Mark Potapczuk	Research Aerospace Engineer, Icing Branch/Propulsion Division (retired in 2021)
	Richard E. Kreeger	Research Aerospace Engineer, Icing Branch/Propulsion Division
SME, GRC	Ashlie Flegel	Deputy Project Manager, Hybrid Thermally Efficient Core Project
	Christopher Porter	Research Aerospace Engineer, Icing Branch/Propulsion Division
	Thomas Ratvasky	Research Aerospace Engineer, Icing Branch/Propulsion Division
	Jen-Ching Tsao	Senior Research Engineer, Ohio Aerospace Institute
	Andrew Work	Researcher, HX5 Sierra (currently with Parker Aerospace Corp.)
SME, Langley Research Center	Kristopher Bedka	Research Physical Scientist, Climate Science Branch/Science Directorate
	Steven Harrah	AST, Electronic Instrumentation Systems, Org D319
	Joseph G. Smith	AST, Aerospace Polymeric Materials, Advanced Materials & Processing Branch/Research Directorate
	Christopher Wohl	Research Aerospace Engineer, Advanced Materials and Processing Branch/Research Directorate
SME, GRC facility representative	Kurt Blankenship	Research Pilot, Aircraft Operations Office
	Judith Van Zante	Icing Engineering Technical Lead, Aviation Test Branch/Testing Division
Program liaison, GRC	Dale Van Zante	Aerospace Engineer, Propulsion Flow Dynamics, Acoustics Branch/Propulsion Division
External SME	Mike Bragg	Consultant, Bragg and Associates
Analysis support, GRC	Ru-Ching Chen	Research Aerospace Engineer, Icing Branch/Propulsion Division
Documentation support, GRC	Sandra Mason	Technical Writer/Editor (Alcyon Technical Services JV, LLC), Publishing Services/Logistics and Technical Information Division

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