Aircraft Icing Analysis of Alternatives

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This paper provides a description of a recent comprehensive Analysis of Alternatives (AoA) for icing research. A team of NASA icing subject matter experts (SMEs) was assembled from NASA’s Glenn and Langley Research Centers, which began by gathering inputs from icing stakeholders in industry, Government, and academia. Those inputs, which were grouped into a number of themes, were used by the SMEs to identify needed icing technical elements. Each of these high-level technical elements included the icing physics, modeling capabilities, and experimental capabilities needed to address a particular element. A multivariable analysis technique called TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) was then applied to prioritize the technical elements for several potential future realities. A large number of icing research needs were identified and analyzed to determine the highest priorities for NASA key focus areas and those that will endure into the future. The primary outcome of the AoA is the identification of legacy and newly identified capability areas in priority order to guide future investment.

I. Introduction

In 2020, NASA’s Aeronautics Research Mission Directorate (ARMD) called for crosscutting studies in three NASA skill and capability areas—combustion/emissions, acoustics, and icing1—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 Four,” were Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion (EAP), Small-Core Turbine Engine, and High-Rate Composite Manufacturing. The studies sought to gather input from NASA subject matter experts (SMEs) and external stakeholders, including industry, other government organizations and academia, 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 Supersonics). The time horizon for this assessment is focused on the NASA ARMD Mid Term, 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 is focused on the NASA ARMD Far Term, 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.

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To meet the objectives of the AoA study, it was 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 was assumed that tool development will also include the validation databases. Tools included engineering-level, high-fidelity codes or system-level analysis. It was also assumed that facilities will continue to be well calibrated and well maintained. Methods for measuring and simulating various aspects of icing included 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.

II. Background

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, icephobic materials, 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. Input was also solicited from other NASA Aeronautics Centers. NASA center and branch affiliations were as follows:

- Glenn Research Center (GRC)
  - Icing Branch
  - Turbomachinery and Turbopower Systems Branch
  - Thermal Systems and Transport Processes Branch
  - Facilities: IRT/PSL, Flight Operations
- Langley Research Center (LaRC)
  - Advanced Materials & Processing Branch
  - Science Directorate, Climate Science Branch
  - Electromagnetics and Sensors Branch

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.

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:

- Identification of icing research technical elements
- Identification of the evaluation criteria for each element
- Identification of data filters
- Identification of possible future realities and weights
- SME ratings
- TOPSIS analysis

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 when compared with traditional clean (non-iced) aircraft. With computational ice accretion prediction, for example, there is a need to update the particle collection efficiency and subsequent ice growth, which occur at longer time scales 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. Current NASA Work in Icing

NASA’s mission for a aircraft icing has been to develop the tools, methods, and databases necessary to enable industry to design, develop and certify 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 advances, 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 generator, 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 ice crystal icing in modern engines, which necessitate simulating complex rotating components and highly 3D geometries. NASA has developed a test article whose geometry is representative of an inter-compressor duct and strut region of a turbofan engine. The Simulated Inter-compressor Duct Research Model (SIDRM) will be used to provide ice crystal physics and validation data for development of NASA’s engine icing simulation capabilities.

GRC is actively upgrading capabilities appropriate for basic research: the Revolutionary Icing Materials Evaluation Laboratory (RIMELab) and the Adaptive Icing Tunnel (AIT). The RIMELab includes a modified lap joint test capability for measuring ice adhesion, grain structure microscopy, a walk-in freezer 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 miles per hour and temperatures down to -20 degrees C.

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

An Aviation Rulemaking Advisory Committee (ARAC) Ice Crystal Icing working group recommended that the FAA and NASA conduct additional High Ice Water Content flight campaign 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 and the Neil A. Armstrong Flight Research Center.
3. Icing Impacts and Certification Challenges for Future Systems

The certification environment for icing is shown in Figure 1. There are three different icing and ice crystal environments, commonly called Appendices C, O, and D (denoting the location in the Code of Federal Regulations (CFR) where each environment is described):

- Appendix C (14 CFR Parts 25 and 29): Typical icing clouds with smaller supercooled liquid droplets, MVD from 15 to 50 microns and liquid water content (LWC) up to nearly 3 g/m$^3$, can exist anywhere between the surface and 29,000 ft.
- Appendix O (14 CFR Part 25): Environment with supercooled large drops (SLD), including freezing drizzle (FZDZ), with the largest drop diameters up to 500 microns and LWC up to 0.44 g/m$^3$; and freezing rain (FZRA), with the largest drop diameters greater than 500 microns and LWC up to 0.31 g/m$^3$.
- Appendix D (14 CFR Part 33): Ice crystal clouds composed of a distribution of ice crystal sizes with median mass diameters of 50 to 200 microns and total water content (TWC) 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.

![Figure 1. Drop Size and Altitude Range](image)

Supercooled liquid clouds (Appendices 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 power loss events.
III. Icing Analysis of Alternatives Workflow Summary

The Icing AoA approach was initially based upon the workflow used in an unpublished 2019–2020 Materials, Structures and Manufacturing (MSM) 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®. 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 flow chart shown in Figure 2, which illustrates the key steps in the process. The following is a short description of the steps followed:

- The icing AoA study team conducted 47 interviews of both internal and external stakeholders and gathered additional needs from four NASA project areas.
- This information was then used to identify and organize a list of needed technical elements in icing research.
- 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.
- Four potential future realities were defined in order to investigate technical elements that may be higher ranked under different circumstances in the future of aviation.
- 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 review process of the stakeholder inputs and refined definitions of the technical elements and evaluation criteria. After this iteration was performed, the TOPSIS analysis was repeated and yielded more consistent results.
- Finally, the results of the final TOPSIS analysis were used to identify priority and enduring needs in icing.

1. Interviews

Through dedicated interviews, the team collected technology barriers and needs from a broad section of the icing stakeholder community. It 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 several NASA projects and technical areas and U.S. Government agencies. 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).

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, International Civil Aviation Organization (ICAO) meetings, and SBIR reviews. The stakeholder input gathered through this effort represents feedback from more than 50 companies, organizations, Government agencies, and academic institutions.

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

- Priority needs for NASA Aeronautics (TRL 5-6 by 2025 to 2035, especially for the “Fab Four”)
- Enduring needs for the aviation community (defined as TRL 5-6 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.
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 Projects and Offices

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. 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 SMD Earth Science Division.

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:

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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?

2. Summary of Interview Inputs
   The following summary by interview segment identifies themes that emerged. Specific icing needs were 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. A high-level summary of interview themes is provided here.
   
   A. 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
      – It is a neutral party to which industry and regulators reach out for assistance
      – Provides experimental and computational tools
      – It is the nation’s “memory” for icing research
   
   B. 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.
   
   C. Certification issues were a significant concern for many interviewees.
      – New requirements will have large impacts on vehicle design, cost, and certification.
   
   D. Icing tools (codes and facilities) are widely used and will continue to be used.
   
   E. The need for icephobic coatings and surface treatments will become more important in the future.
   
   F. New concepts have complex aeropropulsive geometries for which icing impacts are not well understood.
   
   G. Ice detectors will need to distinguish between various types of weather conditions.

3. Technical Elements
   Technical elements associated with priority research needs were identified directly from the interview summaries. Lists of important technical elements were then developed from the interview segments. The technical elements came primarily from industry and government agency stakeholders, as well as 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 was omitted to keep the information manageable. Detailed work that was omitted may have included, for example, physics studies on droplet splashing on wet surfaces, ice particle breakup on fan blades, or development of specialized temperature probes. The original list was combined into 23 elements within four categories: Icing performance impact, Ice accretion geometry definition, Ice protection and detection systems, and Icing weather and characterization.

The technical elements in each of these four categories are defined in Table 1 as follows:

<table>
<thead>
<tr>
<th>Table 1. Technical Elements</th>
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<tbody>
<tr>
<td><strong>(a) Icing Performance Impact</strong></td>
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<tr>
<td>Element no.</td>
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<tr>
<td>1</td>
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<tr>
<td><strong>(b) Ice Accretion Geometry</strong></td>
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<td>Element no.</td>
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</tbody>
</table>
Table 1. Technical Elements (cont’d)

(c) Ice Protection and Detection Systems

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

(d) Icing Weather and Characterization

<table>
<thead>
<tr>
<th>Element no.</th>
<th>Technical element</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Terminal area characterization</td>
<td>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</td>
</tr>
<tr>
<td>21</td>
<td>Urban area characterization</td>
<td>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</td>
</tr>
<tr>
<td>22</td>
<td>High-altitude ice crystal characterization</td>
<td>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.</td>
</tr>
<tr>
<td>23</td>
<td>Small-scale weather forecast/howcast</td>
<td>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</td>
</tr>
</tbody>
</table>

The four selected categories grouped the technical elements at a high level, not necessarily with equivalent work packages. The definitions in Table 1 were provided to the team to clarify the meaning of each element.

4. 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 2. Also shown in the table are the ranking scales that were used for each criterion. For 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. NASA ARMD research priorities were included in the pull criteria as shown in Table 2. Individual SMEs input their ratings based on knowledge of current research plans in each of the Fab 4 areas described in the introduction (Transonic Truss-Braced Wing (TTBW), Electrified Aircraft Propulsion...
The next set of criteria were labeled “Safety and Certification” to capture the criteria listed in Table 2. These criteria all had the same rating scale in terms of the benefit applied to each technical element. SMEs rated the Safety

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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.

The “Disruptibility” criterion was used to capture the extent of future improvement associated with each technical element. Disruption is the amount that 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 de-icer (>50 percent increase in efficiency) may be more disruptive by comparison, allowing de-icing 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 being successful. 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.

5. Future Realities

An important part of this study was the identification of different scenarios, or possible future realities. The TOPSIS analysis was conducted for the 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. The weights were additional inputs to the TOPSIS analysis. The near/mid term is considered to be 2025 to 2035; the far term is considered to be 2035+. Those potential future realities were:

- Delayed Return to Growth Due to COVID–19
- Return to Growth With Reduced Carbon Emissions
- Ultra-Efficient and Quiet Aircraft
- 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.
6. Evaluation Criteria Weights and SME Ratings

Weights for each of the evaluation criteria 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 Ref. 1. 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 had the lowest weight for the fourth future reality, Emerging Market for AAM Vehicles.

An Excel spreadsheet was created by combining the technical elements with the criteria and filters. 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.

7. TOPSIS Analysis

The TOPSIS multivariable analysis was applied to the SME ratings to produce a set of scores useful for prioritizing the technical elements. TOPSIS analysis requires consistent and precise definitions of technical elements, criteria, filters, and weights in order to yield meaningful results.

TOPSIS is a numerical algorithm that cannot independently assign meaning to technical elements regardless of the inputs, and so the results break down when the definitions are poor or inconsistent. It was difficult to keep the inputs (technical elements, criteria, filters, and weights) well defined and consistent when considering the interests of multiple stakeholders and with the many different perspectives that result from the consideration of a complex subject such as aircraft icing. Many of the inputs were very subjective, thus allowing for a wider range of interpretations. A reconciliation process helped remedy this by forcing many people with different viewpoints to reconcile their interpretations and definitions, providing an enhanced basis for consistency and rigorous definitions of terms that were unattainable by individuals working alone. Defining terms and reconciling ratings among SMEs led to more productive reconciliation of disagreements and greater understanding overall. These conversations would not have taken place had there not been a TOPSIS analysis. These well-debated inputs helped to ensure that meaningful results were obtained with the TOPSIS tool.

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.
IV. Results and Discussion

This study was called an Analysis of Alternatives because a large number of needs in the icing research area were identified and analyzed to determine the highest priorities for four of NASA’s key focus areas as well as those that will endure into the future. Table 3 shows the ranking of the 23 technical elements based on the TOPSIS analysis for the four future realities considered among the 4 categories.

Table 3. Technical Element Rankings Across Future Realities

<table>
<thead>
<tr>
<th>Category</th>
<th>Element no.</th>
<th>Technical elements</th>
<th>Future reality ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Delayed Return to Growth</td>
</tr>
<tr>
<td>Icing Performance Impact</td>
<td>1</td>
<td>Airframe performance prediction</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Engine performance prediction</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Rotor/propeller performance prediction</td>
<td>0.60</td>
</tr>
<tr>
<td>Ice Geometry Definition</td>
<td>4</td>
<td>Ice shedding</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3D ice accretion—standard icing</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3D ice accretion—ice crystals</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>3D ice accretion—FZDZ/FZRA</td>
<td>0.83</td>
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<tr>
<td></td>
<td>8</td>
<td>3D ice accretion on rotating systems</td>
<td>0.80</td>
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<tr>
<td></td>
<td>9</td>
<td>Thermal ice protection system (IPS)</td>
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</tr>
<tr>
<td></td>
<td>10</td>
<td>Mechanical IPS</td>
<td>0.46</td>
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<tr>
<td></td>
<td>11</td>
<td>Altitude scaling for thermal IPS</td>
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<tr>
<td></td>
<td>12</td>
<td>Icing condition scaling</td>
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<td></td>
<td>13</td>
<td>Altitude scaling for ice crystal icing</td>
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<td>Ice Protection and Detection System Technology</td>
<td>14</td>
<td>Water/ice particle concentration factors</td>
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<tr>
<td></td>
<td>15</td>
<td>Icephobics</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>Low-weight and power IPS</td>
<td>0.63</td>
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<tr>
<td></td>
<td>17</td>
<td>Low-radar IPS</td>
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<td></td>
<td>18</td>
<td>Ice detectors</td>
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<td></td>
<td>19</td>
<td>Onboard remote sensing</td>
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<td>Icing Weather and Characterization</td>
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<td>Terminal area characterization</td>
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<tr>
<td></td>
<td>21</td>
<td>Urban area characterization</td>
<td>0.38</td>
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<tr>
<td></td>
<td>22</td>
<td>High-altitude ice crystal characterization</td>
<td>0.31</td>
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<tr>
<td></td>
<td>23</td>
<td>Small-scale weather forecast/nowcast</td>
<td>0.27</td>
</tr>
</tbody>
</table>
An important part of this study was the identification of these different possible future realities. The TOPSIS analysis was conducted for the 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.

The rankings changed based on the future reality considered. The value shown in Table 3 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 elements and are shaded in a very light blue.

Several technical elements ranked highly across most of the potential 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.

1. Key Findings for Transonic Truss-Braced Wing (TTBW)

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. 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 3 below.

![Figure 3: Two-dimensional ice predictions using LEWICE code showing larger ice shape relative to airfoil size for the same icing condition.](image)

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, 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 4 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.

![Standard Icing (20 μm cloud) vs. Freezing Rain (>40 μm cloud)](image)

**Figure 4: Comparison of icing challenges on transonic truss-braced wing (bottom-up view)**

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.
- Similarity and service history cannot be solely 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.

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, FZDZ and FZRA. This includes both unprotected and protected surfaces 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.

2. Key Findings for Small Core Engines

Icing challenges for engines occur both from impacts of supercooled liquid water droplets and from the ingestion of ice crystals. Figure 5 below illustrates some of those icing challenges for small-core engines, 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.

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 in-service turbofan engine. This was as a result of ice accretion in the area of the exit guide vanes resulting in blockage of the core flow path and ultimately rollback. Fixing the issue 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. The additional anti-icing heat likely reduced engine efficiency as it increased bleed-air requirements. Such design “fixes” can compromise efficiency goals of future engines, as well. In 2020, the FAA published an Engine Ice Crystal Icing Technology Plan With Research Needs which provides a summary and identifies technology gaps and research needs in this area.

Discussion with the engine community revealed that in addition to ICI, conventional icing due to supercooled water droplet accretion remains a concern due to buildup on nacelles, spinners, and fan blades. Ingestion of shed ice from these components can damage downstream components. Shedding is a major concern for both conventional icing and ICI, and fan imbalance due to asymmetric shedding is also a concern and affects bearing design. Simulation tools are needed to help address these issues. 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. According to the interview results, current simulation tools have limited capability and lack validation not only for ICI, but even for standard icing conditions in an engine environment. All of the engine manufacturer interviewees saw the PSL as a critical path for any new engine certification.

In summary, the icing challenges for Small Core 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 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 not only for ICI, but even for standard icing conditions, in an engine environment.

Figure 5: Icing-related challenges for small-core icing

(fan/spinner icing image and engine cutaway schematic courtesy of Honeywell, Inc.)

The priority needs identified for Small Core icing are:
- 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.

3. Key Findings Advanced Air Mobility (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. 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.

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.

In the near future, AAM vehicles will be expected to have weather-tolerant capabilities to fly in conditions such as icing. Some of the key challenges are:

- 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.

Figure 6: Icing-related challenges facing advanced air mobility vehicles

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

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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.

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

4. Enduring Needs and Other Areas

For other NASA priority areas such as Electrified Aircraft Propulsion, High-Rate Composite Manufacturing, and Commercial Supersonic Technology, 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.

Several icing technologies identified in the analysis are crosscutting. These include (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. Furthermore, such analysis tools will enable icing considerations to be accounted for earlier in the design process, resulting in safer and more efficient vehicles and enabling 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, centrifugal 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. 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

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be an area of research. 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.

Finally, low-weight, low-power IPSs are an area of particular importance in future realities where a low carbon footprint and electric propulsion are expected to be prominent.

V. Conclusions

NASA’s mission in icing is to provide leadership and to provide U.S. industry with the tools, methods, and databases needed 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.

The icing stakeholder community desires that NASA have the capability to conduct fundamental icing physics studies in the public domain to improve both computational and experimental capabilities. 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.

This study identified priority needs in icing research for three of the ARMD Fab Four. As a result, icing research will be conducted to support the technology maturation of the TTBW airplane. This work includes predicting, validating and understanding the impact of icing on the airplane design and potential fuel burn benefit as well as continued study of icephobic materials. In addition, icing research will be conducted to improve computational simulation of ICI inside engines applicable to thermally efficient small cores. Finally, icing research will be conducted for rotor and propeller systems to support new AAM vehicles.

Beyond the Fab Four, ARMD will be working towards predicting ice accretion performance impacts supporting CbA efforts. In addition, planning is beginning for research to improve supercooled water icing tools for the front end of the engine including the fan as this still is a challenge to the aviation community. Underlying these priorities is supporting research in development of computational tools (GlennICE) and in enduring needs.

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

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