NASA/TM—1999-208904 AIAA–99–0243

A Review of NASA Lewis' Development Plans for Computational Simulation of Aircraft Icing

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January 1999

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Prepared for the
37th Aerospace Sciences Meeting & Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 11–14, 1999

National Aeronautics and
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January 1999

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A REVIEW OF NASA LEWIS' DEVELOPMENT PLANS FOR COMPUTATIONAL SIMULATION OF AIRCRAFT ICING

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The use of computational methods in the simulation of flight in icing conditions is an ongoing research effort by the Icing Branch at the NASA Lewis Research Center. The development of accurate, robust, well-documented, well-maintained computational tools is a major function of the research activities of the Icing Branch, in collaboration with its grantees and contractors. The goal of the Icing Branch's efforts is to provide simulation methods that can be used to aid in design, testing, certification, and qualification efforts related to flight in icing conditions. This paper will detail the current research and plans for future efforts in the development of computational tools for simulation of ice accretion, ice protection systems, the effects of ice on aircraft performance characteristics, and the behavior of aircraft systems subjected to icing conditions.

Introduction

Computational simulation in icing can be divided into several key elements. These are ice accretion prediction, ice protection system performance, and icing effects on aircraft behavior. The research activities required for creation of these computational tools consists of the examination and characterization of the underlying physics for each of these elements, determination of the relative importance and influence of these processes for accurate simulation of aircraft icing, and the analytical modeling and software development needed to express the physics in terms of numerical analysis techniques. In addition to such fundamental research, there are also important activities associated with code validation, maintenance, and support which must be factored in to development plans in order to provide a useful tool to those organizations requiring such capabilities.

The ice accretion codes developed at NASA Lewis attempt to predict the growth of ice on aircraft surfaces for environmental conditions representing those that could be experienced in flight. The two-dimensional ice accretion code, LEWICE, consists of four modules for calculation of ice growth on a body subjected to atmospheric icing conditions. These modules calculate the flow field surrounding an aircraft body, water droplet trajectories and impact on the body, the mass and energy balance which determines the amount of water that freezes, and the shape of the resulting ice layer that forms during a given time interval. LEWICE has undergone a re-engineering process in order to produce a more stable and accurate code consistent with the current physical model of the ice growth process. Fundamental research in icing physics has indicated the need for a redefinition of this model. Plans are in place to develop a new model of the process and to construct an updated version of the ice accretion code to reflect this new model. The three-dimensional ice accretion code, LEWICE3D, is based on three-dimensional fluid flow and trajectory analysis coupled to a two-dimensional ice growth analysis. This code also employs a single time step process due to the relatively large computational times and the difficulties associated with grid generation for three-dimensional ice shapes. Advances in computational methods and increases in computer speeds now make it possible to develop a fully 3D ice accretion code. Plans for such a development effort include activities in icing physics, computational modeling, and grid generation.

In addition to simulation of ice accretion on an aircraft or aircraft sub-systems in flight, the Icing Branch is developing a computational model of the NASA Lewis Icing Research Tunnel (IRT). This tool, when completed, will allow researchers to obtain important insights into the possible outcomes of their experiments prior to the actual test. This could help in designing better experiments, in increasing the productivity and efficiency of a test program, and in gaining some insight into the outcome of a test due to the increased diagnostics available from a well crafted computational simulation.

NASA's simulation of ice protection devices is currently based on extension of the thermal analysis in ice accretion methods to include thermal systems, either hot-air or electrothermal. Current efforts include validation testing and eventual incorporation into updated versions of the LEWICE code once version control and maintenance procedures have been finalized. Support efforts for this development process include testing of thermal ice protection systems under controlled icing conditions in the NASA Lewis Icing Research Tunnel.

The effects of ice growth on the performance of aircraft can also be simulated using computational fluid dynamics codes specially tuned to account for the distinctive characteristics of ice shape geometries. This can include adapting grid generation methods to account for the details of ice shapes, incorporating roughness effects into turbulence models, and altering transition models to reflect the extended length of transition that is characteristic of boundary layer growth on rough surfaces. Planned efforts in these areas will lead to more accurate prediction of the aerodynamic effects of ice growth and also to the inclusion of icing effects in flight simulator software. Development of such methods should aid in determining which ice shape characteristics are most critical to the performance of the aircraft thus allowing more rational determination of appropriate wind tunnel and flight tests. Additionally, development of flight simulation methods should enhance safety by allowing pilots to experience flight in icing conditions prior to experiencing it for the first time in flight.

The Icing Branch has a comprehensive plan for the development of computational simulation methods. Activities range from studies in fundamental icing physics to software development processes to validation efforts. This plan includes in-house efforts and collaborative activities with our research partners. The ultimate goal of this effort is to produce useful tools for industry and government organizations to enhance aircraft safety and to aid in design and certification efforts.

Goals and Objectives

The aviation industry currently uses computational icing simulation tools to assist in its efforts to evaluate the impact of exposure to icing conditions on the performance of an aircraft and of an aircraft's subsystems. This evaluation process can occur during many phases of the aircraft's design, manufacture, and operational lifetime. Figure 1 illustrates such potential uses of icing simulation tools for a typical commercial transport. Depending on the area of interest and on what information is being sought, different code capabilities will be required in order to provide accurate solutions to the designer or certification official. It is therefore imperative that the computational simulation tool be used in the appropriate circumstances and the developer of such a tool adequately delineate the range of capabilities for the software system and that the software be constructed so as to meet the requirements designated to assure system accuracy, reliability, and usability.

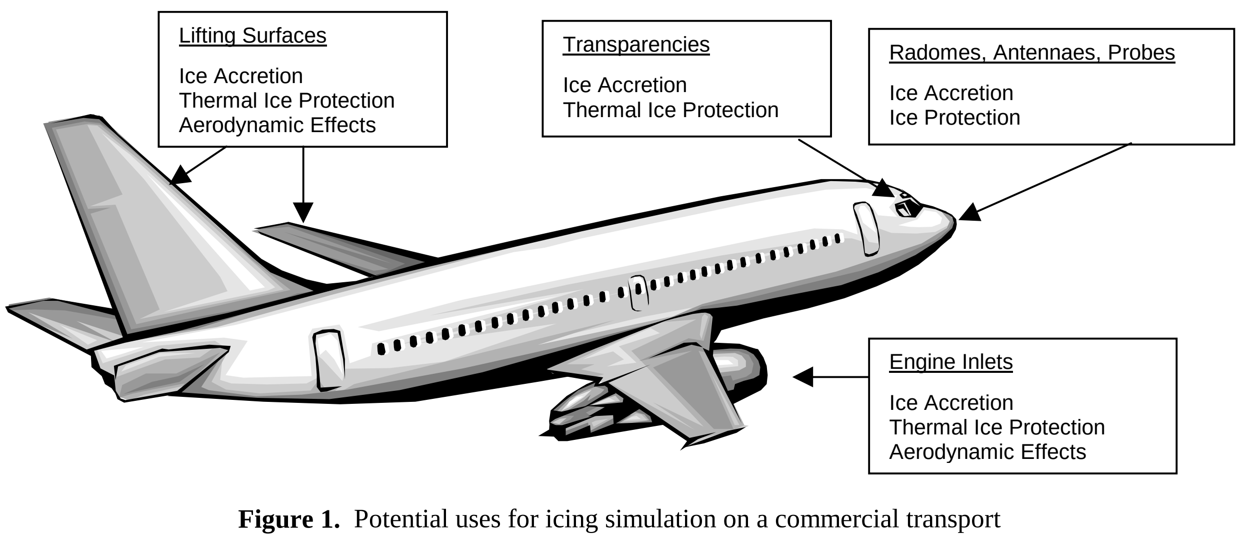

Figure 1. Potential uses for icing simulation on a commercial transport

The Icing Branch has developed several tools for icing simulation over the years and continues to work towards increased fidelity of the physical models incorporated into the software, as well as towards enhanced usability with respect to the currently existing simulation tools of our customers.

With these thoughts in mind, several goals for icing simulation development efforts can be established. These goals form the framework from which our strategic plans are established and help determine which solution paths to pursue in accomplishing the elements of such plans.

Goal 1: Provide accurate and reliable icing simulation tools to the aerospace community

The development of accurate and reliable simulation software is a challenging task which requires an understanding of icing physics, aerodynamics, droplet dynamics, validation and verification issues, software development principles, and support requirements. As the comprehensive nature of this goal has become more apparent, it has helped reshape the strategic path upon which our simulation development efforts are headed. Not only must we be concerned with the understanding and modeling of the governing physical phenomena, but we must also incorporate into our engineering effort an increased awareness of how the software is ultimately used.

Goal 2: Serve as a resource for information on icing simulation methods and underlying icing physics

Once simulation tools have been developed, the knowledge accumulated by the developer (in the groupwise sense) can itself become a valuable resource for the aerospace community. The Icing Branch has always strived to share the information gained from its simulation development efforts with the broader icing community. This must be taken one step further however by incorporating the needs of the community into its plans for software development, improvement, and verification. This was most recently demonstrated in the NASA Aircraft Icing Forum held at Lewis during June of 1998. There are also plans for periodic computational worksops that will provide the user community software updates, interactive training, and a forum for information exchange and problem solving techniques.

Goal 3: Stimulate a greater understanding and awareness of the impact of in-flight icing on all aspects of aircraft operations

The development of simulation tools and accumulation of knowledge regarding the impact of operation in icing conditions are only part of the overall aim of our research efforts. In order to make these goals meaningful, the Icing Branch endeavors to make its work available to the aerospace community and to all other interested parties. Specifically in terms of the research effort itself, this goal is partially achieved by reaching out to other organizations in cooperative relationships with the purpose of performing fundamental research critical to accurate simulation of icing phenomena and its consequences.

From these goals, the Icing Branch has developed over the years a comprehensive approach to icing simulation. The research efforts and strategic plans drafted to direct those efforts can by no means be accomplished by the Icing Branch alone. Thus, much of our effort is wrapped around a combination of research performed in-house as well as support for and collaboration with outside research organizations. The plans being presented in this paper reflect not only the thoughts of the Icing Branch but also the input of our research partners as well as the input from end users of the simulation tools being developed.

Icing Simulation Development Plan

Looking at the simulation needs from Figure 1 and considering the goals statements described above, a plan has been constructed to coordinate the efforts of researchers at NASA as well as to insure that our collaborative activities with other research organizations are directed towards a shared vision of computational icing simulation development. That plan has always been a living document, changing in time as the needs of the aerospace community are identified and as emerging technology provides alternate avenues of development for new simulation capabilities. The most recent manifestation of the NASA Lewis Icing Simulation Development Plan was identified in broad outline at the aforementioned Icing Forum. What is presented here is derived from that plan but includes a more detailed examination of the specific research tasks envisioned to implement that plan. The tasks discussed represent those activities that have been identified to date which advance us along the path towards a fuller representation of an aircraft icing encounter and its consequences.

The scope of the computational icing simulation effort at NASA Lewis is quite broad and is divided into three key areas: ice accretion simulation, ice protection system simulation, and the effects of icing on aircraft aerodynamics. In discussing the research needed to support these development efforts, the topic of icing physics will also be covered as a major factor of the overall simulation research effort. Since we are focussing on computational simulation of the physical processes involved in the icing event, three other related elements of the NASA base research program will not be discussed. These three areas are icing scaling, experimental techniques for icing simulation (i.e. tunnel testing methods and icing tanker testing), and aircraft stability and control issues.

Ice Accretion Simulation

The computational tools being developed at NASA to simulate the accretion of ice on aerodynamic surfaces, LEWICE and LEWICE3D, have a long history and have been used in many circumstances from design to analysis to certification. The current development efforts for those codes are focussed on extending the range of their application and on enhancing the rigor of the process leading to their modification, verification, and support. The development path for these two tools has always followed separate but inter-related tracks, one for two-dimensional simulation and another for three-dimensional simulation. This separate track approach evolved from the fact that LEWICE was a 2D code and it was felt that the requirements of a 3D code were sufficiently different as to encourage the creation of a new code instead of the modification of an existing 2D code.

LEWICE (2D)

The current objectives for further development of the two-dimensional LEWICE software system are twofold. These objectives are to insure reliable, accurate performance of the software through application of software management techniques and to expand the capability of the software through incorporation of new knowledge of the physics of icing, as it becomes available.

The first objective and the highest priority for NASA's icing simulation development plans is to create and implement a more rigorous software development environment using LEWICE as a pilot project. This is being undertaken in order to insure that the simulation product being distributed to the icing community has undergone thorough redesign, testing, and documentation. The LEWICE software management plans are modeled after the Capability Maturity Model for Software (CMM), which is a detailed roadmap for software process improvement developed by the Software Engineering Institute at Carnegie Mellon University.[1] This should allow an increased level of control over current and future modifications to the software which are undertaken to incorporate new capabilities or to address those deficiencies identified in the software system. Some of those details will be discussed below and a more thorough description of this effort can be found in the paper by Levinson, et al[2].

The first and most important outcome of the software process improvement project to date has been to identify what software management processes mean for the creation and development of research software systems and how they can be applied to the LEWICE ice accretion code. That is, the software development life cycle was identified as an important tool for guidance in crafting plans for LEWICE development. This life cycle describes specific activities that must be undertaken to develop, verify, and maintain any large software product.

To date the team has accomplished the following tasks in applying the principles of the CMM to LEWICE:

- Formulation of a LEWICE Software Development Standards document which consists of a Coding Standard, Development Practices, and Automated Revision Control Procedures. This document describes the current procedures for construction and maintenance of LEWICE
- Development of a baseline version of the code which conforms to the Coding Standard. This consisted of restructuring of the subroutines, regrouping of common blocks, consistent implementation of naming and numbering schemes, enhanced modularization, and creation of prologs for each subroutine
- Testing of the baseline version for range capabilities and current ice shape modeling capability by comparison to a large database of experimental ice shape tracings
- Implementation of team-based planning and development efforts
- Implementation of an automated revision control system to insure that the procedures can be followed consistently

Further work is planned to apply all of the elements of the CMM to the LEWICE code as they would normally be applied during the maintenance phase of the software development cycle. As such, the team is currently or will in the near future undertake the following activities.

- Develop a Software Configuration Management Plan that will contain specific information on configuration identification, control, audit, and review. The plan will also detail project configuration management responsibilities

- Establish and implement Software Formal Inspections
- Prepare a LEWICE Software Requirements Specification document in order to determine what is expected from LEWICE and to formulate a basis for evaluation of testing and future code modifications
- Implement the changes to the LEWICE code required to meet the specifications of the requirements document and employ the formal software inspection procedures to ensure compliance with those requirements

While there is still much to be done, the LEWICE software is currently under significantly better, more reliable control now than when this project initiated. The result of this process improvement effort will be a new version of the software, which is designated LEWICE 2.0. It is expected that the methods outlined above will continue to be refined and that the lessons learned from this pilot project will guide the Icing Branch in future software development projects.

The second objective for LEWICE development is to continue the incorporation of new physics and new capabilities into the code, consistent with the software management plans mentioned above. With respect to icing physics, several efforts have been sponsored over the past few years[3-5] and additional efforts are underway currently. These efforts focus on creating a more thorough understanding of the ice accretion process and on how to develop a more complete model of that process than is currently available in LEWICE.

The ice accretion model used in LEWICE to date has been based on the formulation described by Messinger[6]. The model is essentially a one-dimensional, steady-state thermodynamic control volume analysis applied at discrete locations on the surface of a body for finite time intervals. The control volume dimensions and time intervals are configured in such a way as to allow repetitive application of the analysis over the entire surface of the body and for time periods representing actual icing encounters. This approach, despite all of the inherent approximations, has proven to be quite good at predicting ice growth for single airfoil geometries over a significant range of icing conditions. Wright and Rutkowski[7] have most recently demonstrated this capability in their comprehensive experimental to computational comparison effort.

For most icing conditions, this model does a very good job of predicting ice growth on aircraft surfaces. However, for conditions of near freezing temperatures and clouds with high liquid water content, the Messinger model does not adequately describe the dynamic behavior of the ice-water mixture existing on the surface. As a result, there are some elements of the ice accretion process that are not adequately modeled in LEWICE. These include: water film dynamics on a rough surface, the role of ice roughness in boundary layer development and in resulting convective heat transfer augmentation, and the effects of droplet splashing and droplet break-up on water catch. The length and time scales associated with these processes are significant elements which must be accounted for in any model. For instance, the size of the ice roughness with respect to the water film thickness could be critical for determination of how unfrozen water is distributed on the surface under the influence of the shear forces imposed on the water by the surrounding air flow. As a consequence of this water film distribution process, the time scales for water motion on the surface and for freezing of that water must be understood in order to assure proper representation during a given time step of the computational simulation.

During the past several years, efforts at gaining further insight into the processes governing ice accretion have included research activities within the Icing Branch and by several collaborative efforts with other organizations. Olsen and Walker[8] conducted some of the initial work in this area via high-speed motion pictures of the icing process. Their work indicated that water on the surface might not be behaving as previously thought and led to more recent investigations by Shin[9] and Hansman.[10] Cumulatively, these efforts have suggested that the interplay of droplet impingement, water film dynamics, heat transfer, and ice roughness growth form a much more complex sequence of events than is modeled by a control volume analysis. The dynamics of the process seem to occur at length scales below that of the roughness (i.e. ≤ 1mm) and as such could be very difficult to simulate if it is indeed necessary to reproduce all of the details of the process. It seems preferable at this point in time to conduct the research necessary to understand these interactions with the goal of developing models that incorporate the effects of such phenomena without requiring their reproduction on such small scales.

In pursuit of such a model (or models), more recent research has focussed on two of the areas mentioned previously which are not modeled adequately in LEWICE. The first of these efforts centered on determining the influence of ice roughness on boundary layer development and heat transfer. One of the characteristics of ice roughness is that its size can be as large as or greater than the thickness of the boundary layer. Since most roughness modeling assumes roughness heights much smaller than the boundary layer thickness, some experimental work was performed to examine the effects of much larger roughness elements.

Winkler[11] performed Laser Doppler Velocimeter (LDV) studies of flow over hemispherical roughness elements to determine the structure of the flow immediately surrounding these elements. His work covered isolated roughness elements as well as two patterns of roughness elements and indicated that vortex patterns generated by the roughness play a significant role in convective heat transfer on the elements themselves as well as on the downstream behavior of the heat transfer process. Although, no correlation for inclusion into LEWICE was forthcoming, this work can be used to correlate with more elaborate models of the heat transfer process. As a follow-up to that study, work is currently underway on using Direct Numerical Simulation (DNS) methods to reproduce the experimental results with the idea that a DNS approach could be used to develop a relationship between roughness geometric parameters (eg. height, width, spacing, etc.) and heat transfer augmentation. If established, this relationship could then be used as a correlation parameter in the simple integral boundary layer model in LEWICE.

Other work on heat transfer augmentation has been conducted by Bragg, et al[12] and Dukhan, et al.[13] The work by Bragg, et al centered on the evaluation of boundary layer behavior on airfoils with varying degrees of roughness. They examined velocity components in the flow surrounding such geometries using hot wire probes.

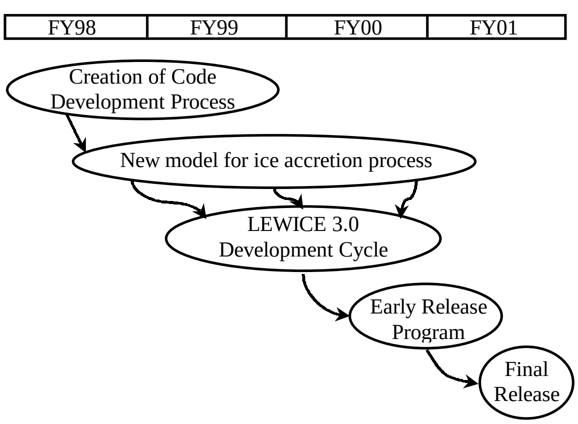

Figure 2. LEWICE development path

Their results indicated that the boundary layer transition region extended over significant portions of the airfoil and that the current modeling method, assuming a single transition point, was in error. Dukhan, et al[13] used metal castings of actual ice shapes, from accretions deposited on flat plates, to obtain average heat transfer coefficients for varying roughness levels. Their results indicated that heat transfer augmentation increased with relative roughness height until it reached a plateau which corresponded with the roughness height at a level equivalent to the boundary layer thickness. Thereafter, any augmentation was strictly due to increased surface area.

At this point in time, what is needed is to take a comprehensive look at these and other heat transfer experiments and then determine if sufficient information is available to construct a correlation or model for use in codes such as LEWICE. Such an activity is planned for the near future to guide future research or to begin construction of a new model.

The other physical process currently under examination is the dynamics of the flow of water on the ice surface roughness. As part of this examination, Rothmayer is constructing an analytical model of the interaction of the water film with the surrounding air flow in an attempt to calculate the roughness levels that may be expected to develop under varying conditions of water loading, air speed, and temperature. The concept is to use the equations governing hydrodynamic stability and the resulting wavelengths in the water layer to suggest the possible roughness sizes that could be expected to occur during the freezing process. What is expected is a correlation that will determine the ice roughness level as a function of the above input parameters for localized regions on the airfoil/ice shape geometry. If hypothesized correctly, these roughness predictions can then be used in conjunction with the heat transfer augmentation relations developed from that work to result in a more physically realistic representation of the heat transfer input to the ice accretion energy and mass balance routines.

These two objectives of the LEWICE development plan, software process improvement and icing physics model development, when completed will lead to a future release of the software. This future release will incorporate our current understanding of the ice accretion process, include the features and capabilities needed by the user community, and be designed, tested and released according to accepted standards for software development. The process will occur in the sequence shown in Figure 2.

Since both the development process and the software content will be changing over this period, there will be an opportunity for input from the user community into the nature of the resulting simulation tool. As such, NASA will be developing requirements for a next version of LEWICE that will cover all elements of the new software system. Input into the determination of the appropriate requirements that the software shall satisfy must come from many sources. The end user can provide information on what range of input conditions should be covered and what accuracy is needed for desired output quantities. The developer can then determine what techniques can be employed to satisfy those requirements. The specification of these requirements will then shape the entire development process and will include the following:

- Specifications for aircraft systems and sub-systems that are to be modeled with the software. This plays a critical role on selection of major components of the software as well as on the type of verification testing that is undertaken.
- Accuracy requirements for quantities such as ice shape (this could encompass a number of geometric features), impingement limits, roughness, or feathers
- Specifications on icing cloud conditions that will be modeled, such as, droplet size and distribution, temperature range, and liquid water content
- Accuracy requirements for intermediate physical quantities of importance such as velocities, pressures, local collection efficiency, heat transfer terms, mass flux terms, ice density, water runback, and others.
- Requirements on non-physical parameters of importance such as controls on time step size selection, control volume or grid spacing, input parameter error checking, error checking of internal sub-routines, error messages, selection of information for output printing, and format specification for print and plotting output files.

This detailed specification of requirements will be used to guide the design process and to help in determination of the level of fidelity needed for the governing equations of the various physical processes being simulated as well as for their computational representations within the code. For example, if ice growth on a multi-element wing geometry is to be modeled, the requirements on the accuracy of ice shape and droplet impingement results could determine the selection of the nature of the flow code being used in the calculation. Thus, requirement specification is not a trivial task, indeed it has major implications on all subsequent software design, testing, and acceptance.

Once the new software system is in place, it enters into a well-defined maintenance phase that will be based on the experience gained in the current re-engineering effort of the most recent version of LEWICE, as described above. This cycle of renewal for the LEWICE software system will continue as new capabilities and new models of the physics of icing become available and are considered desirable additions by the user community.

LEWICE3D

Although the two-dimensional version of LEWICE is the most widely used software tool developed by the Icing Branch, requests for three-dimensional ice accretion simulation capabilities have increased over the past several years. This need has been met by the development and use of LEWICE3D.[14,15] This software is based on extension of the LEWICE two-dimensional ice growth model to selected streamlines or geometric cuts along three-dimensional surfaces coupled with full 3D versions of flow field and droplet trajectory calculations. Currently, the ice growth calculation is limited to a single time step covering the entire icing exposure. In this configuration, the software has been used successfully to evaluate droplet impingement patterns and ice growth for aircraft geometries ranging from engine inlets to radomes to wings, and finally to complete aircraft configurations.[16] A typical example of the LEWICE3D output can be seen in Figure 3, ice growth and impingement patterns for a commercial transport engine inlet.

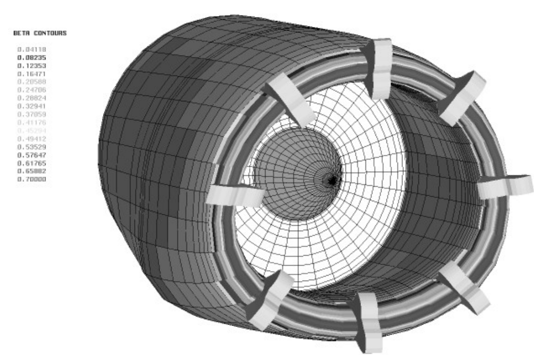

Figure 3. Ice shapes and collection efficiency values for a commercial transport engine inlet

An analogous development path to that for the 2D case has been outlined for LEWICE3D as well (see Figure 4). Building on the process improvement activities of the LEWICE pilot project and incorporating new ice accretion physics, as described later in this document, LEWICE3D will make the transition from a quasi-3D research code to a full 3D analysis tool. The final product will thus require the development of a full 3D ice growth module and include the capability to perform multiple time step calculations of ice growth for complex 3D aircraft geometries. Significant input from the user community with respect to required capabilities of such a tool will be needed, as detailed specification of requirements that are reasonable and achievable will be critical to the success of such an ambitious development effort.

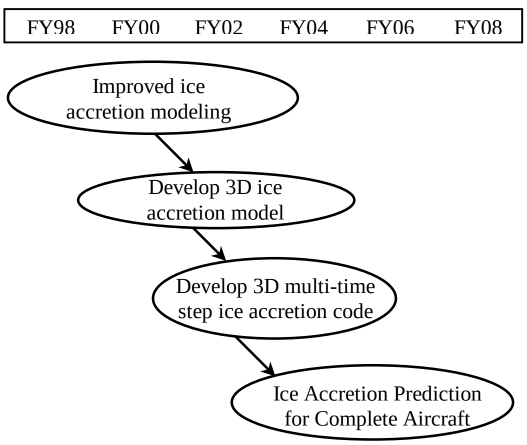

Figure 4. LEWICE3D development path

Recent developments in computer hardware and in computational fluid dynamics as well as in associated fields such as grid generation and turbulence modeling have made it possible to consider more routine use of three-dimensional modeling for analysis of conditions such as ice growth patterns and the effects of ice accretion on aerodynamics. Also, those organizations performing 3D aerodynamic calculations typically have their own preferred software solution. As a result, the Icing Branch will continue to develop LEWICE3D as a code that can be interfaced with a variety of flow field codes.

From the development path diagram outlined above, it can be seen that the initial work element needed for the 3D code is essentially the same as the work for the 2D code. That is, the recent developments in our understanding of the ice growth process must be organized into a model that will improve upon the current capability in glaze ice simulation. In addition to the features that must be addressed for the 2D case, ice growth modeling for 3D geometries must be able to account for the unique "scallop" ("lobster-tail") formations (See Figure 5) that occur on wing or tail surfaces with large sweep angles. The mechanism that creates these formations is not understood at this time, thus making modeling of such features difficult if not impossible.

Figure 5. Scallop ice formation along the leading edge of a swept NACA0012 wing.

The current work on this subject is being undertaken at the Icing Branch by Vargas.[5,17] His results indicate that scallop formation can be characterized by three different modes; complete scallops, incomplete scallops, and no scallops. The main driver for which of these formations occurs is the sweep angle of the wing. It appears as though when some critical sweep angle is reached the ice growth rates of the glaze ice feathers, away from the stagnation region, can overtake the ice growth region near the stagnation region and the feathers then grow and merge into ridges. These ridges are oriented perpendicular to the local streamline direction and are spaced periodically in the spanwise direction, thus giving the "scallop-like" appearance.

These investigations have provided insight into the structure of the scallop ice shape formation and suggest how a model based on correlation with the sweep angle could be constructed. However, questions still remain as to the mechanisms producing this behavior and the periodic nature of the structures. Continued investigation of these 3D processes is required before a full 3D ice accretion model can be expected to reproduce such structures

Another significant effort directed at providing information for enhanced modeling has been some recent work by Papadakis, et al[18] on evaluation of droplet impingement for 3D geometries such as multi-element airfoils and engine inlets. Their work (an example of collaborative research between NASA and another organization) has provided information that will be used to evaluate and improve the droplet trajectory modeling included in both the two- and three-dimensional versions of LEWICE.

This work was undertaken to examine some differences that had been observed between computational results and prior experiments. Under conditions where there are significant sections of a geometry with low curvature and the freestream air flow is essentially parallel to the surface, the droplet trajectory calculations can indicate impingement much further aft on the body than is indicated by either direct impingement measurements or is inferred by observation of ice growth on the surface. As such, model geometries were chosen that would highlight this behavior and would help determine whether this is a measurement error or a deficiency in the modeling method. To date, the test program has been completed and evaluation of the results is currently in progress.

One of the features not currently included in LEWICE3D, that is a key element of the 2D version, is the ability to perform multiple time step calculations of the ice growth. While single time step calculations can provide valuable information on ice mass, general shape, and relative accumulation at various locations on the body of interest, a multiple time step calculation is preferable if a more detailed ice shape geometry is required. This would generally be the case if the predicted geometry were to be used for subsequent aerodynamic evaluation. This capability comes at significant cost from increased complexity of the modeling problem and from additional computational time for each time step.

Numerical Simulation of the Icing Research Tunnel

Codes such as LEWICE and LEWICE3D provide simulation of the ice growth on bodies in unbounded domains subjected to uniform cloud conditions. The conditions in an icing simulation facility, such as the IRT, can be somewhat different than such a scenario due to the varying cloud uniformity, the presence of the tunnel walls, and the nature of the tunnel aerodynamics. In order to investigate these effects and to ultimately develop a tool which could be used to assist in the design of icing experiments, NASA has initiated a research activity designed to develop a numerical simulation of the Icing Research Tunnel.

The goal of this simulation effort is to computationally reproduce the cloud conditions in the test section of the IRT for the entire range of icing conditions that the tunnel can produce. Further, it is desired to eventually incorporate modeling of various test articles in order to predict droplet impingement patterns and ice shapes on such articles as they would occur in the IRT. Such a capability has several obvious benefits. The first is that potential changes to the IRT, whether structural or functional, might be simulated prior to their implementation in order to assess their effects on the salient features of the icing cloud. In combination with the modeling of a test article, such a capability would allow researchers planning test programs in the IRT to evaluate possible outcomes of the testing and thus adjust either the test article or the test matrix in order to maximize the usable data obtained during the test entry. Finally, such a capability would allow researchers to understand the effects that tunnel geometric features and model installation components have on the ice shape accreted on their test article. This, in turn, would provide a greater understanding of the test results and provide insight into expected in-flight icing results for the same test article.

As a first step towards development of such a tool, NASA has sponsored development of a computational simulation of the portion of the IRT starting at just upstream of the spray bars through the test section and ending at the diffuser exit. Hancir and Loth[19] are using the NPARC code, a 3D structured-grid Navier-Stokes code, to simulate the aerodynamics in the IRT and have modified the KIVA code, a code developed for fuel droplet spray modeling, to simulate the droplet behavior from the exit of the spray nozzles to beyond the test section region. This new software tool is called K-ICE. This simulation of the droplet behavior differs from that of the LEWICE codes in that the influence of the turbulence in the airflow is accounted for in the calculation.

Figures 6 and 7 show the distribution of water droplets passing through a vertical plane in the IRT test section, with and without the influence of free-stream turbulence respectively. These plots indicate that the turbulence in the IRT can play a significant role in the dispersion of the droplets from the spray nozzles. Without the free-stream turbulence the cloud pattern in the IRT would have large spatial fluctuations in the LWC, thus degrading the usefulness of the resulting ice shape accretions.

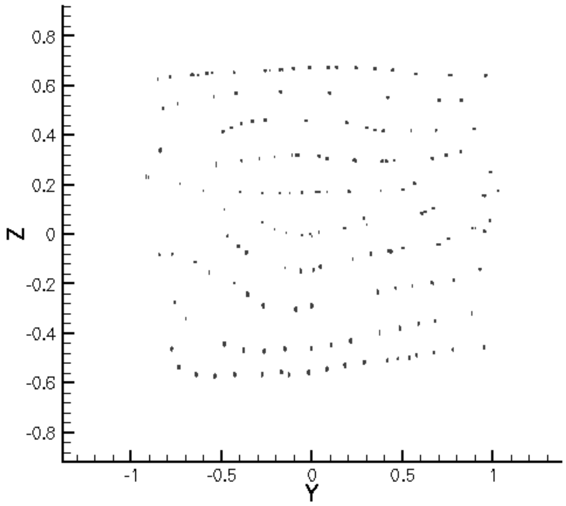

Figure 6. Droplet dispersion pattern at test section of the IRT without the effects of tunnel turbulence.

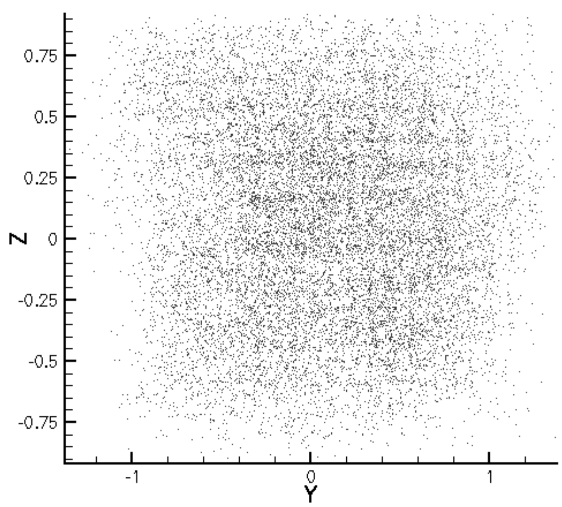

Figure 7. Droplet dispersion pattern at test section of IRT with effects of tunnel turbulence included.

Results such as these help increase the understanding of the physical mechanisms driving the icing process and allow researchers to determine what elements of the process are important to model accurately in a computational simulation. Continued work is needed to increase confidence in results of this simulation method. This will require comparisons with experimental information, some of which has already started and is reported by Hancir and Loth[18]. In addition, as with the software development process outlined earlier for LEWICE, a comprehensive set of requirements will have to be developed and the software system being created from a combination of NPARC and K-ICE will need to eventually come under that same software management process.

Ice Protection System Simulation

The prediction of ice protection system behavior is a valuable capability for both the designer and the organization seeking to obtain certification of their aircraft. This capability is most useful when combined with an ice accretion prediction tool in order to determine the ability of a given design to operate as either in an anti-icing or de-icing mode. Of particular interest would be the capability to examine a matrix of design and off-design points with respect to device operating parameters as well as icing conditions. The Icing Branch has developed some additional features for the LEWICE code that allow just such a simulation for several types of thermal ice protection systems.

In the last version of LEWICE, several additional subroutines were added to allow users to simulate the behavior of an electro-thermal or a hot-air ice protection system. In both cases a specified heat flux value is required from the user whether for embedded electrical heater elements or to simulate the hot air heat flux on the interior walls of the heated body. Internal layers of insulation and structural materials can also be simulated as long as thickness and thermal conductivity can be provided. Some comparison work has been done for this code addition and has been documented in the report by Miller, et al.[20] Their work indicated good agreement for the range of conditions of the experimental program.

Another addition to LEWICE has been developed based on the ANTICE code of Al-Khalil[21]. This code predicts the behavior of anti-ice thermal systems including the effects of water runback in the case of a so-called ‘running wet’ system. The same experimental database developed for the LEWICE thermal ice protection system additions can be used to evaluate the ANTICE code.

Plans for these two codes include incorporation into a future release of LEWICE sometime after the release of LEWICE 2.0. This staged release process is being used because these additional capabilities have not been subjected to the internal re-engineering discussed earlier. Once the process of making these software sub-systems conform to the LEWICE Software Development Standards, they will then be available in an updated version of LEWICE 2.0.

Further work in this area is needed both on creation of more validation information and an expansion of the modeling to include the behavior of the hot-air jet for such systems. Some additional experimental testing for thermal system analysis is currently planned, as are further comparisons between computational and experimental results.

Finally, there are other methods of ice protection, which use non-thermal approaches to ice removal. Chiefly, these are mechanical systems and chemical systems. Mechanical systems use a variety of techniques to break the bond between the ice and the underlying aircraft surface material. These can range from pneumatic boots attached to the aircraft surface to magnetic coils embedded under the aircraft skin which induce eddy currents in the skin when an electric current is passed through them. Chemical systems operate by exuding a fluid freezing point depressant onto the surface that prevents ice formation or carries away existing ice by combining with it and dropping the freezing point below the ambient conditions. Modeling of either mechanical or chemical systems is not currently included in the Icing Branch research plan.

Effects of Icing on Aerodynamics

Once a series of representative ice shapes have been developed, either from computation or experiment, it is desired to assess the effects of such shapes on the aerodynamics of aircraft components. As in the case of the ice shapes themselves, this can be performed using either computational or experimental methods. The ability to calculate performance degradation resulting from an ice accretion can be a very useful tool for quickly examining the impact of a large array of accretions subjected to varying flight conditions. The challenges associated with performing such calculations are the same as those for the CFD community at large with the added complications of accounting for the irregular geometries and the complex flow behavior associated with ice shapes.

Aerodynamic analysis of iced airfoils, wings, and complete aircraft can potentially be performed using a number of tools of varying sophistication and complexity. Methods can range from well crafted correlation schemes based on a large database of prior test information on similar geometries to the most complex 3D Navier-Stokes analysis using unstructured adaptive grids. Selection of the appropriate computational or experimental tool should be based on an examination of what information a given method can reliably provide using the minimal amount of computational time and consistent with the experience of the user. In the past, the Icing Branch has sponsored just such work by considering the capabilities of potential flow codes,[22] interactive boundary layer methods,[23] and structured grid as well as unstructured grid Navier-Stokes methods.[24,25] The aim of our work has always been and continues to be to use generalized CFD tools and to modify them as needed to account for the unique requirements of computing flow over iced surfaces.

Presently, the Icing Branch is working on development of techniques necessary for accurate simulation of iced aircraft aerodynamics with Navier-Stokes codes that utilize structured grids. The first step in such a computational simulation is creation of the grid. This can lead to a number of complications with respect to the grid method successfully completing the computation and with the suitability of the grid if it does run to completion. Most of the issues revolve around how to adequately deal with the ice shape features that are on the scale of the roughness.

Since ice roughness is large enough to be captured by ice tracing techniques, these features are present in the geometry files used as input to the grid generator. In many cases, the ice tracings represent these roughness elements as small surface features with high curvature, either concave or convex. Most structured grid methods (and even unstructured grid methods) have a hard time putting a grid around such a shape. A research activity directed at addressing this issue is currently underway and has several phases of development. These phases are outlined in Figure 8. This effort is directed at providing capabilities that can be used with a number of different codes in order to allow the eventual user community the greatest flexibility with regard to selection of flow field simulation software.

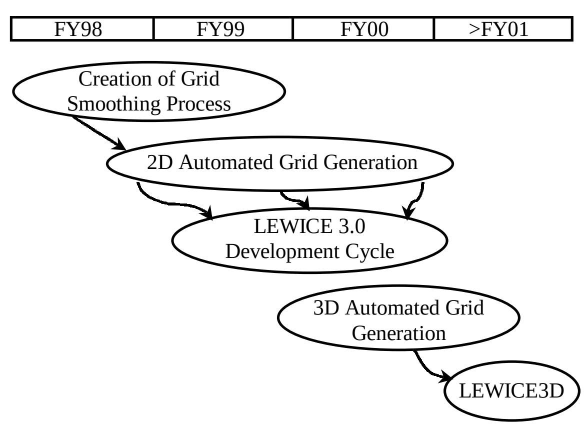

Figure 8. Ice shape grid generation development path

One of the first activities to provide some tangible outcome is the development of a smoothing routine to address the issue of transforming ice shape data into geometry files that can yield high quality structured grids without sacrificing geometric details required for accurate simulation of the flow field behavior. This software - which has been used in the analysis of performance degradation for an iced airfoil geometry as described in Chung, et al[26] - basically assigns control points to the original input data, redistributes the control points to be equally spaced over the interval of interest, and can then decrease the number of control points based on a user selected value. An example is shown below, in Figure 9, for a highly magnified section of a 2D ice shape tracing.

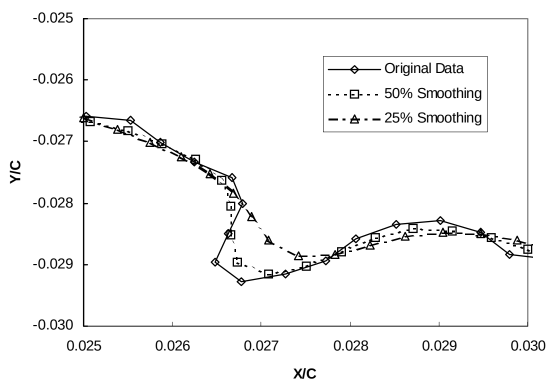

Figure 9. Ice shape segment before and after smoothing

The initial results from application of this technique indicate that reducing the number of control points to 50 percent of the original number allows for creation of high quality grids while preserving the essential aerodynamics of the flow near this surface. Further studies of this nature, along with a determination of acceptance criteria for simulation of iced geometry aerodynamic characteristics, are needed in order to determine appropriate usage for such a technique.

Following the smoothing process, a grid must be generated using the new ice shape coordinates. Previous work in this area[24,25] has shown that this can be a difficult and time consuming process. In order to reduce the effort associated with grid generation, some work has currently been initiated that should lead towards the development of an automated grid generation tool. If successful, not only would this lead to a decrease in effort on the part of the researcher but it could also make use of grid based flow codes in a multi-time-step LEWICE code feasible.

Once a grid has been developed, the work of producing an accurate simulation of the iced airfoil/wing performance degradation must be undertaken. When the conditions of interest are near stall and can contain separated flow regions as well as considerable unsteadiness, this can take quite some time. The Icing Branch has been evaluating the use of 2D and 3D Navier-Stokes codes for such analysis for several years. Most recently Chung[26] has used the NPARC code to examine performance degradation for the airfoil (2D) and wing (3D) of a commercial turboprop aircraft. Some sample results from that analysis are shown below in Figures 10 and 11. Figure 10 shows the grid developed for one airfoil with an ice ridge near the leading edge. Figure 11 shows lift curves for that airfoil with and without the ice shape for a specific configuration. The two sets of curves represent two alternate settings for the aileron. The Spalart-Allmaras turbulence model was used for that calculation. Use of other turbulence models can result in small but noticeable differences in the results. It is worth noting that, a significant amount of grid refinement was required to insure that the results were not grid dependent.

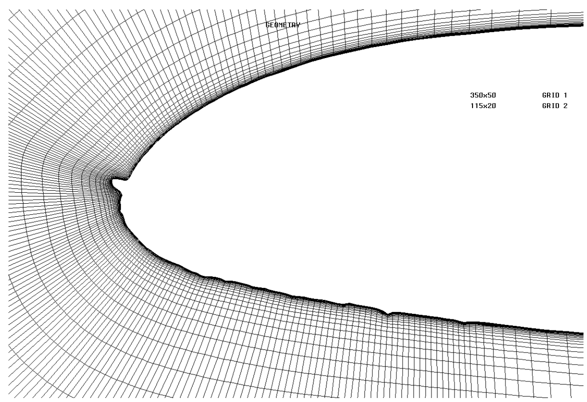

Figure 10. Grid for an ice ridge formation on the leading edge of an airfoil from a regional transport turboprop aircraft.

In order to further develop the accuracy and reliability of aerodynamic analyses such as this, further development of modeling for turbulence, roughness, and transition must be undertaken as well as the creation of appropriate experimental information for validation of such modeling. Work in these areas will not only be useful for performance degradation but also for ice accretion modeling especially if Navier-Stokes codes are to be used in such simulations.

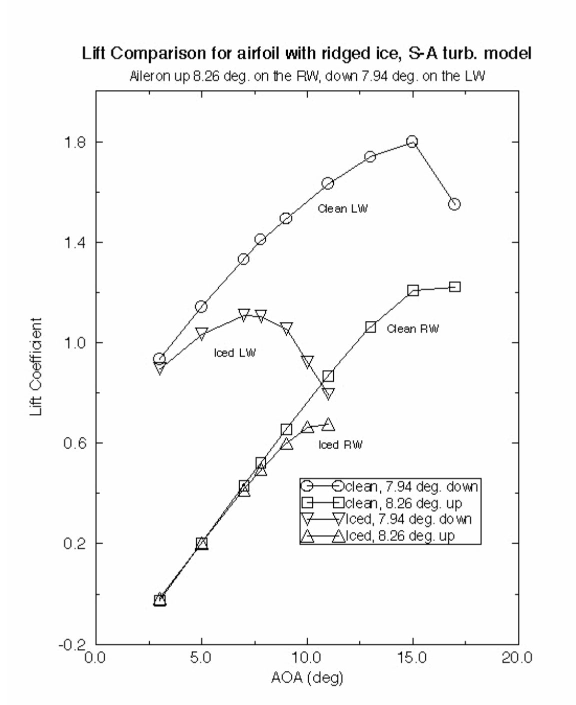

Figure 11. Lift calculations for an ice ridge formation on the leading edge of an airfoil from regional transport turboprop aircraft

Validation of Simulation Tools

The evaluation of how well these simulation tools are performing has been a subject that has been touched upon in several places throughout the previous discussion. The concept of validation is a difficult one, in that; it can mean different things to different people. The concept can become particularly difficult when considered in the light of potential use of icing simulation tools in the certification process.

The desire on the part of the user, whether applicant or certification authority, is to know that the output of a given simulation tool is sufficiently accurate. The difficulty arises in the phrase 'sufficiently accurate'. It is by no means clear as to what this means with respect to the various output quantities of the simulation tools discussed above nor is it evident 'how accurate' the tools need to be. Currently, each developer and each user can qualitatively assess these output quantities with respect to available experimental information and judge for themselves the level of accuracy of the simulation.

It is time to start establishing quantitative measures for evaluation of the various output quantities of these simulation tools. Such an effort will require cooperation and collaboration among developers and users of the tools in order to assure appropriate standards. The Icing Branch has initiated activities of this nature internally through use of the CMM and development of requirements documents for its computational simulation methods. We hope that in the near future more comprehensive efforts will be undertaken on this issue to insure acceptance of all current icing simulation tools and of others to be developed in the future.

Summary of Current Research Efforts

Computational simulation of an icing encounter, whether in free flight or inside an icing wind tunnel, is a complex and multi-disciplinary undertaking. The research efforts encompass the fields of aerodynamics, thermodynamics, heat transfer, computational fluid dynamics, icing physics, and software development. The Icing Branch along with its research partners in government, academia, and industry continues to develop a research program directed at understanding the important elements of the icing process and at producing reliable and accurate simulations of the process using the results of that research.

The current efforts underway in this program include:

- Re-engineering of LEWICE using well-established software development methods adapted for use in the icing research environment
- Fundamental studies of the physics of icing directed at development of an updated model of the icing process for use in LEWICE and LEWICE3D
- Continued development of LEWICE3D to expand its capabilities with respect to types of geometries modeled and eventually to include multi-time-step capability
- Development of a single thermal ice protection simulation capability to be included in LEWICE
- Creation of a numerical simulation of the Icing Research Tunnel including the capability to model objects located in the test section
- Development of methods for grid generation and aerodynamic analysis suitable for the complexities of ice shape geometries and their associated flow fields
- Creation of experimental data needed to provide accurate information for assessment of the output of the various simulation tools being developed

These research efforts are being undertaken in order to achieve the goals outlined at the start of this paper. The details of the research plan can change with time and necessarily do so based on the changing research environment. However, the usefulness of identifying such goals is to insure continuity and a rational evolution of the plan as it changes with time and with the needs of the icing community.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1999	Technical Memorandum

4. TITLE AND SUBTITLE

A Review of NASA Lewis' Development Plans for Computational Simulation of Aircraft Icing

5. FUNDING NUMBERS

WU–548–21–23–00

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–11517

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—1999-208904
AIAA–99–0243

11. SUPPLEMENTARY NOTES

Prepared for the 37th Aerospace Sciences Meeting & Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 11–14, 1999. Responsible person, Mark G. Potapczuk, organization code 5840, (216) 433–3919.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 01, 02, and 34 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The use of computational methods in the simulation of flight in icing conditions is an ongoing research effort by the Icing Branch at the NASA Lewis Research Center. The development of accurate, robust, well-documented, well-maintained computational tools is a major function of the research activities of the Icing Branch, in collaboration with its grantees and contractors. The goal of the Icing Branch's efforts is to provide simulation methods that can be used to aid in design, testing, certification, and qualification efforts related to flight in icing conditions. This paper will detail the current research and plans for future efforts in the development of computational tools for simulation of ice accretion, ice protection systems, the effects of ice on aircraft performance characteristics, and the behavior of aircraft systems subjected to icing conditions

14. SUBJECT TERMS	15. NUMBER OF PAGES
Aircraft icing; Computational modeling	21
	16. PRICE CODE
	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	