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NASA's Aircraft Icing Technology Program

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NASA'S AIRCRAFT ICING TECHNOLOGY PROGRAM

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SUMMARY

NASA's Aircraft Icing Technology program is aimed at developing innovative technologies for safe and efficient flight into forecasted icing. The program addresses the needs of all aircraft classes and supports both commercial and military applications. The program is guided by three key strategic objectives: (1) numerically simulate an aircraft's response to an in-flight icing encounter, (2) provide improved experimental icing simulation facilities and testing techniques, and (3) offer innovative approaches to ice protection. Our research focuses on topics that directly support stated industry needs, and we work closely with industry to assure a rapid and smooth transfer of technology. This paper presents selected results that illustrate progress toward the three strategic objectives, and it provides a comprehensive list of references on the NASA icing program.

INTRODUCTION

NASA supports an aircraft icing technology program at the NASA Lewis Research Center in Cleveland, Ohio. Although Lewis Research Center is mainly responsible for propulsion and power, it is also responsible for icing because the NASA Icing Research Tunnel (IRT) is located at Lewis. The IRT was built in 1944, during World War II, and it was used heavily to support the development of ice protection systems for the military aircraft of that era. The tunnel has been in operation ever since 1944, but its use was rather limited for the period between 1955 and 1978, during which time there was no formal icing research program at Lewis.

In 1978, because of the strong need expressed by both the U.S. and the European aircraft icing communities, NASA reestablished its icing program at Lewis. Since 1978, use of the IRT (by NASA, the military, and industry) has increased steadily to the point where it has become one of NASA's busiest wind tunnels. The icing technology program at Lewis has likewise increased steadily since 1978. It is interesting to note that Europe also has a strong and growing aircraft icing technology program.

References 1 to 3 review major elements of NASA's new icing technology program, up to about mid-1989. Reference 4 provides a selected bibliography of the aircraft icing work done between 1939 and 1955 by NACA (predecessor to NASA). Reference 5 surveys the state-of-the-art, internationally, in computer icing simulation and experimental icing simulation.

The purposes of this paper are to review the strategic objectives for NASA's icing program, to present selected results obtained since 1989 that illustrate progress toward these objectives, and to provide an updated bibliography of work supported by NASA and its collaborators.

The charter for NASA's aircraft icing technology program is to develop innovative technologies for safe and efficient flight into forecasted icing. The program addresses the needs of all aircraft classes and supports both commercial and military applications. Our research focuses on topics that directly support stated industry needs, and we work closely with industry to assure a rapid and smooth transfer of technology.

The icing program is guided by three strategic objectives:

(1) To develop and validate a system of computer codes that will numerically simulate an aircraft's response to an in-flight icing encounter.

(2) To provide experimental facilities that accurately simulate the natural icing environment and to develop new experimental capabilities and techniques to help the user-community fully utilize these facilities.

(3) To support the development and evaluation of advanced ice protection concepts that offer alternatives to compressor bleed air and other energy-intensive anti-icing systems.

The aircraft industry has emphasized four key payoffs from the NASA icing program:

(1) Validated computer codes and accurate experimental icing simulations will substantially reduce developmental and certification testing. This translates into reduced time and costs.

(2) Numerical simulation will reduce the high risk of flight testing in icing conditions as these simulations become accepted as an alternative to some flight

testing. A complete numerical simulation of an aircraft's response to an icing encounter appears possible and economically feasible in the future.

(3) Accurate numerical simulations will allow earlier assessment of the effect of ice protection requirements on new aircraft designs. This assessment is especially important for future military aircraft that require severe weather capability and low observability, where ice protection must be considered in the initial design stages.

(4) Advanced, low-power deicers now under development may offer viable alternatives to conventional bleed systems or energy-intensive electrothermal anti-icing systems. Next generation aircraft will be powered by advanced turbofan engines with higher bypass ratios and smaller core flows. Since the first priority for compressor bleed is cabin pressurization and air conditioning, there may be inadequate bleed for conventional hot air anti-icing.

Besides receiving support from NASA, the program is also supported by the FAA Technical Center, the Propulsion Directorate of the U.S. Army Aviation Systems Command, and the U.S. Air Force Air Logistics Command. We also participate in joint or cooperative programs with industry, the FAA, the DOD, and academia. These cooperative efforts avoid duplication of resources and facilities and expedite technical communication and transfer of technology to the user community.

COMPUTER ICING SIMULATION

As noted in the INTRODUCTION, a key strategic objective of the icing program is to develop and validate a system of computer codes that will numerically simulate an aircraft's response to an in-flight icing encounter. Selected examples of our code development work and code validation experiments are presented in this section.

Computer Codes and Validation

The key phenomena that must be adequately modeled in any airfoil icing analysis are illustrated on the left in Fig. 1. These include the flow field around an airfoil with leading edge ice, which can cause flow separation and reattachment; water droplet impingement locations and flux; surface roughness; heat and mass transfer; and the thermodynamic energy balance that determines where ice forms.

Icing tunnel tests and flight tests in natural icing conditions provide actual ice shapes and aero-performance data that can be used to validate code predictions. An airfoil under test in the NASA Icing Research Tunnel is shown on the right in Fig. 1.

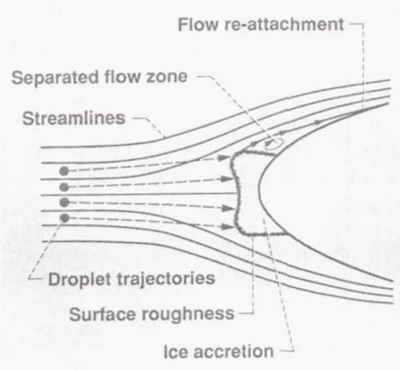


Figure 1.—Ice accretion modeling and experimental validation.

The basic codes in use or under development by NASA are:

(1) Flow codes combined with water droplet trajectory codes
(2) Ice accretion codes
(3) Flow codes for predicting component and aircraft performance in icing
(4) Thermal deicer codes

These codes are being used, modified, or developed to conduct icing simulations on fixed-wing lifting surfaces, engine inlets, and rotor blades. Industry uses these codes (or modifies them and incorporates them into their own codes) for preliminary design studies, aero-performance predictions, design and analysis of proposed ice protection systems, and analytical support of the icing certification or qualification process.

Later in our program, codes from the above list will be integrated into a system of codes that will numerically simulate the response of a complete aircraft to an in-flight icing encounter.

Flow/droplet trajectory codes. These codes were discussed in Refs. 1 to 3, and such codes are part of the ice accretion codes, which are discussed below.

Ice accretion codes. Figure 2 shows predicted ice growths on an airfoil at sequential times during exposure to an icing cloud. These shapes were predicted with the NASA LEWICE two-dimensional (2D) ice accretion prediction code (Ref. 6). The flow field streamlines calculated with a 2D Navier-Stokes solver are also shown in Fig. 2. Notice the separation bubble and reattachment zone behind the ice shape. LEWICE predictions agree well with ice formed on airfoils during icing tests in the IRT and also with ice formed on the Twin Otter Icing Research Aircraft during flights in naturally occurring supercooled clouds (Ref. 7). The LEWICE code has been distributed to over 35 organizations, and we continue to receive about one request per month.

In our continuing efforts to upgrade and enhance the capabilities of LEWICE, we support fundamental studies on the physics of the ice accretion process (Refs. 8 to 11). Figure 3 shows a test setup used to observe ice growth on a cylinder. By illuminating the surface of the ice with a laser sheet, a time history of the ice profile was constructed (Ref. 11). This sequence of profiles suggested a multizone heat transfer model that was different from that used in LEWICE.

At the right of Fig. 3 is the ice shape predicted by a version of LEWICE modified to include the multizone heat transfer model (Ref. 11). The analysis and experiment agree remarkably well. This multizone model is undergoing further study and refinement, especially regarding surface roughness and its effect on heat transfer and transition location.

NACA 0012 airfoil, 0° AOA

N-S flow field prediction

LEWICE ice shape prediction

Figure 2.—Ice accretion prediction with LEWICE and flowfield prediction with ARC2D.

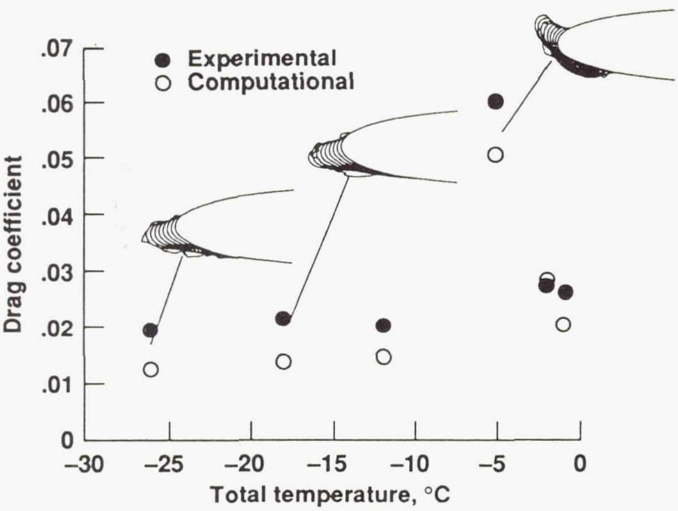


Figure 3.—Ice shapes and drag coefficients; predicted versus experimental.

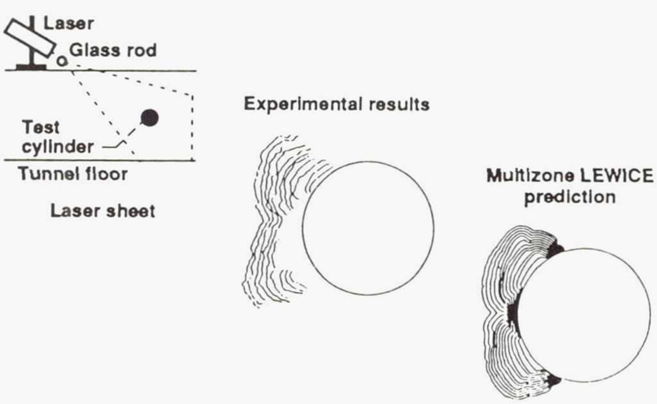


Figure 4.—Incorporation of new code routines into LEWICE to more closely model observed physics.

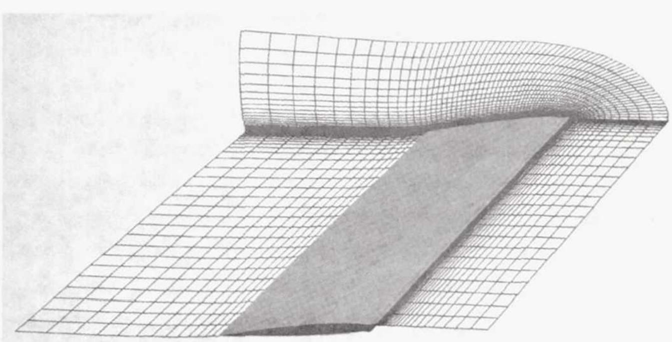
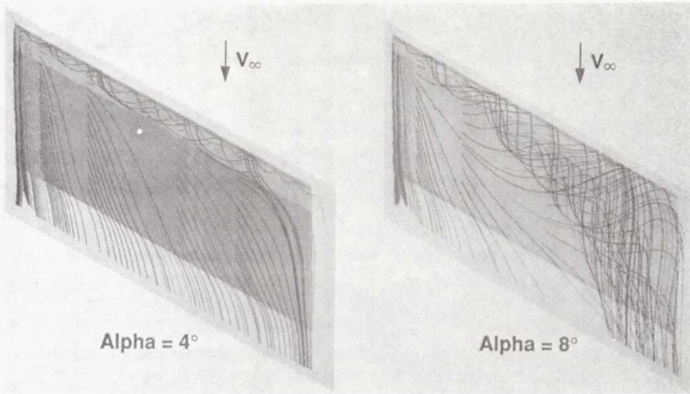


Figure 5.—Grid for Navier-Stokes analysis of a swept, finite-length wing and vertical tunnel wall.



Particles trajectories for sweep angle of 30°

Figure 6.—Navier-Stokes predictions of streamlines about a swept wing with leading edge ice.

2D flow codes for predicting performance. Ice on an airfoil causes decreased maximum lift, decreased stall angle, increased stall speed, and increased drag. Thus, we need to predict not only the ice shape, but also its effect on aeroperformance. We have therefore upgraded the LEWICE code by incorporating an interactive boundary layer (IBL) code that calculates lift and drag changes (Refs. 12 and 13). Figure 4 compares the LEWICE-IBL predictions (Ref. 13) for ice shape and drag with corresponding experimental results (Ref. 8). Ice was accreted on a 21-in. chord, NACA 0012 airfoil in the IRT. Air temperature has a strong effect on ice shape and its resultant drag. Runs were made at several different air temperatures, while cloud conditions and airspeed were kept the same. The predicted and measured ice shapes agreed well, as did the drag coefficients. Especially encouraging was the ability to predict the dramatic drag increases observed experimentally at temperatures near -5 °C.

3D flow codes. The aerodynamics of modern swept wing aircraft is dominated by three-dimensional effects. NASA therefore supports development of 3D flow codes that can model the flow over swept, semi-span wings with leading edge ice. Figure 5 shows the geometry and gridding used in a Navier-Stokes analysis of a 30° sweep, semi-span wing attached to a vertical wall (Refs. 14 to 16). The leading edge coordinates include a leading edge ice shape. This particular airfoil geometry has the same coordinate geometry as an actual model airfoil being tested in a dry-air wind tunnel. The wind tunnel testing is designed to provide a comprehensive aerodynamic data base for validating 3D viscous codes (Refs. 17 and 18).

Results from the Navier-Stokes analysis (Ref. 15) are shown in Fig. 6 as streamlines above the surface of the swept wing. At 4° angle of attack, a small separation bubble exists behind the ice. Near the leading edge, the separation bubble vortex has a strong spanwise component that grows larger as it moves outboard. But for the most part, the flow reattaches and we should not expect to see large losses in lift.

At 8° angle of attack, the leading edge ice causes a larger separation bubble. The resulting leading edge vortices have a strong spanwise component that grows very large as it moves outboard. Much of the outboard section of the wing is in separated or reverse flow, so we should expect to see a large dropoff in lift as we move outboard. It is interesting to note that the ice causes a leading edge stall, as opposed to the more familiar bluff body stall that starts at the airfoil trailing edge and moves further forward with increased angle of attack.

Although the Navier-Stokes analysis is very accurate, it requires long run times on a supercomputer. An interactive boundary layer (IBL) code coupled with a potential flow code models less of the detailed physics, but requires far less computational time. At this time, NASA is supporting development of both approaches because the IBL approach has potential to be a good engineering design tool, and the Navier-Stokes approach has the potential for accurately modeling the detailed physics.

Figure 7 shows a 30° swept, semi-span wing model with simulated leading edge ice installed in a dry air wind tunnel (Refs. 17 and 18). The wind tunnel testing is designed to provide a comprehensive aerodynamic data base for validating 3D codes, such as the Navier-Stokes analysis and the 3D interactive boundary layer (IBL) analysis.

This model has five chordwise rows of surface static pressure taps, and is attached to a three-component force balance in the wind tunnel wall. Flow diagnostics include laser velocimetry, laser sheets, and helium bubble seeding and tracking.

Figure 8 shows a comparison between the Navier-Stokes predictions discussed above and the wind tunnel results for lift coefficient versus span, at 4° and 8° angles of attack (α) (Ref. 15). The agreement is nearly perfect.

In the dry-air wind tunnel testing of this model (Refs. 17 and 18), the flow was seeded with helium bubbles and high-speed videography was used to observe the bubbles' trajectories. The experimentally observed helium bubble trajectories will be compared with the streamlines predicted by the Navier-Stokes code.

Airplane performance in icing. A major result from the numerical simulation of an aircraft icing encounter is the predicted changes in aircraft performance and stability caused by ice. Thus, NASA is supporting development of a computer code that will predict performance and stability of modern aircraft with given ice shapes on the lifting surfaces. This work will be carried out along with ongoing efforts to develop ice accretion codes for 3D surfaces. Later, at the appropriate time, the ice accretion codes will be incorporated into the aircraft performance and stability code.

Figure 9 shows the pressure distribution over the NASA Twin Otter icing research aircraft as calculated with a nonviscous panel code. Flight data from the Twin Otter will be used to validate the code at full-scale Reynolds numbers. First the Twin Otter will be flown in clear air with "styrofoam" ice shapes on its tail surfaces (Refs. 19 and 20), and next it will be flown in naturally occurring supercooled clouds.

In addition to flight testing with the Twin Otter, NASA will conduct dry-air wind tunnel testing of a subscale model of a modern swept-wing aircraft with simulated ice on its lifting surfaces. The wind tunnel results will provide code validation data for a modern aircraft configuration. This will be a joint program between NASA Lewis and NASA Langley. After a good experimental data base has been acquired for a subscale model in dry air wind tunnel, we plan to conduct flight testing with a modern swept wing aircraft to acquire a validation data base at full-scale Reynolds numbers.

Thermal deicer codes. NASA has sponsored the development of a series of transient heat conduction codes that numerically model electrothermal deicer

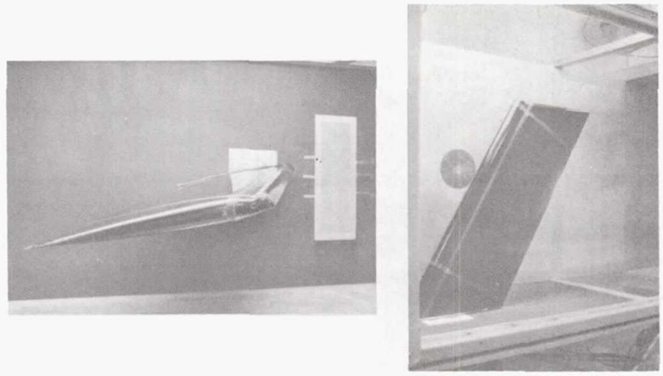


Figure 7.—Swept, finite-length wing with leading edge ice shape installed in dry air wind tunnel.

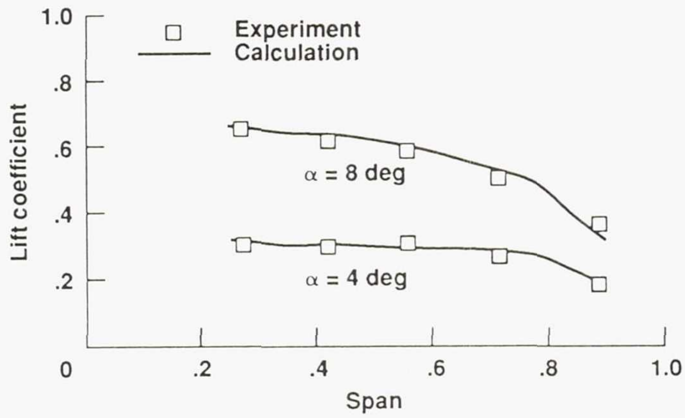


Figure 8.—Lift coefficient along span of iced wing with 30° leading edge sweep; comparison between Navier-Stokes predictions and wind tunnel data.

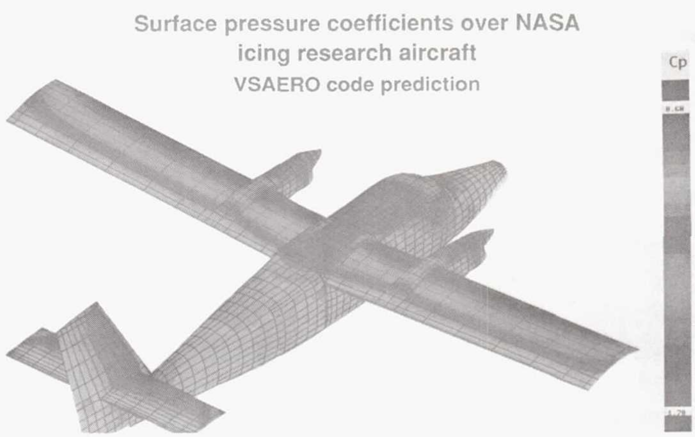


Figure 9.—VSAERO predictions for surface pressure coefficients over NASA Twin Otter icing research aircraft.

operation. These codes, developed by the University of Toledo, are used by industry to analyze and design thermal deicer systems. The model consists of electrical heater strips surrounded on one side by insulation and aircraft structure, and on the other side by insulation and the wing leading edge covered with ice. The codes calculate the temperature distribution inside the deicer-wing-ice assembly and determine the heat required to melt the ice at the ice-wing interface. The codes also include the ability to follow the melt line which has water on one side and ice on the other. Reference 21 reviews the codes developed by the University of Toledo up to 1988. Recently, Toledo has incorporated an electrothermal deicer analysis capability into LEWICE (Ref. 22). This was accomplished by replacing a subroutine in LEWICE that balanced the energies at the ice surface, with a subroutine that performs this same energy balance, as well as calculates all the time-temperature transients below the ice surface, for all the layers of the deicer and wing as well as within the ice layer itself. This enhancement to LEWICE allows us to calculate the dynamic processes of ice growth, ice melting, and ice shedding. This new capability should prove useful for determining optimum heater power levels and heater on-off times required to melt and shed ice with minimum power usage and with avoidance of water runback and freeze beyond the deicers.

EXPERIMENTAL ICING SIMULATION

NASA has two major commitments in our strategic goal for experimental icing simulation: first, to provide experimental facilities that accurately simulate the natural icing environment; and second, to develop new experimental capabilities and test techniques to help the user community fully utilize these facilities. Examples of these new capabilities and techniques are the subscale rotor testing in the NASA Icing Research Tunnel (IRT), which will be discussed below, and a new three-component force balance for the IRT.

The NASA Icing Research Tunnel and the NASA Twin Otter flight research aircraft are used extensively for code validation, advanced ice protection development, and in the case of the IRT, for testing actual aircraft components.

NASA Icing Research Tunnel

Icing wind tunnels undoubtedly offer the most versatile approaches to icing testing. It generally costs much less to test components in an icing wind tunnel than in flight, and conditions can be much more closely controlled and repeated. In icing tunnel testing, productivity is high, and safety risk is very low. But there definitely is an appropriate role for flight testing, as discussed elsewhere (Refs. 3, 5, 19, and 20).

A schematic of the NASA Lewis Icing Research Tunnel is shown in Fig. 10. The components shown in the inserts are upgraded systems that were installed when the IRT was rehabilitated in 1986-87. In addition to having all the systems of a conventional dry-air tunnel, an icing tunnel has two unique systems: (1) a water spray system that injects water droplets into the airstream to create a supercooled cloud and (2) a refrigeration system and heat exchanger that cools the air to temperatures as low as -20 °F. The heat exchanger is in the leg just upstream of the spray bars. Closed-loop refrigerated tunnels can "dial in the weather" any time of the year and are therefore very productive.

The IRT is the largest refrigerated icing wind tunnel in the world. The test section is 6 ft high by 9 ft wide by 20 ft long. The maximum airspeed for an empty IRT test section is 300 mph, but model blockage greater than 20 percent significantly reduces maximum airspeed. The nozzle spray system produces supercooled clouds that can be controlled over a range of liquid water contents from 0.5 to 2.5 g/m^2 and water droplet median volumetric diameters from 15 to 40 μm.

The IRT is one of NASA's busiest wind tunnels; in 1988 it logged 1330 hr of actual test time. It carries a 2-year backlog of research and development testing for NASA, the military, and industry. We conduct many joint programs with the military and with industry. Reports describing the IRT and its calibration are given in Refs. 23 to 25.

In 1987, the American Society of Mechanical Engineers (ASME) designated the Lewis Research Center's IRT an International Historic Mechanical Engineering Landmark for its leading role in making aviation safer for everyone (Fig. 11).

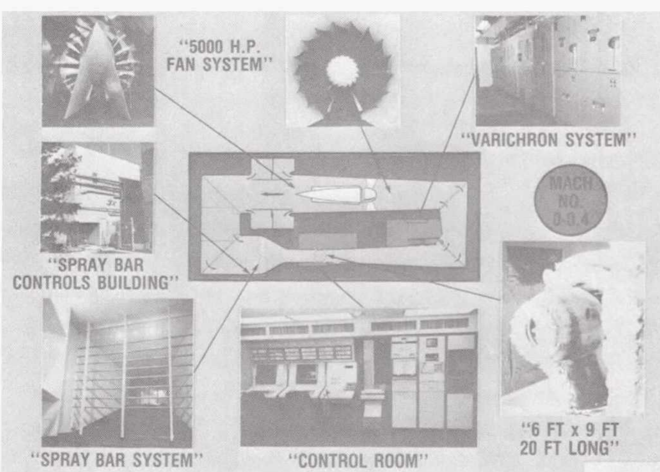


Figure 10.—NASA Lewis Icing Research Tunnel.

Figure 11.—Photo of plaque that designates the IRT an ASME International Historic Engineering Landmark.

NASA Twin Otter Flight Research Aircraft

The NASA Lewis icing research aircraft shown in Fig. 12 is a modified DeHavilland DH-6 Twin Otter (Refs. 26 to 28). The aircraft maximum range for icing research flights is 300 nmi. Cruising speed is 170 kn at sea level and 182 kn at 10 000 ft. An oxygen system is available for altitudes up to 15 000 ft.

The aircraft is equipped with electrothermal anti-icers on the propellers, engine inlets, and windshield. Pneumatic deicer boots are located on the wing outboard of the engine nacelles, on both the horizontal and vertical stabilizers, on the wing struts, and on the rear landing gear struts. The pneumatic deicers located on the vertical stabilizers, wing struts, and landing gear struts are nonstandard items that provide additional research capability for measuring component drag through selective deicing. The aircraft is equipped with several standard instruments for measuring icing cloud properties (Ref. 29).

Wing leading edge ice shapes are measured in flight with a stereo photography system. Wing section drag is measured with a wake survey probe mounted on the wing behind the region where the stereo photos are taken. A noseboom is used to measure airspeed, angle-of-attack, and sideslip. A flight test system measures flight dynamics along a flight path. The system includes a data acquisition system and an inertial package that contains rate gyros, directional gyros, and servo accelerometers.

The icing flight research aircraft acquires in-flight data that can be used to validate ice accretion and aeroperformance computer codes and to confirm that the IRT adequately simulates natural icing. As noted above, NASA is developing an airplane performance and stability code for modeling flights in icing. The Twin Otter, with its flight test package, is being used to acquire a performance and stability data set for calibration and validation of these codes.

Subscale Rotor Testing in the IRT

This section on subscale rotor testing in the IRT illustrates a recent example of NASA's commitment to develop new test techniques to help the user community fully utilize the IRT.

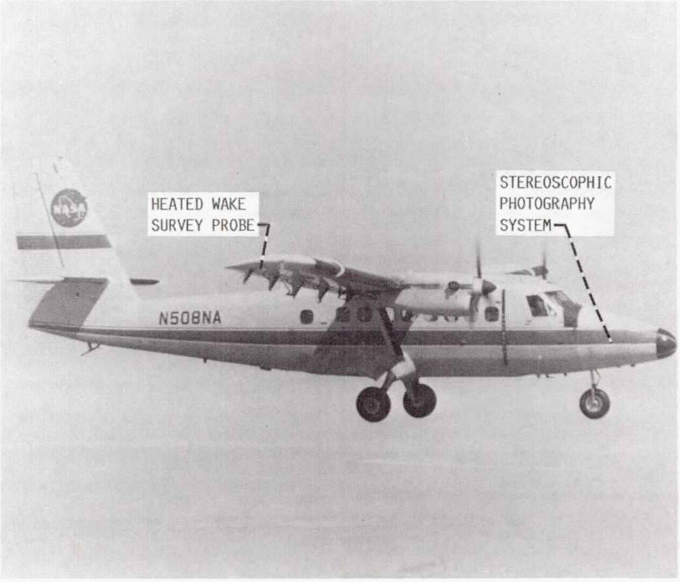


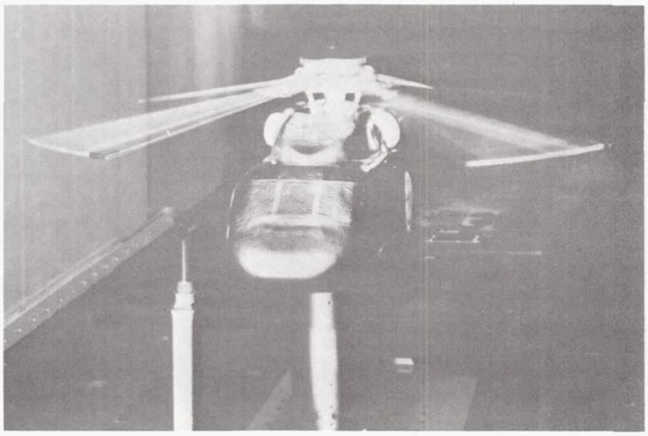
Figure 12.—NASA Lewis Icing Research Aircraft.

Flight testing in natural icing is currently the only acceptable means for certifying that a helicopter rotor can perform safely in the icing environment defined by the full Federal Aviation Administration (FAA) FAR Part 25 Appendix C icing envelopes. The U.S. Rotorcraft industry estimates that it would cost about 15 million dollars to certify a helicopter in natural icing to the FAR 25 requirements; and they feel that this cost is prohibitively high. Although it is not well-known, only one civilian helicopter is certified by the FAA for flight into known icing conditions; that helicopter is the French Super Puma. it took the French nearly 10 years of flight testing in natural icing to win that certification.

For several years, NASA and the U.S. rotorcraft industry have been engaged in a joint effort to develop new methods that could help reduce the cost and time needed to certify and qualify U.S. rotorcraft for icing. These methods include (1) computer codes that reliably predict full-scale rotor performance in icing and (2) experimental techniques for testing subscale model helicopter rotors in the IRT to acquire data for validating the codes and to develop a better understanding of the effects of icing on rotor performance. The methods derived from this joint effort will also advance the state-of-the-art methods for predicting the effects of ice accretion and shedding for the Advanced Ducted Propeller and other thrusting devices.

Figure 13 shows a subscale helicopter being tested in the IRT. The model consists of a UH-60 Blackhawk helicopter fuselage, four NACA 0012 blades (5-in. chord, 6-ft diam), a fully articulated rotor head, and a six-component force balance housed under the Blackhawk fuselage.

Figure 14 shows the rotor torque rise caused by ice accretion versus time in icing for the model shown in Fig. 13. The experimental results are compared with an analytical prediction developed by Flemming (Refs. 30 and 31). The rotor icing analysis includes an ice shedding model, which is necessary for good agreement with the experiment. The analysis also includes empirical airfoil performance-in-icing data that was acquired in another test program funded by NASA (Ref. 30). The comparison between theory and experiment, as shown here, is remarkably good for the conditions of this particular test run. Similar agreement between theory and experiment was also found for lift loss versus time in icing.



Scale model of UH-60 Blackhawk helicopter with 4 NACA 0012 blades, fully articulated rotorhead, and 6-component force balance

Figure 13.—Subscale model rotor testing in the IRT.

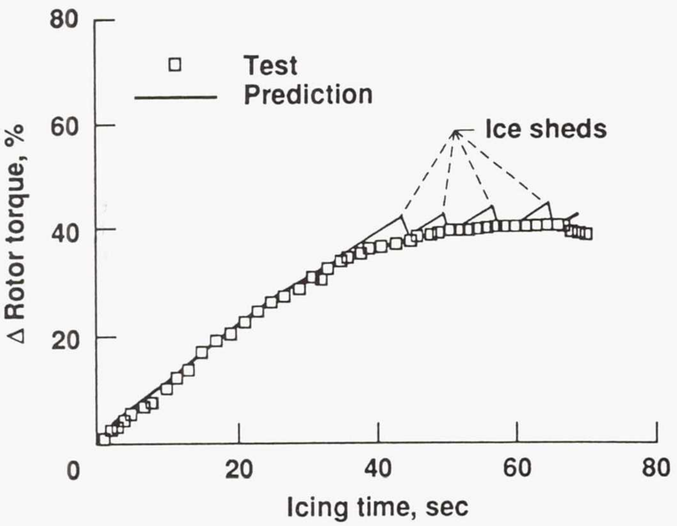


Figure 14.—Delta rotor torque versus time in icing.

The four U.S. helicopter companies have received all the data from this test program. Selected results from this program, which include both analytical modeling and experimental validation, have been reported in several technical reports (Refs. 31 to 34). The complete results will be published in a final contractor report. We are also planning a second test entry into the IRT to expand the original icing flight test envelope and to further study rotor performance at warmer outside air temperatures.

ADVANCED ICE PROTECTION SYSTEMS

As mentioned in the INTRODUCTION, NASA also supports the development and evaluation of advanced ice protection systems that offer lower-power alternatives to evaporative anti-icing systems, such as electrothermal or compressor bleed air systems. One promising alternative is the new class of electromechanical and pneumatic impulse deicers that use only 10 to 20 percent of the power used by evaporative anti-icing systems. Impulse systems have pulse times less than a millisecond and surface accelerations up to 1000 g's, which impart forces strong enough to shatter, debond, and expel the ice. The impulse systems have the potential for maintaining ice thicknesses very thin, both before and after actuation.

In broad terms, impulse systems fall into one of three categories: electro-expulsive, eddy-current, and high pressure pneumatic. The first two approaches employ a capacitor bank energy storage system that supplies a short, high pulse of electrical current to produce a repulsive action between two conductors that rapidly distorts the airfoil's leading edge. The third approach uses a short pulse of high pressure gas to achieve the distortion.

Electro-expulsive deicers consist of a double layer of electrically conducting strips in an elastomeric blanket that covers the leading edge. Current discharges into the top and bottom conductors in opposition, which produces opposing magnetic fields that rapidly force the strips apart. Eddy-current repulsion deicers are divided into two types: The first (known as electromagnetic impulse deicers) employ thin spirally wound pancake solenoidal coils that fit inside the wing, up against the leading edge. The second (known as eddy current repulsion deicer) employs a flat conductor sheet (in which is cut a spiral conductor pattern) embedded in elastomeric material that fits over the outside of the wing leading edge. When a capacitor is discharged into either type of spiral conductor, the current pulse causes a rapidly changing magnetic field that induces eddy currents in the airfoil metal leading edge. The eddy currents and spiral currents produce opposing magnetic fields that rapidly deform the leading edge. Pneumatic impulse deicers have tubes underneath a boot that covers the leading edge of the wing. A high pressure air pulse inflates the tubes and rapidly distorts the boot.

Mr. Len Haslim, of NASA Ames Research Center, invented the electro-expulsive deicer system. Data Products of New England (DNE) has purchased the NASA rights to Haslim's invention and are developing the system further (Ref. 35).

Since, by definition, deicers allow ice to accumulate on the aircraft surfaces before the deicers are actuated, ice particles will shed from the surfaces during actuation. If deicers are used on engine inlets, the engine must ingest ice particles without sustaining damage to fan blades or other components. For this reason, NASA has initiated the development of a structural analysis code for determining the response of engine fan blades to ice impact.

USAF/NASA low-power ice protection technology program. Our current goal is to develop an experimental data base for the low-power impulse deicers. To that end, we have conducted a joint USAF/NASA/industry program to test promising impulse deicers systems in the NASA IRT. In this test program, a total of eight impulse deicers systems, supplied by six companies, were individually tested in the IRT under identical conditions (Ref. 36).

Figure 15 shows an airfoil with a deicer system installed on the leading edge. Although not obvious from the photo, the deicer boot covers about the first 15 percent of the airfoil chord. This airfoil geometry was chosen because its 0.5-in. leading edge radius

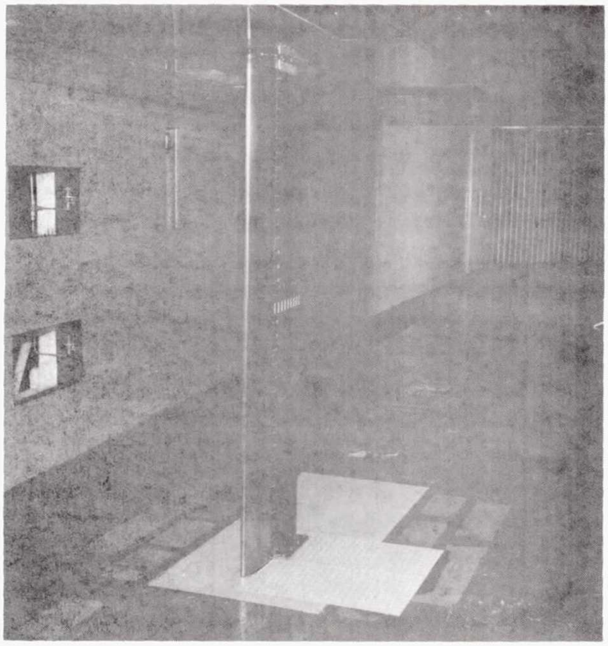


Figure 15.—NACA 0012 airfoil (21-in. chord) installed in IRT. Deicer systems were applied to the leading edge of the airfoil.

represented a challenge for most manufacturers, and because we were trying to simulate the small leading edge radii used on inlets of some military aircraft.

In testing impulse deicers the following parameters were measured to characterize deicer performance: (1) maximum size of shed ice particles for a given ice thickness and pulse energy; (2) minimum thickness of ice that can be removed for a given pulse energy; (3) amount, texture, and height of residual ice remaining on the surface before and after deicer actuation for several different times between actuations; (4) energy per unit area or per unit span length required for one deicer actuation; and (5) weight per unit area of deicer coverage.

In evaluating deicer performance, the systems must be tested under the full range of expected icing conditions. Experience has shown that two conditions give impulse deicers the most trouble: near-freezing conditions that produce soft, mushy ice with water between the ice and deicer surface; and cold, rime icing conditions that cause the ice to adhere strongly to the deicer (Refs. 37 and 38).

Figure 16 shows a sequence of photos that capture an ice shedding event by means of high speed videography. Events can be captured at speeds up to 6000 frames per second. The video tape provides a digitized record that can be examined frame by frame on a conventional computer monitor to follow the ice breakup process. The digitized data also allows estimating the size of the largest particles shed during an actuation. Special image processing software is being developed to automate the estimation of particle sizes and possibly to obtain size spectrums as well.

Figure 17 shows ice being expelled from a cylinder by an eddy-current repulsion deicer strip that was undergoing development testing in the IRT. The work was done under a NASA Small Business Innovative Research Contract. This particular deicer can be applied over the outside of a component; it causes only minimal intrusion into the component.

Figure 17.—Eddy-current repulsion deicer actuation during development tests in IRT as part of a NASA SBIR.

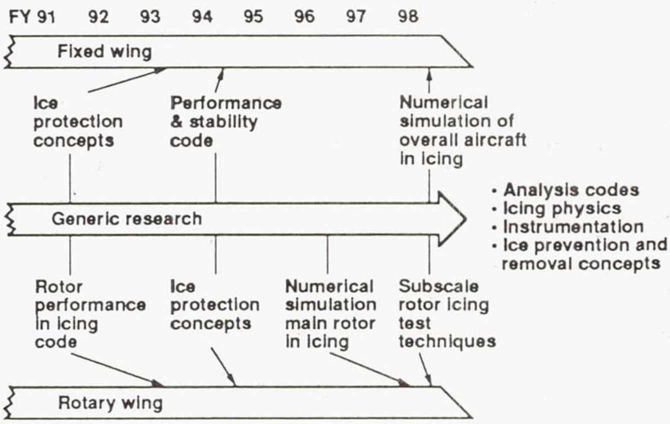


Figure 18.—NASA Aircraft Icing Technology Program Plan.

AIRCRAFT ICING TECHNOLOGY PLAN

The Aircraft Icing Technology Program has a strong, focused research effort supporting the strategic objectives for both fixed and rotary wing aircraft (see Fig. 18). The various analytical codes that support ice accretion, aeroperformance, and ice protection are developed in the focused research. Companies and Government agencies receive these codes while they are still in the research stage so that NASA may get feedback on the user's experience with the codes and on desired additional capabilities. Icing physics research supports the development of analytical models for ice accretion, ice shedding, and ice removal. Droplet sizing instrumentation is essential for validating droplet trajectory codes and ice accretion codes.

Figure 18 shows that while the strategic objectives are met in the outyears, codes, subscale model rotor test techniques, and advanced ice protection concepts are continually worked throughout the program and results are promptly delivered to industry for inclusion in their own icing program.

Figure 16.—High-speed videography to capture ice shedding event (1000 frames/sec).

CONCLUDING REMARKS

The key strategic objectives of NASA's Aircraft Icing Technology Program are (1) to numerically simulate an aircraft's response to an in-flight icing encounter, (2) to provide improved capabilities and techniques for ground and flight icing testing, and (3) to offer innovative approaches to ice protection.

With a comprehensive computer code development program in place, we are progressing toward producing a methodology for numerically simulating the response of a complete aircraft to an icing encounter. At the same time, the codes are being used extensively by industry and Government in support of their icing programs.

Through a strong joint program with the U.S. helicopter industry, we have demonstrated that subscale model rotor testing in an icing wind tunnel provides valuable data for developing and validating computer codes that predict rotor performance in icing. The encouraging progress to data justifies further work in subscale model rotor testing in support of icing certification.

Through our joint USAF/NASA/industry test program we have succeeded in developing an extensive, but preliminary, data base on the new class of electromechanical and pneumatic impulse deicers. Because each impulse deicer needs a detailed evaluation under a wide range of icing conditions and under various operating modes, these systems will require much more testing.

Our good working relationships with industry, academia, and other Government agencies results in a combination of our individual resources, avoids duplication of effort and facilities, and expedites technology transfer to the user community.

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16. Abstract

NASA's Aircraft Icing Technology program is aimed at developing innovative technologies for safe and efficient flight into forecasted icing. The program addresses the needs of all aircraft classes and supports both commercial and military applications. The program is guided by three key strategic objectives: (1) numerically simulate an aircraft's response to an in-flight icing encounter, (2) provide improved experimental icing simulation facilities and testing techniques, and (3) offer innovative approaches to ice protection. Our research focuses on topics that directly support stated industry needs, and we work closely with industry to assure a rapid and smooth transfer of technology. This paper presents selected results that illustrate progress toward the three strategic objectives, and it provides a comprehensive list of references on the NASA icing program.

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