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NASA'S AIRCRAFT ICING TECHNOLOGY PROGRAM

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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 capabilities and techniques for ground and flight icing testing, and (3) offer innovative approaches to ice protection. Our fundamental 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 presentation reviews progress toward the three stated strategic objectives.

Program Charter

- **Develop innovative technologies for safe and efficient flight in icing conditions.**

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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. Our fundamental 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.

Program Strategic Objectives

- Numerical simulation of an aircraft's response to an in-flight icing encounter
- Improved capabilities and techniques for ground and in-flight icing testing
- Innovative approaches to ice protection

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The icing technology program is guided by three strategic objectives: first, to develop and validate a system of computer codes that will numerically simulate an aircraft's response to an in-flight icing encounter; second, to provide experimental facilities that accurately simulate the natural icing environment and to develop new experimental capabilities and techniques to fully utilize these facilities; and third, to support the development and evaluation of advanced ice protection concepts that offer alternatives to compressor bleed air anti-icing systems.

Payoffs

Computer and experimental icing simulations

- **Reduced certification time and costs**
- **Fewer hours of high risk flight testing**
- **Effect of icing on new aircraft designs**

Advanced low power deicing systems

- **Alternatives to compressor bleed air**

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The aircraft industry has repeatedly emphasized the payoffs they will realize from the NASA icing program. Validated computer codes and accurate experimental icing simulations will substantially reduce developmental and certification testing. This translates into reduced time and costs.

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

Flight testing in icing conditions carries a high risk that will be reduced as numerical simulations become an acceptable alternative to some flight testing.

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 with low observability, where ice protection must be considered in the initial design stages.

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. Advanced, low-power deicers now under development may offer viable alternatives to conventional bleed systems.

Computer Codes & Validation

- Potential & viscous flow codes
- Water droplet trajectory codes
- Ice accretion codes
- Thermal deicer codes
- Airplane performance code

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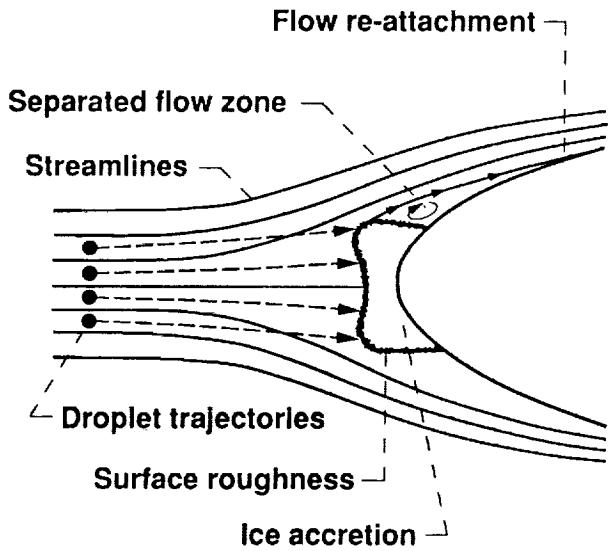
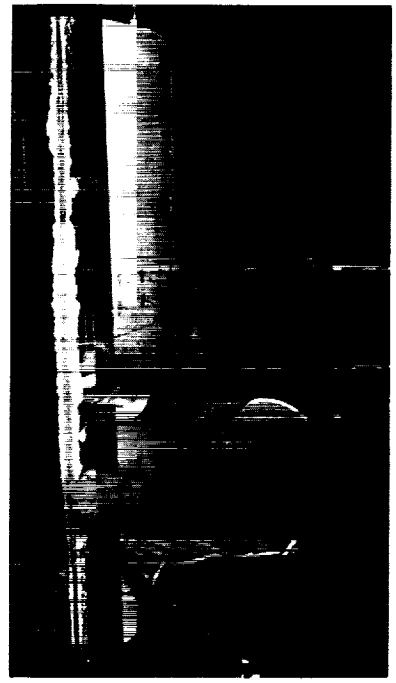
This figure lists the basic codes in use or under development by NASA Lewis. These codes are being used, modified, or developed to conduct icing simulations on fixed-wing lifting surfaces, engine inlets, and rotor blades.

Industry uses these codes and their own modifications for preliminary design studies, aeroperformance predictions, design and analysis of proposed ice protection systems, and analytical support of the icing certification or qualification process.

Codes from this list will be integrated into a system of codes that will numerically simulate the complete response of aircraft to an in-flight icing encounter.

Ice Accretion Modeling/Validation





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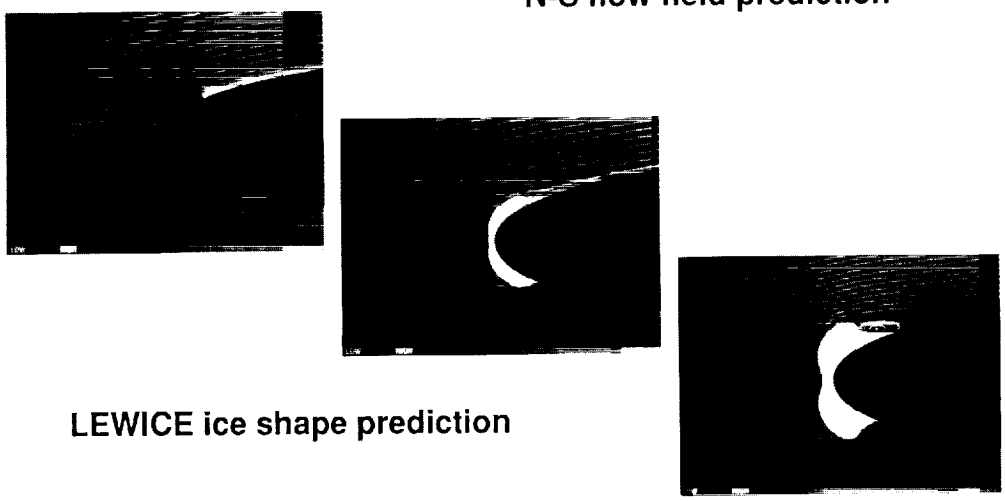
The key physical processes that must be adequately modeled in any airfoil icing analysis methodology are illustrated on the left. These include proper modeling of the flow field around an airfoil with leading edge ice, which can cause flow separation and reattachment; water droplet impingement locations and flux; surface roughness; heat and mass transfer; and a thermodynamic energy balance for determining where ice forms.

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

Ice Accretion/Aeroperformance Predictions

NACA 0012 airfoil, 0° AOA

N-S flow field prediction



LEWICE ice shape prediction

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This figure 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 ice accretion prediction code. LEWICE predictions agree well with ice formed on airfoils during icing tests in the Icing Research Tunnel (IRT) and also with ice formed on the Twin Otter icing research aircraft during flights in super-cooled clouds.

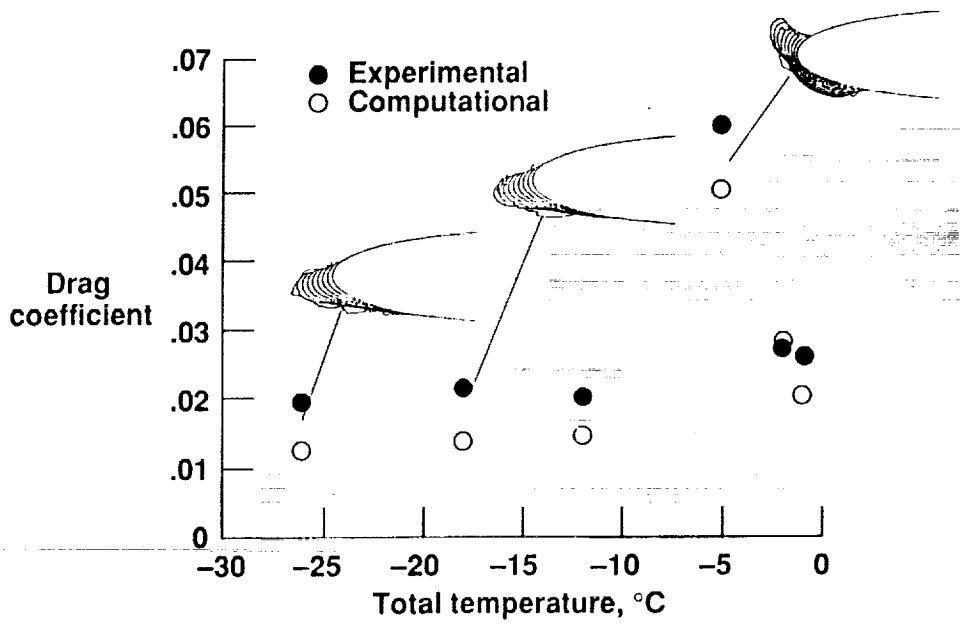
The LEWICE code has been distributed to over 35 organizations, and we continue to receive about one request per month.

The flow-field streamlines calculated with a Navier-Stokes solver are also shown here. Notice the separation bubble and reattachment zone behind the ice shape.

Ice Shapes and Drag Coefficients

Predicted Versus Experimental

Interactive boundary layer code upgrade of LEWICE



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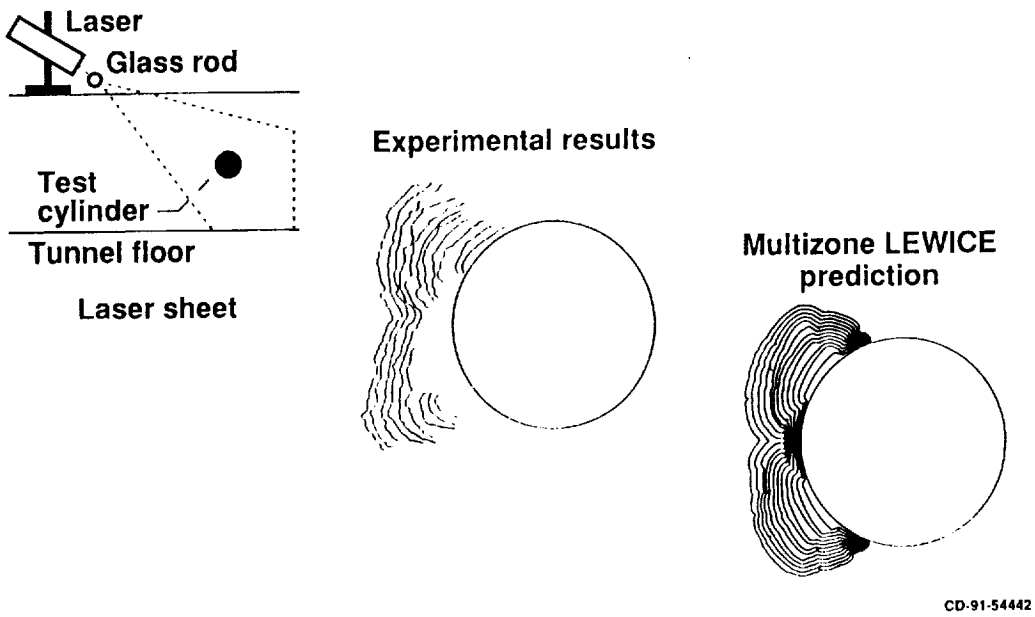
Ice on an airfoil causes decreased lift and C_{Lmax}, decreased stall angle, increased stall speed, and increased drag. Thus, we need to predict not only the ice shape, but also its effect on aeroperformance. We have therefore upgraded the LEWICE code by incorporating an interactive boundary layer (IBL) code that calculates lift and drag changes.

This figure compares the LEWICE-IBL predictions for ice shape and drag with corresponding experimental results. 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.

Multizone Roughness Model for LEWICE

Incorporated new routines in LEWICE that more closely model observed physics



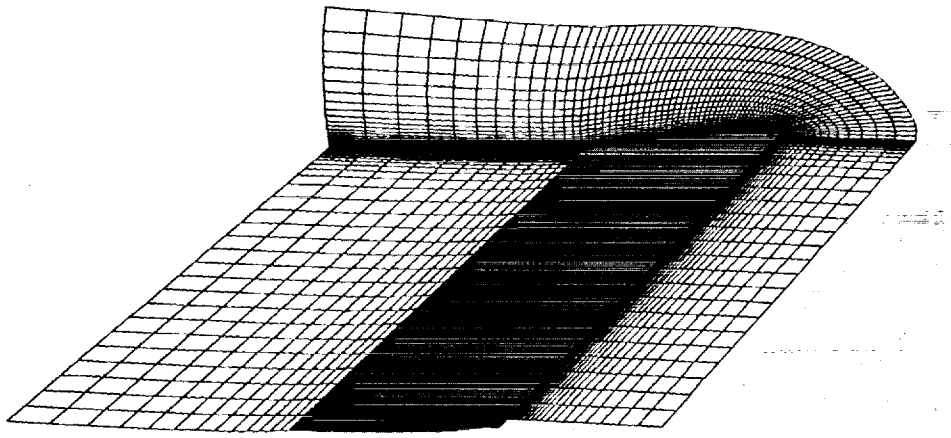
In our continuing efforts to upgrade and enhance the capabilities of LEWICE, we support fundamental studies on the physics of the ice accretion process.

This figure shows a test setup used to observe ice growth on a cylinder. By illuminating the surface of the ice with a laser sheet, we constructed a time history of the ice profile (shown in the middle diagram). This sequence of profiles suggested a multizone heat transfer model that was different from that used in LEWICE.

At the right is the ice shape predicted by a version of LEWICE modified to include the multizone heat transfer model. 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.

3D Iced Wing Aerodynamics



Grid for Navier-Stokes analysis of a swept, finite wing and vertical tunnel wall

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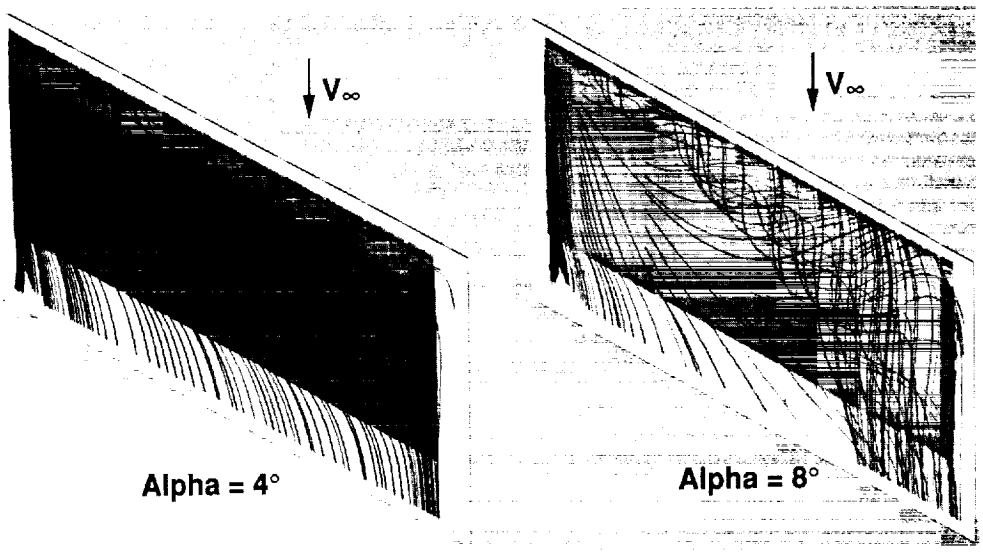
The aerodynamics of modern swept-wing aircraft is dominated by three-dimensional effects. NASA is therefore developing 3D flow codes that can model the flow over swept, finite-length wings with leading edge ice. This figure shows the geometry and gridding used in a Navier-Stokes analysis of a 30° sweep, finite-length wing attached to a vertical wall. The leading edge coordinates includes a leading edge ice shape.

This particular airfoil geometry has the same coordinate geometry as an actual model airfoil we are testing in a dry wind tunnel. The wind tunnel testing is designed to provide a comprehensive aerodynamic data base for validating 3D codes.

Navier–Stokes Analysis for Swept Wing with Leading Edge Ice



Particles trajectories for sweep angle of 30°

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One of the results from the Navier-Stokes analysis is shown in this figure as streamlines above the surface of the swept wing. The streamlines were divided into various color groups to help keep track of the flow.

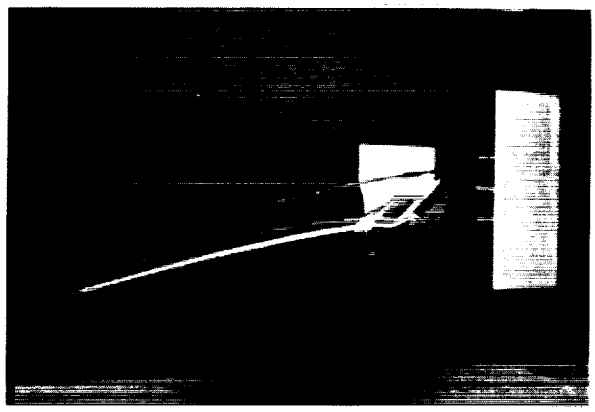
At a 4° angle of attack, a small separation bubble exists behind the ice, but the flow reattaches. Near the leading edge, the flow has a strong spanwise component.

At an 8° angle of attack, the leading edge ice causes the flow to separate, and the resulting leading edge vortices have a strong spanwise component. Near the tip, the tip vortex interacts with the spanwise vortices to turn the flow toward the free-stream flow.

In the dry wind tunnel testing of this model, we will seed the flow with helium bubbles and use high-speed videography to observe the bubbles' trajectories. The experimental streamlines will be compared with the analytical predictions.

Dry Wind Tunnel Testing

Goal: Acquire an experimental data base for validating aeroperformance codes



Swept, finite wing with simulated ice on leading edge shown installed in wind tunnel

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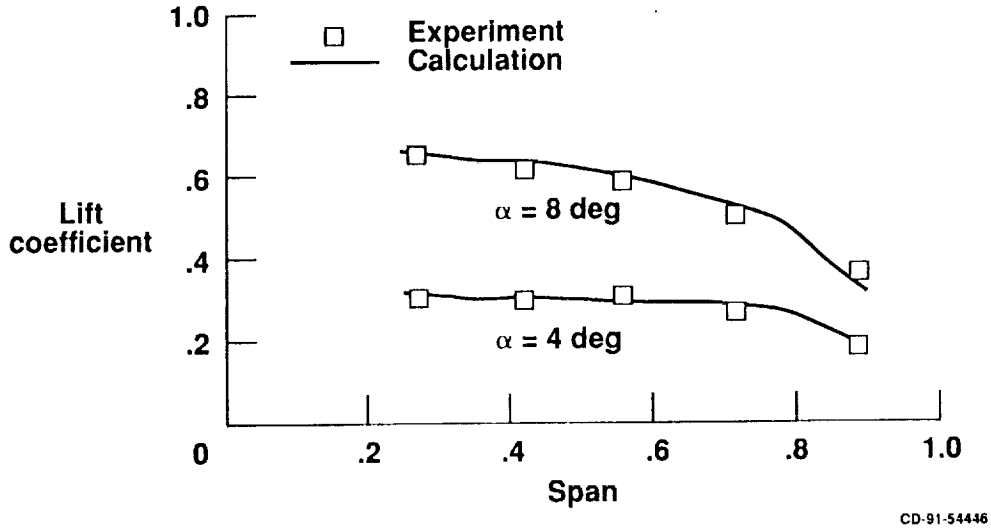
This figure shows a 30° swept wing model with simulated leading edge ice installed in a dry wind tunnel. The wind tunnel testing is designed to provide a comprehensive aerodynamic data base for validating 3D codes, such as the Navier-Stokes analysis and the 3D interactive boundary layer analysis.

This model is heavily instrumented for surface pressures and is attached to a three-component force balance in the wind tunnel wall. Flow diagnostics include laser velocimetry and helium bubble seeding and tracking.

Lift Coefficient Along Span of Iced Wing with 30° Leading Edge Sweep

Comparison between Navier-Stokes predictions and wind tunnel data



A comparison is shown here between the Navier-Stokes predictions and the wind tunnel results for lift coefficient versus span at 4° and 8° angles of attack. The agreement is nearly perfect.

Although the Navier-Stokes analysis is very accurate, it requires long run times on a supercomputer. An interactive boundary layer code coupled with a potential flow code is less accurate, but requires far less computational time. At this time, we are developing both approaches because the IBL approach is a good engineering design tool, and the Navier-Stokes approach is a good tool for modeling the detailed physics.

Airplane Performance in Icing

Goal

Develop a computer code that predicts performance and stability of modern aircraft with given ice contaminations on the lifting surfaces.

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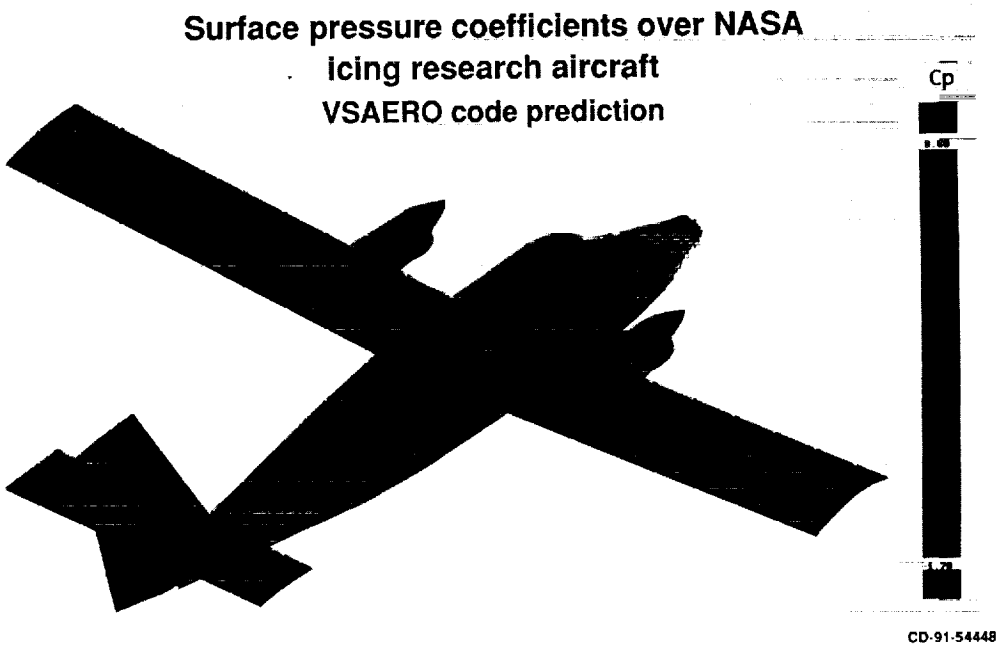
An important aspect of the numerical simulation of an aircraft's response to an icing encounter is the changes in aircraft performance and stability caused by ice. Thus, we are developing a computer code that predicts performance and stability of modern aircraft with given ice shapes on the lifting surfaces. This work will be carried out along with an ongoing effort to develop ice accretion codes for 3D surfaces. Later we will incorporate the ice accretion codes into the aircraft performance and stability code.

Airplane Performance in Icing

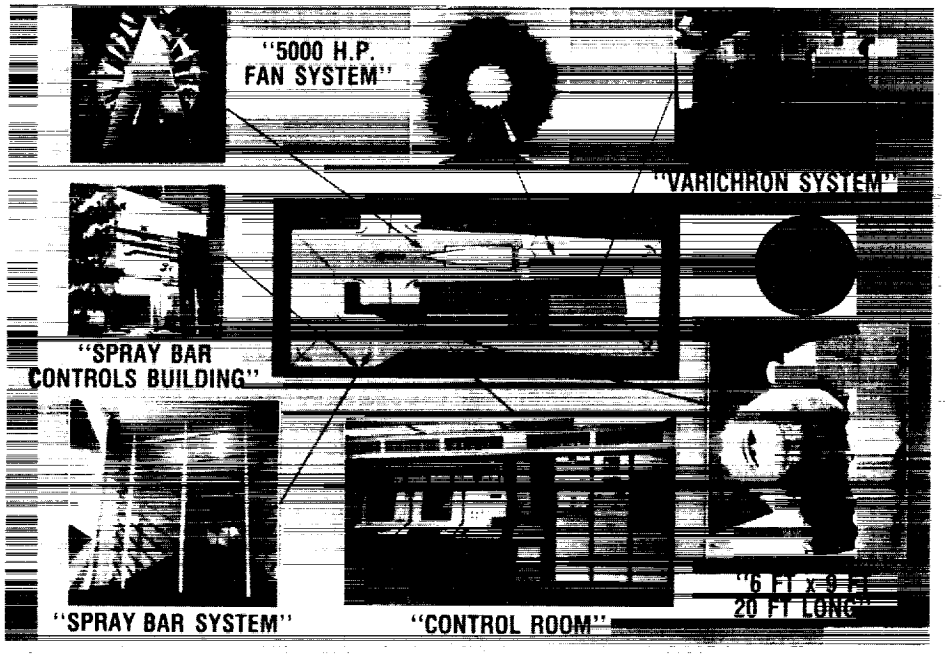


This figure shows the pressure distribution over the NASA Twin Otter icing research aircraft as calculated with an aircraft performance and stability code. Flight data from the Twin Otter will be used to validate the code at full-scale Reynolds numbers. First, the Twin Otter will be flown in dry air with "styrofoam" ice shapes on its tail surfaces, and later it will be flown in supercooled clouds.

In addition to the Twin Otter flight testing, we will conduct dry 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.

After we have acquired a good data base from the wind tunnel, we will use flight testing with a modern swept-wing aircraft to acquire a validation data base at full-scale Reynolds numbers.

Experimental Icing Simulation Techniques
NASA Icing Research Tunnel



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In the area of icing facilities, NASA has two major commitments: first, to provide experimental facilities that accurately simulate the natural icing environment; and second, to develop new experimental capabilities and techniques that fully utilize these facilities.

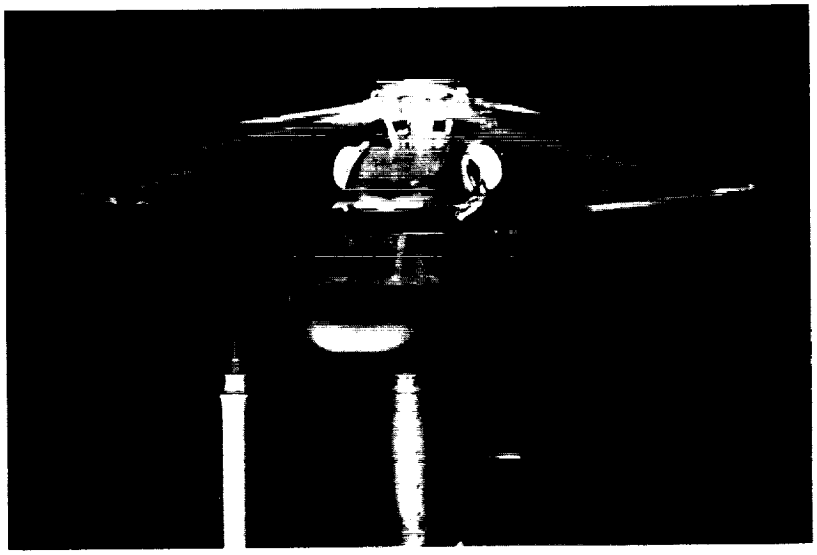
The NASA Icing Research Tunnel and the NASA Twin Otter flight research aircraft are used extensively for code validation, advanced ice protection development, and actual component testing of commercial and military aircraft.

A schematic of the NASA Lewis Icing Research Tunnel (IRT) is shown in this figure. The components shown in the inserts are upgraded systems that were installed when the IRT was rehabilitated in 1986-87. The IRT is the largest refrigerated icing tunnel in the world. The test section is 6- x 9-ft, and 20 ft long. Two unique capabilities of the IRT are its spray nozzle system that creates the supercooled cloud and the heat exchanger and refrigeration plant that allow control of the air temperature down to -30 °F. In effect, we can "dial in the weather" any time of the year.

The IRT is one of NASA's busiest and most productive wind tunnels; in 1988 it logged 1330 hr of actual test time. It carries a 2-year backlog of work.

The IRT is used by NASA, the military, and industry for research and development testing. We conduct many joint programs with the military and with industry.

Experimental Icing Simulation Techniques Subscale Model Rotor Testing in the IRT



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

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Only one civilian helicopter, the French Super Puma, is certified in the United States for flight into forecasted icing conditions. It took 10 years of flight testing in natural icing to win that certification.

The U.S. rotorcraft industry estimates that, if flight testing in natural icing is the only acceptable means for certification, it would cost about 15 million dollars to certificate a helicopter. This cost is prohibitively high.

For several years, NASA and the U.S. rotorcraft industry have been engaged in a joint effort to develop new methods of reducing the cost and time needed to certify and qualify U.S. rotorcraft for icing.

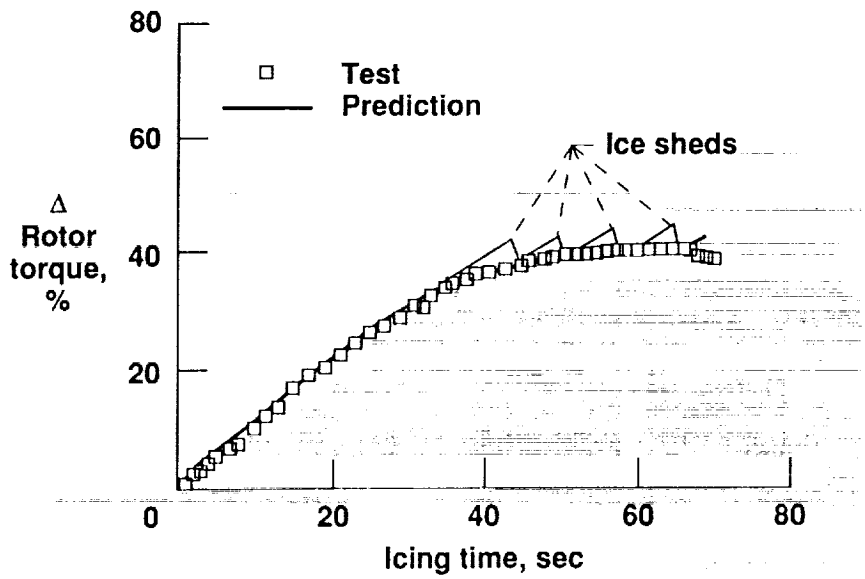
These methods include (1) computer codes that reliably predict full-scale rotor performance in icing and (2) experimental techniques for testing subscale model helicopter rotors in the IRT to acquire data for validating the codes and to develop a better understanding of the effects of icing on rotor 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.

This figure shows a subscale helicopter model 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.

Subscale Model Rotor Testing In the IRT

Rotor Torque vs Icing Time



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This figure shows the torque rise caused by ice accretion on the rotors versus time in icing. The experimental results are compared with an analytical prediction developed by Sikorsky Aircraft. 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.

The comparison between theory and experiment, as shown here, is remarkably good for this particular test run. We also found similar agreement between theory and experiment for lift loss 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, are being reported in several technical reports. 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 icing flight test envelope and to further study rotor performance at warmer outside air temperatures.

Advanced Low Power Ice Protection Systems

Goal

- Develop data base on low power deicers.

Approach

- Test eight different impulse deicer systems in NASA icing tunnel.
- Develop a structural analysis code for ice impact on engine fan blades.

CD-91-54452

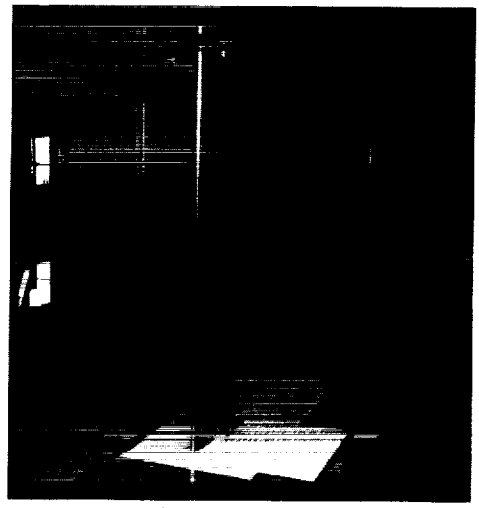
NASA also supports the development and evaluation of advanced ice protection systems that offer lower-power alternatives to hot gas bleed and electrothermal heaters. The new class of electromechanical and pneumatic impulse deicers has stirred interest because they use only 10 to 20 percent of the power used by hot air systems.

Also of interest are some new, but largely untested, higher efficiency capillary tube thermal systems. We will not be discussing these systems, but NASA expects to test them in the future through collaborative efforts with industry.

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 eight different impulse deicer systems in the NASA IRT. We have also supported this effort through a Small Business Innovative Research Contract.

Since ice accumulates on the aircraft surfaces before the deicers are activated, ice particles will be shed from the surfaces during activation. 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.

Air Force/NASA Low–Power Ice Protection Technology Program



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

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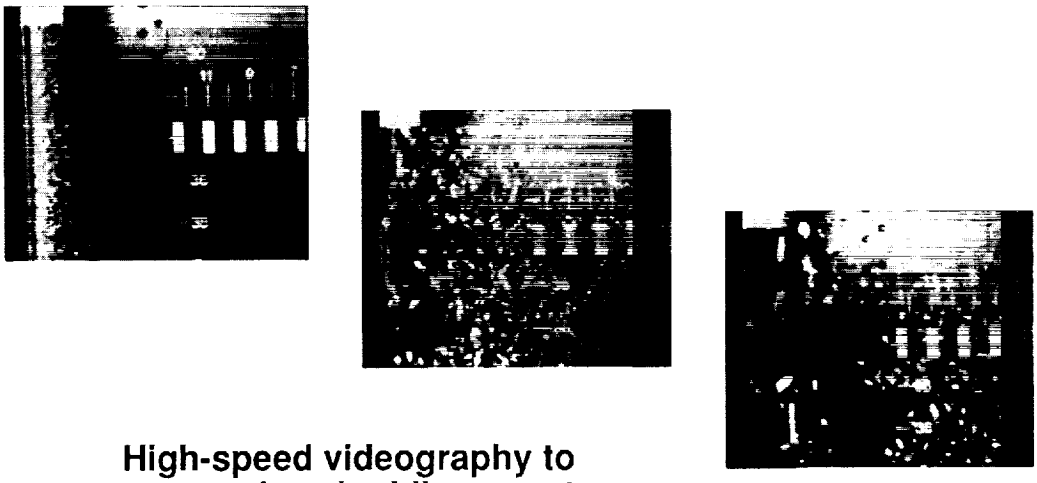
In the test program, eight different impulse deicer systems supplied by six companies were individually tested in the IRT under identical icing conditions. The systems employed pneumatic, eddy-current repulsion, or electro-expulsive means for ice removal.

This figure shows an airfoil with a deicer system installed on the leading edge. This airfoil geometry was chosen because its half-inch leading edge radius represented a challenge for most manufacturers, and because we are trying to simulate the small leading edge radii used on some military aircraft.

The deicers were characterized by four experimentally measured parameters: (1) maximum size of the shed ice particles; (2) amount, texture, and height of residual ice that remained on the surface after deicer activation; (3) energy per unit area required for one deicer activation; and (4) weight per unit area of deicer coverage. The deicers were tested under warm glaze ice conditions and cold rime conditions.

Air Force/NASA Low–Power Ice Protection Technology Program



High-speed videography to capture ice shedding event

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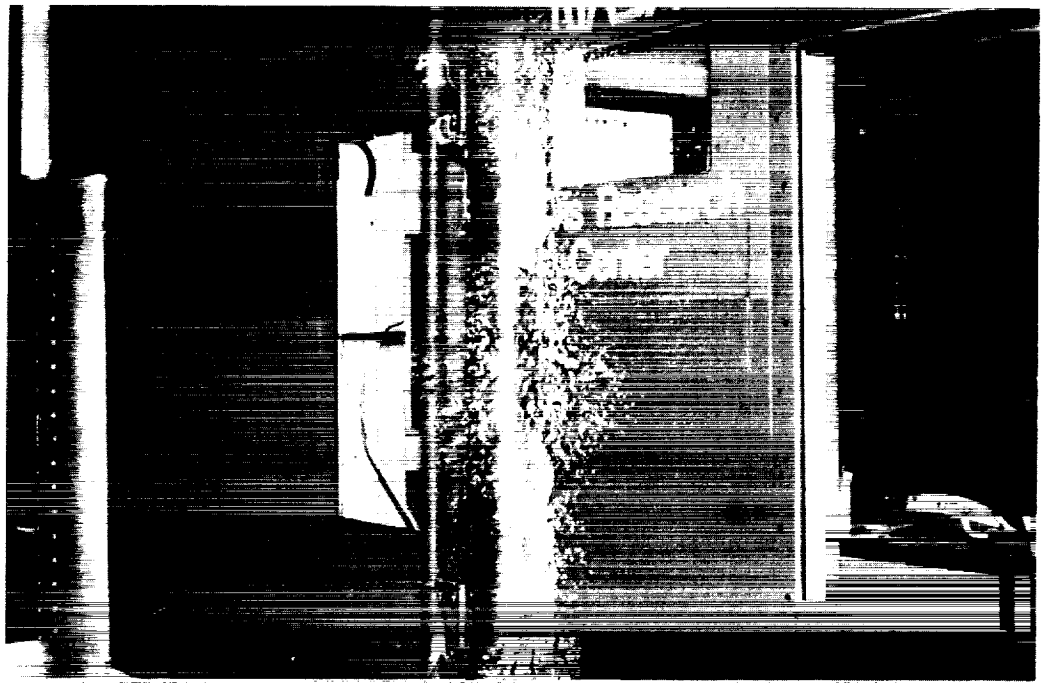
Our ability to capture an ice shedding event by means of high-speed videography is illustrated here. The video photos allowed us to estimate the size of the largest particles shed during an activation and to follow the ice breakup process in the airstream.

Low–Power Deicer Technology



Eddy-current repulsion deicer undergoing development tests in IRT as part of a NASA SBIR contract

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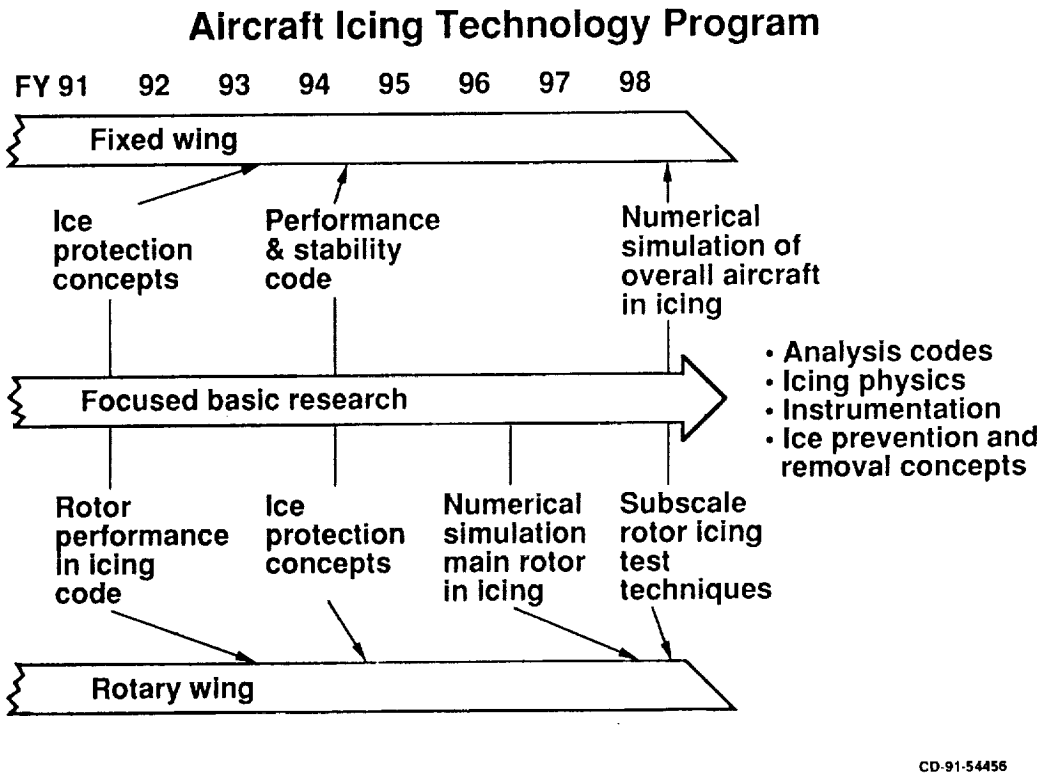
This figure shows ice being expelled from a cylinder by an eddy-current repulsion deicer strip that was undergoing development testing in the IRT. The work was done under a NASA Small Business Innovative Research Contract. This particular deicer is of interest to NASA because it can be applied over the outside of a component while causing only minimal disturbance to the inside of the component.



The Aircraft Icing Technology Program has a strong, focused research effort supporting the strategic objectives for both fixed and rotary wing aircraft.

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, shedding, and removal.

Droplet sizing instrumentation is essential for validating droplet trajectory codes and ice accretion codes.

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 promptly delivered to industry for inclusion in their own icing program.

CONCLUSION

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 ultimately 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 date 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.