NASA Technical Memorandum 83031
AIAA-83-0204

NASA Lewis Research Center's Program on Icing Research

J. J. Reinmann, R. J. Shaw, and W. A. Olsen, Jr.
Lewis Research Center
Cleveland, Ohio

Prepared for the
Twenty-First Aerospace Sciences Conference
sponsored by the American Institute of
Aeronautics and Astronautics
Reno, Nevada, January 10-13, 1983

NASA

ORIGINAL PAGE IS OF POOR QUALITY

NASA LEWIS RESEARCH CENTER'S PROGRAM ON ICING RESEARCH*

J. J. Reinmann, R. J. Shaw, and W. A. Olsen, Jr.

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-1469

Abstract

NASA is again actively involved in aircraft icing research. This paper briefly describes the new research activity in ice protection systems, icing instrumentation, experimental methods, analytical modeling for the above, and in-flight research. The renewed interest in aircraft icing has come about mainly because of the new need for all-weather helicopters and general aviation aircraft. Because of increased fuel costs, tomorrow's commercial transports also will require new types of ice protection systems compatible with the more efficient high by-pass and turboprop engines. And all types of aircraft require better estimates of the aeropenalties caused by ice on unprotected surfaces.

Introduction

If an aircraft is to fly safely through icing clouds, it requires protection on those surfaces that suffer unacceptable aerodegradation from ice accretion. During the 1940's and 1950's, both the NACA and industry helped solve the icing problems for those aircraft that flew IFR (instrument flight rules), which included mainly the commercial and military transports, a few general aviation aircraft, but no helicopters.[1,2]

Today, due to technological advances in avionics and flight controls, nearly all helicopters and general aviation aircraft can be equipped to fly IFR. Yet only a few military helicopters have icing clearances, and no civil helicopter has yet been certified by the FAA for flight into forecasted icing. Many of today's general aviation aircraft are certified for icing, but they rely on ice protection technology that is over 20 years old. The relatively small payload fraction and low power margins of these smaller aircraft mean that their ice protection systems must be light in weight and low in power consumption. Since small objects accrete ice faster than large objects, all the deleterious effects of icing happen faster and are more serious on small, unprotected aircraft: drag rise, torque rise, power loss, lift deterioration, stall angle decrease, and stall speed increase.

Because of high fuel costs, today's large commercial transports need lighter and more efficient ice protection systems. Tomorrow's transport aircraft will need alternatives to the hot-air ice protection system because bleed air will be scarce on the more efficient high-by-pass-ratio engines or high speed turboprop engines.

Thus, the helicopter, general aviation, light transport, and commercial transport aircraft now share common icing requirements: highly effective, lightweight, low-power consuming deicing systems, and detailed knowledge of the aeropenalties due to ice on aircraft surfaces.

NASA has organized a new aircraft icing research program at the Lewis Research Center to help solve the icing problems for modern aircraft. This new program is concentrating on (1) new ice protection systems, (2) new icing instrumentation, (3) improved icing test facilities and testing techniques (especially for helicopters), and (4) widespread use of large, high speed computers to lower development and certification time and cost. Our long-range plan is based on recommendations made in several studies of the icing needs for modern aircraft.[3-7] This report gives an overview of NASA's current efforts in this new icing research program.

NASA Aircraft Icing Program

Figure 1 shows on the left the main elements of NASA's current aircraft icing research program, and on the right the detailed efforts included in each element. We shall briefly describe the research efforts in each element.

Ice Protection Systems

Pneumatic Deicers for Helicopters. Currently, helicopter rotor blades use electrothermal deicers. An alternative is the pneumatic boot deicer, which offers the potential of lower weight, lower power consumption, simpler operating controls, and lower costs. In a joint research program, NASA Lewis and B. F. Goodrich Co. developed pneumatic deicer boots for UH-1H helicopter rotor blades.[8] The best deicer boots tested in the Lewis Icing Research Tunnel (IRT) (Fig. 2) were installed on a U.S. Army UH-1H helicopter at the Army Aviation Engineering Flight Activity at Edwards AFB, California. These boots will be tested on the UH-1H in icing this winter under a joint program between the Army, NASA Ames, and B. F. Goodrich Co.

Electrothermal Deicers. Lewis is developing one- and two-dimensional transient heat conduction codes to analyze electrothermal deicer systems.[9] To obtain validation data for the codes, B. F. Goodrich Co. will install an electrothermal heater blanket on a UH-1H rotor blade section and Lewis will instrument it with thermocouples between the various layers of the heater blanket. The UH-1H blade section will be tested on an oscillating blade rig in the IRT. These tests and the heat conduction codes may help determine proper heater power levels and on/off times as a function of outside air temperature and cloud liquid water content.

---

* Parts of this report were previously presented at the First Internationl Workshop on Atmospheric Icing of Structures sponsored by the Electric Power Research Institute and the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, June 1-3, 1982 (NASA TM-82919)

Glycol Fluid Systems. There is considerable interest in freezing-point-depressant systems. The University of Kansas, under a grant from Lewis, has tested[10] the glycol system on two modern general aviation airfoils in the IRT (Fig. 3). The systems used the modern fluid distributor made of stainless steel mesh by TKS, Ltd., of Great Britain. We have also tested a fluid distributor made of a porous composite material that offers the potential advantages of lighter weight and lower costs than the stainless steel mesh. Further development of the composite distributor is needed before it can replace the stainless steel distributor. Another application for the leading edge fluid distributor is to keep bugs off laminar flow wings. In a joint program between NASA Langley and Lewis, a fluid distributor will be installed on a laminar flow wing and tested for bug and ice protection. Lewis is using all test data on the glycol system to develop a data base and design procedure for the modern porous leading edge fluid distributors, which are more efficient than the distributors tested in the 1940's and 1950's.

Electromagnetic Impulse Deicers. The electromagnetic impulse system offers a potential alternative to the conventional hot-gas anti-icing systems.[5,6] The heart of this system consists of a flat, spirally wound coil of wire installed inside the leading edge of the airfoil. When a capacitor is discharged through the coil, the magnetic field of the coil induces eddy currents in the airfoil skin, causing it to deflect rapidly.

An electromagnetic impulse deicer system for commercial transports was recently tested in the IRT in a joint Lewis/industry program (see Fig. 4). Data from the tests are being analyzed. Lewis has also assembled a NASA/university/industry team to develop the impulse system for both general aviation and transport aircraft. Wichita State University, under a grant from Lewis, has set up an interdisciplinary team composed of aeronautical, electrical, and structural engineers who are working with several airframers and an aircraft electrical components manufacturer. The companies are contributing equipment and design/analysis expertise. The impulse system will be applied to both metal and composite wings and engine inlets. Tests will be conducted in the Lewis IRT, and later in flight if the results warrant it.

Icephobics. Icephobics is the generic name given to any material that, when applied to a surface, reduces the adhesive bond between the ice and the surface. Besides reducing the adhesive bond of ice, an icephobic suitable for aircraft must also resist erosion by rain and sand, must not be carried away with the shed ice, and must withstand exposure to weather including the sun's heat and ultraviolet rays.

As part of a joint program between NASA, the Air Force, and the Army, several icephobic coatings were tested in the IRT. No coating, however, met all of the above criteria. Lewis currently has a grant with Clarkson College of Technology to develop an icephobic coating. Dr. H. Jellinek, the principal investigator for this grant, successfully developed an icephobic coating for the St. Lawrence Seaway locks while he was working for the Army Cold Regions Research and Engineering Laboratory.

Icing Instrumentation

Cloud Instrument Evaluation. In a joint program between Lewis and the Air Force Flight Test Center (Edwards AFB, Calif.) a number of modern and old style icing cloud instruments were compared in the IRT spray cloud to determine their relative accuracy and their limitations over a broad range of IRT operating conditions. The instruments tested were primarily those used to determine drop size and liquid water content (LWC). Each instrument was installed and checked out by its user (owner) or manufacturer to insure that it was operating properly. The IRT spray cloud proved to have adequate repeatablity and spatial uniformity for the needs of the program.

The LWC indicated by all of the instruments tested was compared with the standard IRT LWC calibration. Figure 5 shows that most instruments agreed with each other and the IRT calibration within about ±20 percent; the laser spectrometers, however, generally exhibited a larger scatter in their LWC indications. The data were taken at a very low temperature to avoid any thermal error due to water run-off.

Eight ASSP (Axial Scattering Spectrometer Probe) and three FSSP (Forward Scattering Spectrometer Probe) laser spectrometers for measuring droplet size were compared in the IRT spray cloud. Data from six of the spectrometers were obtained; the others failed for various reasons. The ASSP data showed a scatter of about ±4 μm over the range of 10 to 25 μm. The FSSP data were about 4 μm higher than the ASSP data. Figure 6 shows what a ±4 μm variation in droplet size caused in ice shape and drag on a NACA 0012 airfoil (21-in. chord). The ice shape changed significantly and the resulting drag coefficient changed by a factor of five.

Ice Detectors. Lewis has funded Ideal Research, Inc.[11] to develop an instrument to detect ice on the surface of an aircraft component and to measure the ice thickness and growth rate. The MIAMI (Microwave Ice Accretion Measurement Instrument) consists of a resonant surface waveguide with related electronics and a microprocessor. The wave guide, which mounts flush with the surface, is 0.2 in. wide by 1.41 in. long by 0.393 in. deep. It has a resonant frequency of 6.27 GHz without any ice. As ice builds up, the resonant frequency of the waveguide shifts. A plot of the experimental resonant frequency shift versus ice thickness is shown and compared to an empirical curve fit in Fig. 7. This curve-fit is programmed into the microprocessor to calculate ice thickness and ice growth rate.

Ideal Research, Inc., has demonstrated that the MIAMI works in principle. But further development is required to demonstrate that it can distinguish between water and ice, because under glaze icing conditions both water and ice are present on the surface. This problem seems to be solvable.

Experimental Methods

Icing Research Tunnel. The Lewis Icing Research Tunnel (IRT) is the largest icing wind tunnel in North America (Fig. 8). The IRT has a 6-ft high by 9 ft wide by 20 ft long test section; a top airspeed of 300 mph; a refrigeration plant which produces total air temperatures down to -30° F and which provides for year-round operation; and 77 air atomizing water nozzles which produce a simulated icing cloud with liquid water contents from 0.5 to over 2 g/m^3. The IRT test section operates from sea level (at 0 mph) to 3000 ft altitude (at 300 mph). The IRT was built in 1944; today it is in continual use and constantly has a 2-year backlog of test requests. The IRT can test selected

ORIGINAL PAGE IS OF POOR QUALITY

full-scale components such as airfoils and engine inlets, and it has even tested propellers and aircraft engines in the diffuser leg downstream of the main test section.

Airfoil Performance in Icing. There is a universal need for data on the aerodynamic degradation of two-dimensional airfoils in icing. From tests in the IRT during the 1940's and 1950's empirical formulas were developed[12] that predict lift and drag increments while accounting for chord and thickness of the airfoil, liquid water content and temperature of the cloud, airspeed, and duration of the icing encounter. We recently tested in the IRT two airfoils currently used on general aviation aircraft. One of these airfoils has a blunt leading edge that gives higher maximum lift coefficients and "softer" stall characteristics than the older airfoils that were tested to obtain the empirical formulas. Figure 9 shows the drag predicted from the empirical formula versus the measured drag for the two airfoils over a wide range of icing conditions. Most of the data for the modern airfoils fall within the rather wide spread of results for the older airfoils. But Fig. 9 shows that the empirical formula seriously overestimates the drag for the high LWC tests, which were done only for the modern airfoils. These results point up the need for better analytical methods for predicting airfoil performance in icing.

Other modern airfoils, such as laminar flow control wings and supercritical wings will be tested in the IRT to determine how ice affects the aerodynamic performance of these newer airfoils. NASA Lewis has also contracted with Sikorksy Aircraft to test five modern rotor blade sections in the Canadian National Research Council's high speed icing tunnel. The rotor airfoils are two-dimensional, six-inch chord, scale models. Sikorsky will obtain increments in lift, drag, and pitching moments caused by ice accretion, at Mach numbers up to about 0.7 with the airfoils both fixed and oscillating. They will also document the ice shapes by making molds of the accreted ice. This data for modern airfoils will be made available to the rotorcraft industry for estimating rotor torque rise, and will also be used by NASA to guide their analytical studies in ice accretion modeling and aero performance penalty predictions.

Testing with Artificial Ice. High speed computers are now available and must be used to model the ice accretion process and to analyze the complex flow around airfoils having rough, irregular shaped ice caps that can cause flow separation and reattachment. To determine what physics must be included in the aerodynamic flow model, static pressures must be measured on the surface of the airfoil and the ice cap. These surface pressures are extremely difficult to measure under icing conditions, so we have replaced the actual ice on the leading edge with a wooden replica and obtained static pressures and drag data in the IRT with the icing cloud turned off.[12] Drag results are shown in Fig. 10 for both the real ice and the wood replica (roughness was simulated with grit) for both rime and glaze ice. The drag for the artificial ice agrees satisfactorily with the real ice. Fixed-wing aircraft are often flown with artificial ice in order to determine the aeropenalties due to ice. Artificial ice may some day be applied to helicopter rotor blades to determine aeropenalties.

Helicopter Test Rigs. As mentioned earlier, no civil helicopter is yet certified by the FAA for flight into forecasted icing. A key reason for this lag in technology is the lack of adequate icing test facilities for helicopters and their components. Flight testing in natural icing clouds is expensive because experience indicates that it would take several years of winter flying in natural icing conditions to prove that the helicopter meets icing certification criteria, and even longer to get research type of icing data.

Two icing simulators exist for testing complete helicopters: The Icing Spray Rig, a ground test facility at Ottawa, Canada; and the HISS (Helicopter Icing Spray System), the U.S. Army's inflight icing simulator. The Ottawa Spray Rig tests helicopters in hover or low-speed transition. The HISS tests helicopters in forward flight. Both operate only in the winter season and are subject to the whims of the weather.

The Lewis IRT has tested full-scale engine inlets for nearly all U.S. helicopters that fly IFR. What the helicopter industry lacks is an icing tunnel that can test main rotor blades under simulated flight conditions. In an attempt to see if the IRT can be useful in testing rotor blades, we are building two rotorcraft test rigs (Fig. 11): an oscillating blade rig and a rotating blade rig. The oscillating blade rig will simulate variations in pitch angle during forward flight, thereby giving more realistic ice shape data on full-scale rotor blades. This aerodynamic data may be useful in predicting performance degradation of helicopters without ice protection. The oscillating rotor blade in the IRT may also prove useful for initial testing of deicer systems even though the oscillating rig does not simulate centrifugal forces and the air speed is less than Mach 0.4 in the IRT.

The rotating blade test rig will be used to test an OH-58 tail rotor (about 5 ft in diameter). Rotating blade test results will be compared with oscillating blade test results to determine the importance of centrifugal force and Mach number on ice shape. The main usefulness of the rotating blade rig will be to study the ice formations and to measure the aerodynamic degradation caused by the ice. Model rotors could also be tested in the IRT, but the icing scaling laws must be verified, and nozzles are required to produce water droplet volume median diameters less than 10 μm. We are working toward these goals.

Lewis has been advocating that their now dormant Altitude Wind Tunnel (AWT) be rehabilitated into a propulsion and icing wind tunnel (Fig. 12). The new AWT would have two test sections: a 20-ft diameter section with speeds up to Mach 1 and a 45-ft diameter section with speeds up to 50 knots. The high speed section would test deicers on oscillating, full-scale rotor blades up to blade-tip Mach numbers; it would test helicopter inlets with simulated rotor downwash, and it would do complete rotor tests on typical scale model rotors. The low-speed section would test complete helicopters (with truncated blades), and it would have a rotor whirl rig for testing full-scale rotor blade deicer systems.

Icing Scaling Laws. All icing simulation facilities are limited in the model size they can test and in the air speed, altitude, droplet size, liquid water content, and temperature they can attain. As a consequence they cannot duplicate all of the icing conditions necessary to test an aircraft component. To get around these facility limitations, icing scaling laws were derived in the 1950's;[14] however, these relationships have never been properly verified. Proper experimental verification is extremely difficult because of serious facility and icing instrument limitations.

In an attempt to verify the icing scaling laws, Lewis and AEDC (Arnold Engineering Air Development Center, Tullahoma, Tenn.) have entered into a joint research program. The experimental verification uses the complementary capabilities of the large, low-speed Lewis IRT and the small, high-speed AEDC free jet. Lewis is performing research on the energy balance, the heat transfer coefficients, and the catch efficiency of airfoils to improve the existing icing scaling laws. AEDC is testing several spray nozzles to find one that produces the small droplets required for testing small-scale models and also to improve all icing simulation facilities. Verification tests will consist of testing a series of airfoils under several sets of icing tunnel conditions that are predicted by the scaling laws to give equivalent drag and ice shape results.

Verified icing scaling laws would (1) permit accurate tests at actual facility conditions, which duplicate the results of conditions unattainable by that facility, and (2) permit tests of small-scale models of aircraft and rotors to determine the aeropenalties of icing.

Analytical Methods

The NASA aircraft icing research effort includes extensive aircraft icing analysis. The long-term goal is to use computers to predict the details of an aircraft icing encounter. Computer codes will be developed to predict changes in overall aircraft performance and aircraft handling characteristics due to ice accretions on unprotected surfaces. Other codes will be developed to design ice protection systems and analyze their performance.

Today's large, high-speed digital computers were not available to the NACA icing researchers in the 1940's and 1950's, and up until 1980 virtually no icing analysis codes were published in the open literature. The increasing costs of icing flight tests provide strong motivation to substitute aircraft icing analysis methods for test programs where possible.

Currently we are developing some of the required codes and verifying their accuracy with appropriate experiments. These codes are being developed through a combination of in-house efforts and various grants and contracts. Figure 13 indicates the large number of computer codes required. Also shown are some (but by no means all) of the required interfaces. The figure also shows areas of current research in NASA.

Water Droplet Trajectory Codes. FWG Associates, Inc., is developing a particle trajectory code[15] to calculate two-dimensional trajectories about single- and multi-element airfoils, two-dimensional inlets, and axisymmetric inlets at angle of attack (symmetry plane only). The flow fields are calculated using appropriate Douglas Aircraft potential flow codes.

Atmospheric Science Associates has developed a three-dimensional particle trajectory code for calculating trajectories about three-dimensional nonlifting[16] and lifting bodies. The code can calculate water droplet trajectories about the complete aircraft. Again, appropriate potential flow codes developed by Douglas Aircraft are used to predict the aircraft flow field.

Ice Accretion Modeling Codes. The University of Dayton Research Institute is developing an ice accretion modeling code[17] which will calculate two-dimensional ice accretion shapes on airfoils for rime through glaze icing conditions. The approach extends the work of Stallabrass and Lozowksi[18] and Ackley and Templeton.[19] The code is compatible with the water droplet trajectory code developed by FWG, and allows the airfoil flow field and resultant collection efficiency to be recomputed as the ice accretion changes the airfoil contour.

Transient Heat Conduction Codes. The University of Toledo is developing one- and two-dimensional heat conduction codes to model electrothermal deicers. A preliminary version of the one-dimensional code is given in Ref. 9. The codes include a moving water-ice interface because flight test results indicate that rotor blade surface temperatures can reach 60° F before the ice sheds.

Aerodynamic Performance Codes. The Ohio State University is developing a capability for predicting aerodynamic performance degradation of airfoils due to ice accretions.[20] They start with existing aerodynamic analysis codes for airfoils, and modify them wherever needed to model the flow around airfoils with ice accretions. As a separate activity, Ohio State is developing a method to predict overall aircraft performance degradation that uses the results of the various other two-dimensional codes being developed.

Texas A and M University is using the fixed-wing methodology developed at Ohio State University and extending it to calculate the performance degradation of propellers and helicopter rotors in both hover and forward flight.[21]

As Fig. 13 indicates, several additional computer codes remain to be developed. But first, fundamental experiments must be conducted to gain a better understanding of the physics to guide the modeling efforts. Also of critical importance is accurate verification data to determine computer code capabilities and limitations. Unfortunately little verification data exist and getting some of it will require new icing simulation facilities, test rigs, and instrumentation capabilities.

Flight Research

Lewis has started an icing research flight program using NASA's Twin Otter airplane (Fig. 14). It will be flown out of Lewis during the icing season from November through April. A joint U.S. Army/NASA helicopter flight test program is also discussed below. The flight programs are intended to insure that researchers conducting icing tests in the IRT or developing computer codes in support of icing have first-hand knowledge of how their results compare with flight test results in real icing conditions.

Validation Data for Icing Simulation Facilities. There does not seem to have been any systematic attempt to prove that icing simulators do a reasonable job of duplicating the natural icing conditions. Lewis plans to obtain, during flights in natural icing conditions, ice shapes on standard cylinders and airfoils that any icing simulator can try to reproduce.

For example, the same airfoils and cylinders used in flight will be installed in the IRT where flight icing conditions (airspeed, LWC, drop size, and temperature) will be duplicated. Drag, ice shapes, and ice growth characteristics obtained in the IRT will be compared with those from natural icing. The flight and IRT data comparisons will measure the IRT's ability to simulate natural icing conditions.

Instrument Evaluation. This flight program affords an opportunity to compare several modern cloud instruments with one another and also with the rotating multicylinders and oil slide instruments that were used in the 1940's and 1950's. The Twin Otter will be equipped with all of the modern, flightworthy cloud instruments.

Icing Cloud Data. On each icing flight NASA will collect icing cloud data and give it to the FAA who is collecting and correlating icing cloud data taken at lower altitudes with modern instrumentation.

Meteorology. NASA Langley has developed a numerical code[22] to forecast the future state of the atmosphere at mesoscale. The code is entitled MASS (Mesoscale Atmosphere Simulation System). MASS uses a 50 km grid spacing over North America, with 14 levels in altitude and 51 sec computation time interval. After each icing flight, Lewis gives Langley the location and altitude where the Twin Otter encountered icing. Langley uses this data to validate MASS by backcasting the conditions at the specified location of the icing encounter.

Airplane Performance. NASA and the Ohio State University will conduct inflight icing experiments to measure lift and drag degradation of the Twin Otter's wings, and also overall airplane performance loss. Ohio State will install a heated wake survey probe and a static pressure belt on one of the Twin Otter's wings. Thrust horsepower measurement techniques will be developed. Flight results will be compared with similar results of tests in the IRT on a Twin Otter wing section.

Helicopter Performance. NASA (Lewis and Ames) and the U.S. Army (AVRADCOM, ATL Ft. Eustis, VA and AEFA Edwards AFB, CA) have a joint helicopter flight research program. The purpose of this program is to determine if two-dimensional airfoil data can be used in existing helicopter performance codes to predict hover performance under icing conditions. The Army will fly a UH-1H helicopter in the Canadian Ottawa Spray Rig. After the UH-1H accummulates ice on its rotors, it will be moved out of the cloud and the Army will measure its performance characteristics. The UH-1H will land and NASA will document the ice formed on the rotor blades, using molding techniques and stereo photography. From these molds full-scale, rotor airfoil sections will be made. These sections will be tested in a dry transonic wind tunnel to obtain lift, drag, and pitch moments. This section data will be used in helicopter performance codes to predict hover performance degradation. The predictions will be compared with the measured hover performance.

Concluding Remarks

As you can see from this review, NASA's new icing research program is broadbased, and covers both basic research and engineering applications. The program is well coordinated among the various NASA Research Centers, the FAA, the DOD, universities, industry, and some foreign governments. This coordination eliminates duplication of effort and facilities, and helps assure that we are working on the right problem.

Our planning and research reveal that the icing problem has four main needs: advanced ice protection concepts; improved icing instrumentation; advanced icing analysis methods; and new or improved icing test facilities. Ice accretion modeling and aerodynamic analysis of flows around rough, irregular ice surfaces with separated and reattached flows represents one of the most challenging problems remaining in classical fluid mechanics.

References

1. Reinman, J. J.: Selected Bibliography of NACA-NASA Aircraft Icing Publications. NASA TM-81651, 1981.
2. Bowden, D.T.; Gensemer, A. E.; and Skeen, C. A.: Engineering Summary of Airframe Icing Technical Data. FAA-ADS-4, Federal Aviation Agency, 1963.
3. Peterson, A. A.; Dadone, L.; and Bevan, A.: Rotorcraft Aviation Icing Research Review and Recommendations. (D210-11662-1, Boeing Vertol Co.; NASA Contract NAS3-22384.) NASA CR-165344, 1981.
4. Breeze, R. K.; and Clark, G. M.: Light Transport and General Aviation Aircraft Icing Research Requirements. (NA-81-110, Rockwell International Corp.; NASA Contract NAS3-22186.) NASA CR-165290, 1981.
5. Koegeboehn, L. P.: Commercial Aviation Icing Research Requirements. NASA CR-165336, 1981.
6. Rotorcraft Icing--Status and Prospects. AGARD AR-166, 1981.
7. Engineering and Development Program Plan--Helicopter Icing Technology Research. FAA-ED-18-8, Federal Aviation Administration, 1981.
8. Blaha, B. J.; and Evanich, P. L.: Pneumatic Boot for Helicopter Rotor Deicing. NASA CP-2170, 1980.
9. DeWitt, K. J.; and Baliga, G.: Numerical Simulation of One-Dimensional Heat Transfer in Composite Bodies with Phase Change. NASA CR-165607, 1982.
10. Kohlman, D. L.; Schweikhard, W. G.; and Albright, A. E.: Icing Tunnel Tests of a Glycol-Exuding Porous Leading Edge Ice Protection System on a General Aviation Airfoil. (KU-FRL-464-1, Kansas Univ. Center for Research, Inc.; NASA Contract NAG3-71.) NASA CR-165444, 1981.
11. Magenheim, B; and Rocks, J. K.: Development and Test of a Microwave Ice Accretion Measurement Instrument (MIAMI). NASA CR-3598, 1982.
12. Gray, V. H.: Prediction of Aerodynamic Penalties Caused by Ice Formations on Various Airfoils. NASA TN D-2166, 1964.
13. Bragg, M. B.; Gregorek, G. M.; and Shaw, R. J.: Wind Tunnel Investigation of Airfoil Performance Degradation Due to Icing. AIAA-82-0582, 1982.
14. Dodson, E. D.: Scale Model Analogy for Icing Tunnel Testing. D6-7976, Boeing Airplane Company, 1966.
15. Frost, W. F.; Chang, H.; Shieh, C.; and Kimble, K.: Two Dimensional Particle Trajectory Computer Program. NASA CR to be published.
16. Norment, H. G.: Calculation of Water Drop Trajectories to and about Arbitrary Three-Dimensional Bodies in Potential Airflow. NASA CR-3291, 1980.
17. MacArthur, C. D.; Keller, J. L.; and Luers, J.K.: Mathematical Modeling of Ice Accretion on Airfoils. AIAA Paper 82-0284, 1982.

18. Lozowski, E. P.; Stallabrass, J. R.; and Hearty, P. F.: The Icing of an Unheated Non Rotating Cylinder in Liquid Water Droplet-Ice Crystal Clouds. LTR-LT-96, National Research Council of Canada, 1979.
19. Ackley, S. F. and Templeton, M. K.: Computer Modeling of Atmospheric Ice Accretion. CRREL-79-4, Army Cold Regions Research and Engineering Lab., 1979.
20. Bragg, M. B.; Gregorek, G. M., and Shaw, R.J.: An Analytical Approach to Airfoil Icing. AIAA 81-0403, 1981.
21. Korkan, K. D., Dadone, L.; and Shaw, R. J.: Performance Degradation of Propeller/Rotor Systems Due to Rime Ice Accretion. AIAA-82-0286, 1982.
22. Kaplan, M. L.; et al.: A Mesoscale Eighth Order Numerical Modeling System and the "Red River" Tornado Outbreak of 1979, Parts I and II. Presented at the 12th AMS Conference on Severe Local Storms. (San Antonio, Texas), Jan. 11-15, 1982.

● ICE PROTECTION SYSTEMS	- PNEUMATIC DEICERS FOR HELICOPTERS - ELECTROTHERMAL DEICERS - GLYCOL FLUID SYSTEMS - ELECTROMAGNETIC IMPULSE DEICERS - ICEPHOBICS
● ICING INSTRUMENTATION	- CLOUD INSTRUMENT EVALUATION - ICE DETECTORS
● EXPERIMENTAL METHODS	- ICING RESEARCH TUNNEL - AIRFOIL PERFORMANCE IN ICING - TESTING WITH ARTIFICIAL ICE - HELICOPTER TEST RIGS - ICING SCALING LAWS
● ANALYTICAL METHODS	- COMPUTER CODES FOR: ● WATER DROPLET TRAJECTORIES ● ICE ACCRETION MODELING ● AERO PERFORMANCE PENALTIES ● TRANSIENT DEICER ANALYSIS
● FLIGHT RESEARCH	- VALIDATION DATA FOR ICING SIMULATION FACILITIES - INSTRUMENT EVALUATION - ICING CLOUD DATA - METEOROLOGY - HELICOPTER PERFORMANCE

CD-82-13130

Figure 1. - Elements of NASA's Aircraft Icing Program.

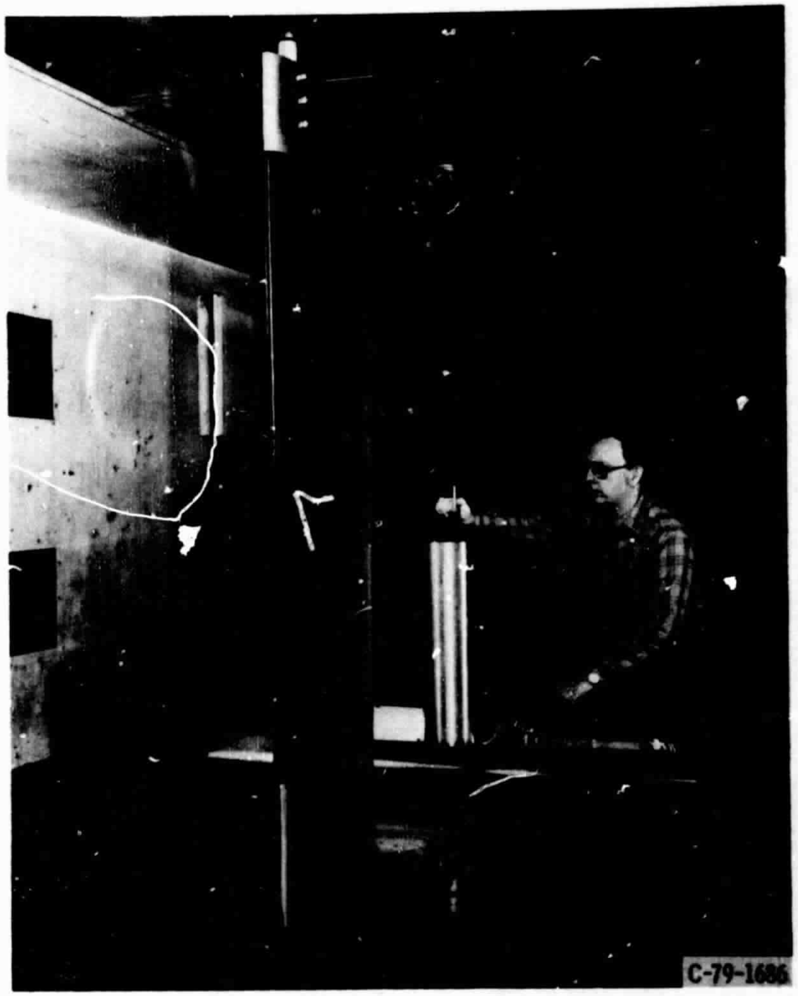


Figure 2. - Pneumatic boot deicer on UH- 1H rotor blade, and wake survey probe in the LeRC Icing Research Tunnel.

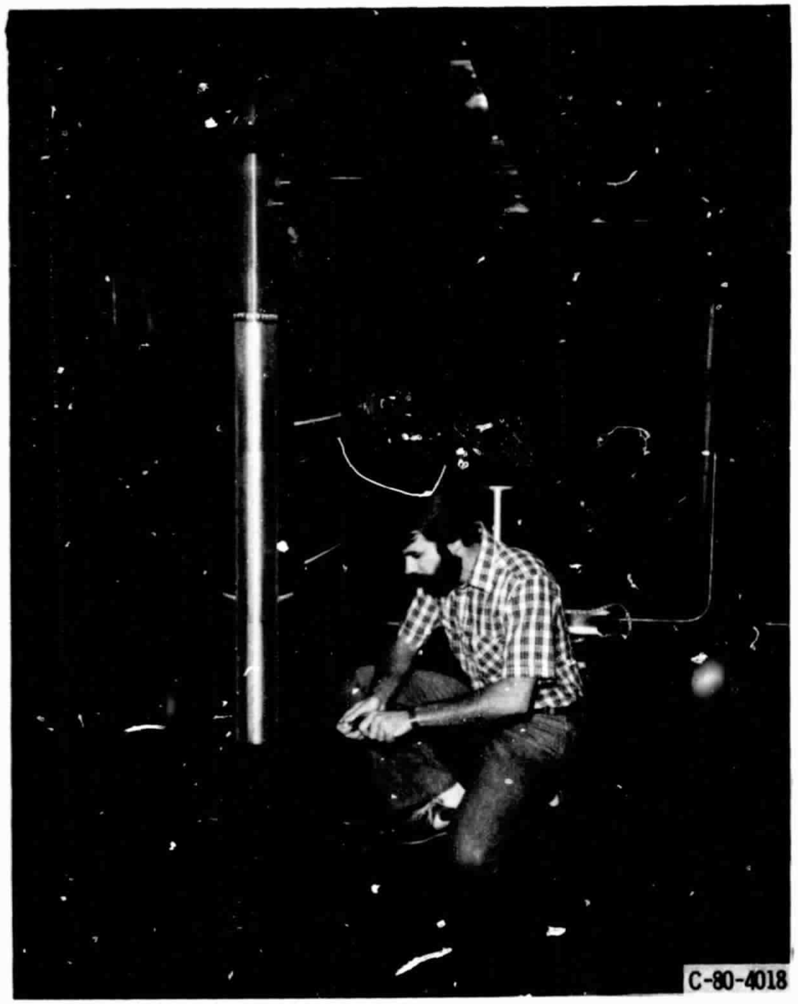
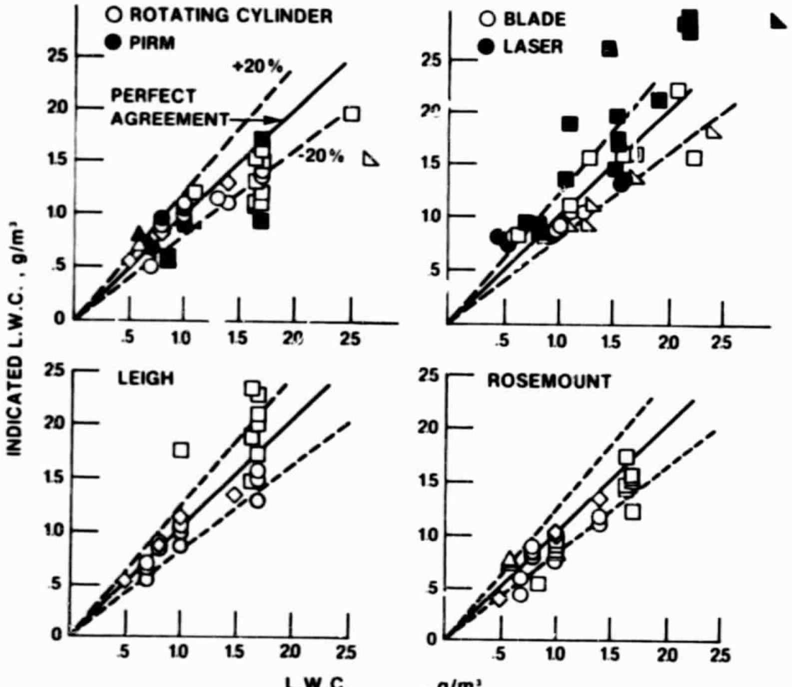


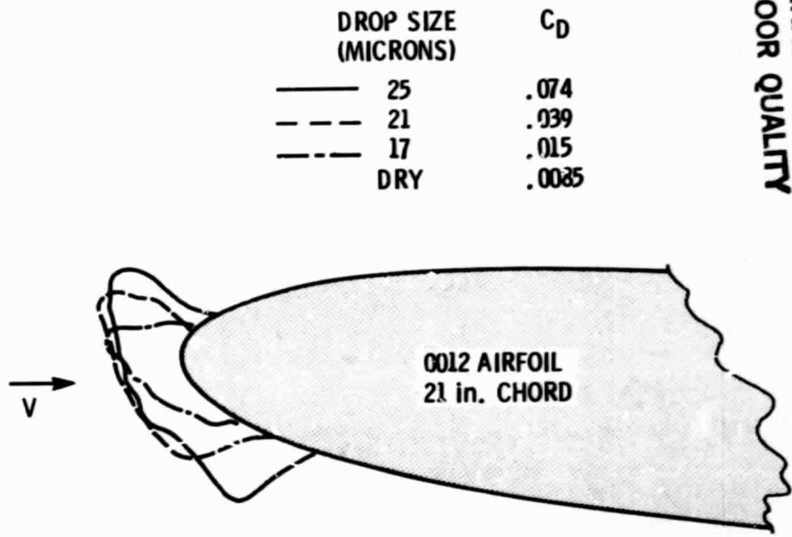
Figure 3. - Glycol fluid distributor (porous stainless steel) on leading edge of wing in the LeRC Icing Research Tunnel.

Figure 4. - Electromagnetic impulse deicer system shown installed in a leading edge slat in the LeRC icing tunnel.



CD-82-13136

Figure 5. - Results of tests comparing several liquid-water-content meters in the Lewis IRT.



AIRSPEED, 130 mph; AIR TEMP, + 18^0 F; LWC, 1.3 G/M^3; TIME 8 min; ANGLE, 4^0

CD-82-13131

Figure 6. - Effect of cloud volume median droplet size on ice shape and drag, from measurements in the Lewis IRT.

ORIGINAL PAGE IS
OF POOR QUALITY

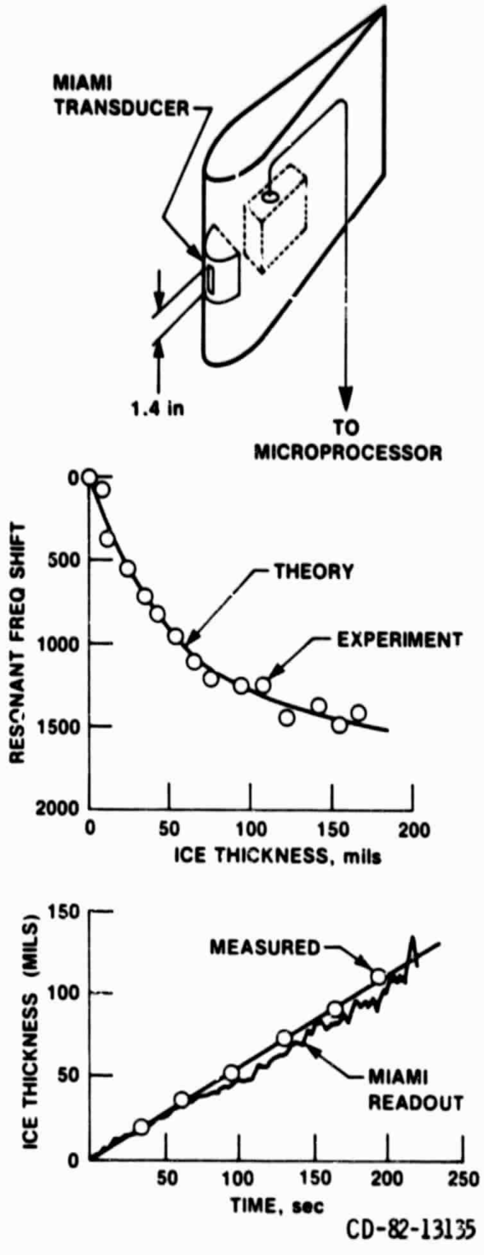


Figure 7. - Relationship between resonant frequency shift and ice thickness for the Microwave Ice Accretion Measurement Instrument (MIAMI).

ORIGINAL PAGE IS
OF POOR QUALITY

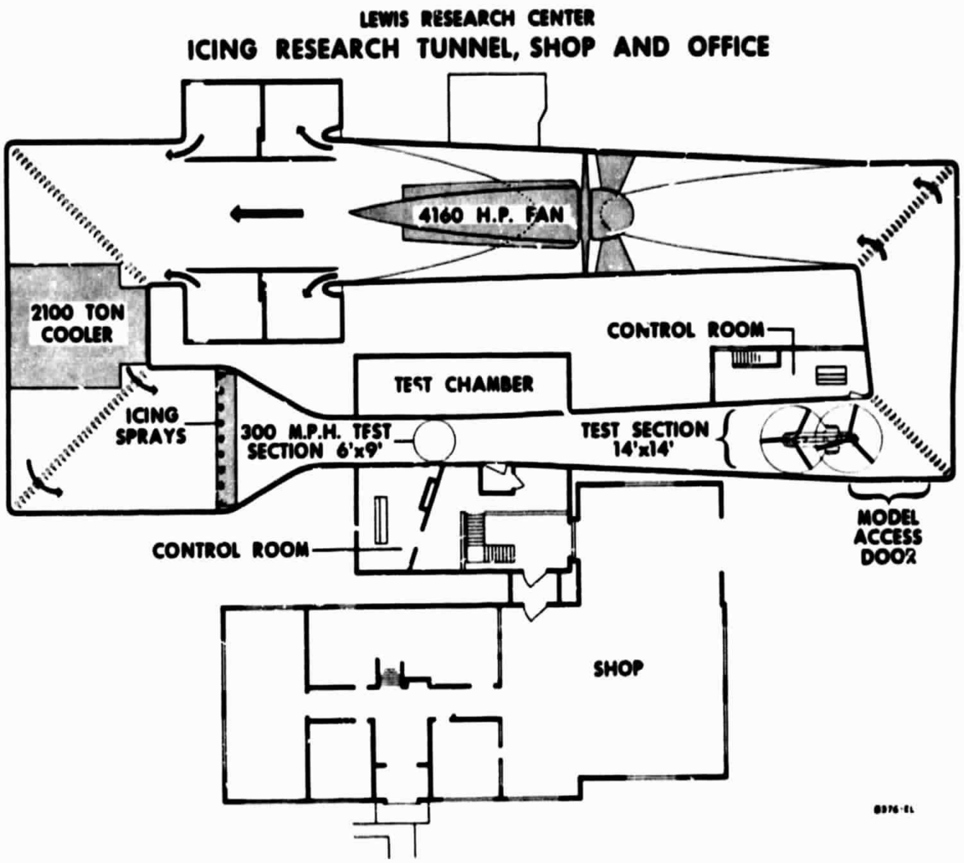
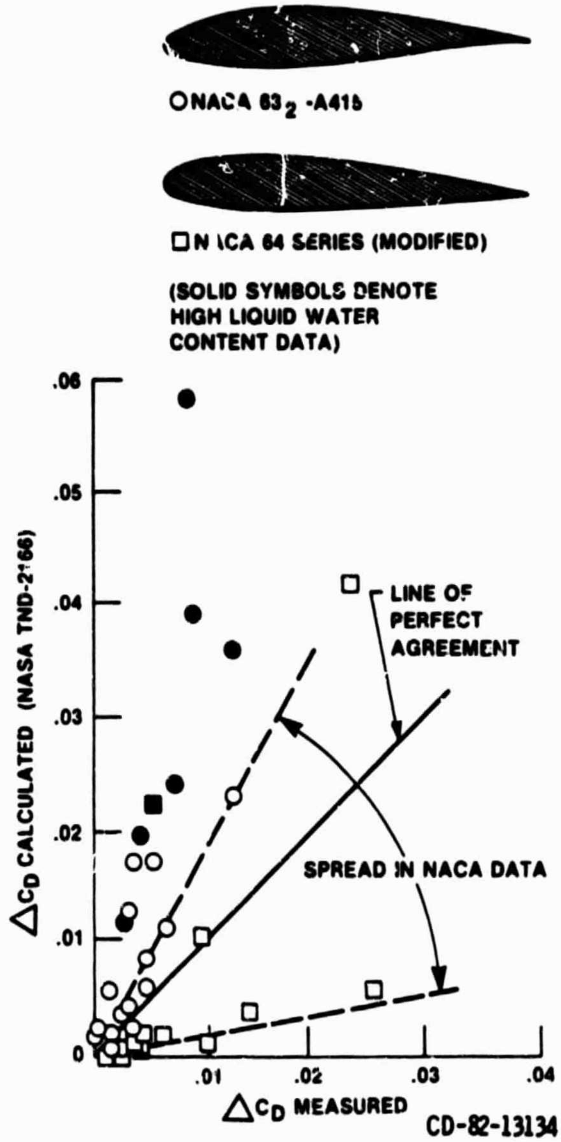


Figure 8. - Loop schematic of the Lewis Icing Research Tunnel.

ORIGINAL PAGE IS
OF POOR QUALITY



CD-82-13134

Figure 9. - Predicted drag increments due to ice accretion (from NASA TN D-2166) versus drag increments measured in the Lewis IRT.

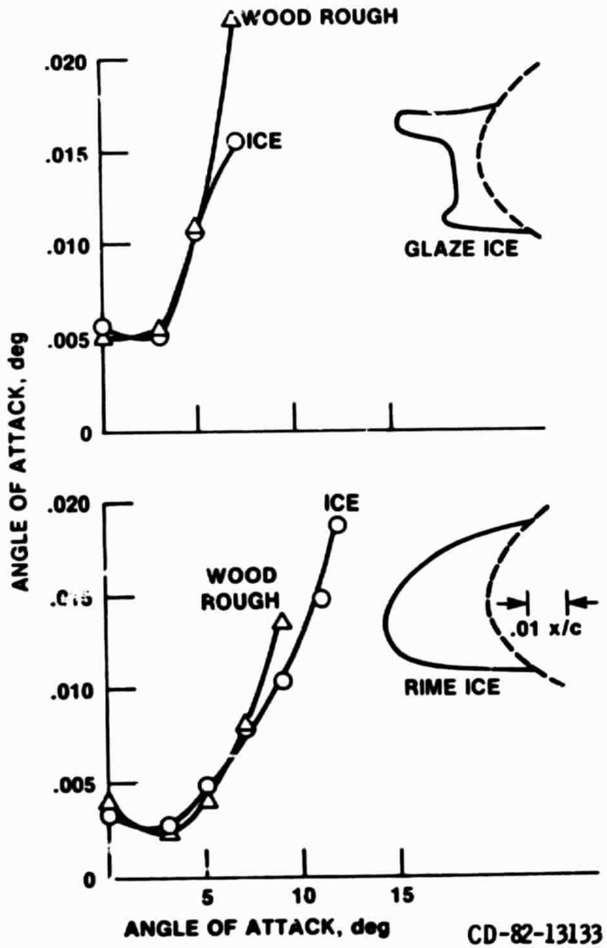


Figure 10. - Drag increments from real ice compared with the drag increments from wooden replicas of the ice.

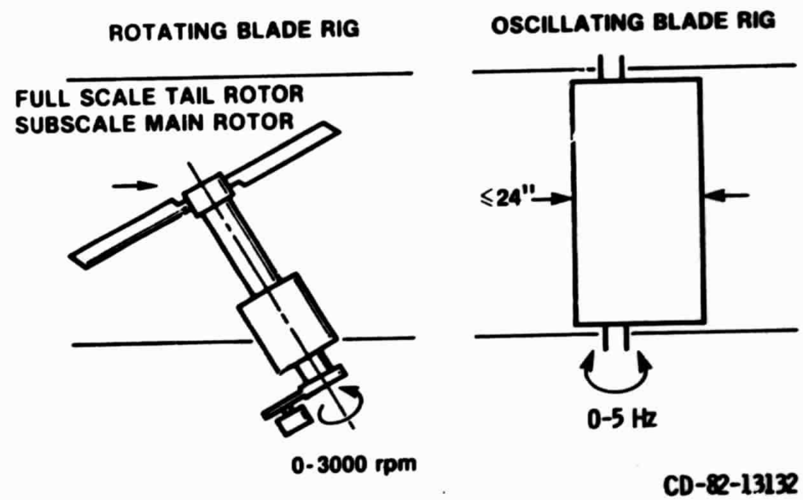


Figure 11. - Rotor blade test techniques being developed for the Lewis IRT.

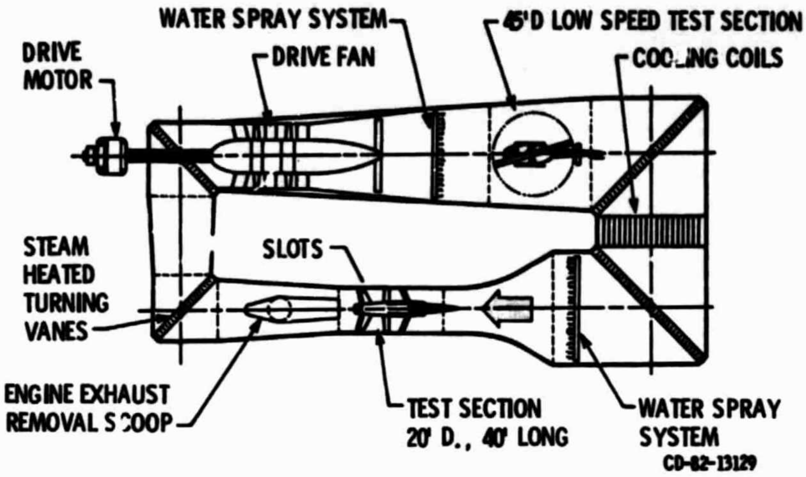


Figure 12. - Flow circuit for proposed rehabilitation of the Lewis Altitude Wind Tunnel (AWT).

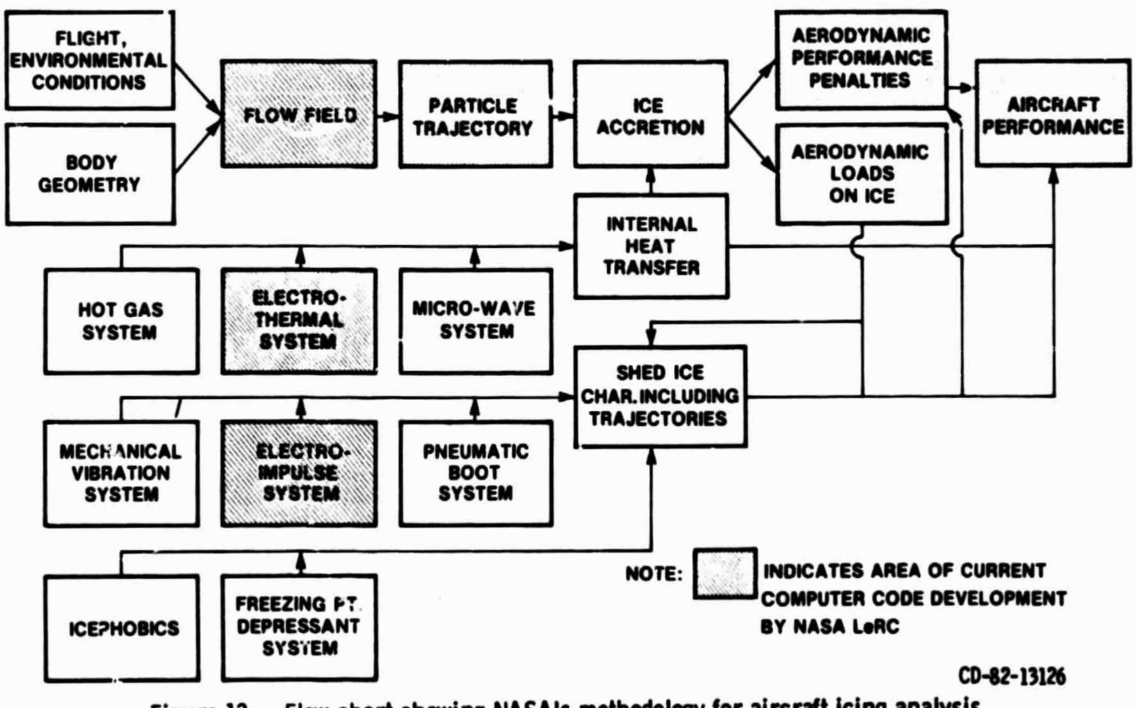


Figure 13. - Flow chart showing NASA's methodology for aircraft icing analysis.

Figure 14. - The NASA icing flight research aircraft.