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THE NASA AIRCRAFT ICING RESEARCH PROGRAM

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SUMMARY

The objective of the NASA aircraft icing research program is to develop and make available to industry icing technology to support the needs and requirements for all-weather aircraft designs. Research is being done for both fixed- and rotary-wing applications. The NASA program emphasizes technology development in two key areas: advanced ice protection concepts and icing simulation (analytical and experimental). This paper reviews the computer code development/validation, icing wind tunnel testing, and icing flight testing efforts which have been conducted to support the icing technology development.

PROGRAM OVERVIEW

The major areas of emphasis of the NASA icing research program are shown in figure 1. The program has a generic portion which is devoted to developing the required fundamental technology. The basic technology is applied with appropriate modifications and alterations to fixed- and rotary-wing specific icing problems. The icing research program is a balanced effort (fig. 2) in that it contains analysis code development/validation, wind tunnel testing, and icing flight research activities. These elements of the program are closely coordinated since all are conducted within the icing rsearch group. In addition, close coordination exists with industry and universities through formal contracts and grants as well as through collaborative and cooperative programs.

Some recent accomplishments of the icing research program will be reviewed by looking at some past activities in two technology areas: ice protection concepts, and analytical and experimental icing simulation. The first area to be reviewed will be ice protection concepts, where the goal is to develop concepts which will result in lighter, more efficient ice protection systems for advanced military and civilian aircraft.

In fiscal year 1987, a 5-year NASA/industry/university program was completed to develop the technology data base for the electromagnetic impulse deicer concept (or EIDI) which shows great promise for providing highly efficient deicing with low power requirements. The major phases of this program are shown in figure 3.

The technology was developed through many different Icing Research Tunnel (IRT) tests of various general aviation and commercial transport components which require ice protection. The hardware was provided by the many aerospace companies that were part of the consortium. Complimentary analytical modeling (structural and electrodynamic) and laboratory tests were conducted at Wichita State University to better understand the key physics associated with EIDI. Natural icing flight tests were conducted with the NASA icing research aircraft to which was affixed a leading edge glove or cuff with the EIDI system installed. Excellent deicing performance was documented in natural icing conditions. As a result of this program, the technology is now in hand for both the general aviation and transport manufacturers to consider EIDI for main wing/tail deicing for future applications.

The electrothermal deicing system has become the de facto standard for the helicopter industry, but the weight, power requirements, and complexity of electrothermal deicing systems has caused the industry to seek alternative concepts. In a joint program with the Army and industry (Bell Helicopter Textron and B.F. Goodrich), a pneumatic boot deicer was applied to the UH1H rotor and highly acceptable deicing capability was demonstrated (fig. 4). Deicing performance was demonstrated in both forward flight conditions behind the Army's spray tanker and near hover conditions at the Canadian NRC's Ottawa Spray rig. Prior to the icing flight tests, tests were conducted in the IRT on a full-scale, fixed-position UH1H rotor section. These tests were used to screen various pneumatic boot configurations and led to the selection of the configuration shown. Two of the attractive features of the pneumatic boot deicer system is that it had relatively few components and the UH1H system weight was only about 40 lb.

As a result of this program, the Army has qualified the UH1H helicopter with pneumatic deicers to fly into forecast icing conditions up to the "moderate" level. Future activities are being conducted by the Army and B.F. Goodrich to acquire the needed field experience especially as related to rain and sand erosion characteristics and the frequency of field repair/replacement required.

The second icing technology area to be reviewed will be analytical and experimental icing simulation. The following activities are included in this technology area:

(1) Developing/validating codes to predict aircraft performance, stability, and control in icing

(2) Improving/validating icing simulation facilities

(3) Conducting natural/artificial icing flight tests

(4) Improving icing instrumentation

First, the development and validation of icing analysis computer codes will be discussed. Figure 5 attempts to show the many codes required to form a comprehensive icing analysis methodology as well as some of the many interfaces required. The individual computer codes currently being developed and validated are as follows:

(1) Trajectory analyses, both two dimensional and three dimensional

(2) Airfoil ice accretion

(3) Aerodynamic performance-in-icing, including airfoil, propeller, rotor (approximate), and complete aircraft (approximate)

(4) Ice protection systems, including electrothermal, electroimpulse, fluid freezing point depressant, and pneumatic boot.

This set of codes forms a core analysis capability which can be used to build a more comprehensive icing analysis capability. Some examples of the various codes being developed and the supporting fundamental and validation experiments being conducted will be given.

A number of two- and three-dimensional trajectory analysis codes have been developed which can calculate water droplet paths around bodies ranging from simple, single-element airfoils to complete aircraft configurations. Appropriate data are required to validate the code accuracies, and one aspect of this experimental research as shown in figure 6. This is a joint NASA/FAA program to measure local water impingement rates (often called local collection efficiencies) on various airfoil, wing, and inlet configurations.

These curves are determined by collecting water mixed with a known concentration of blue dye on blotter strips affixed to the models like the Boeing 737-300 1/4-scale inlet shown. A He-Ne laser system measures the local reflectance of the blotter paper which can be converted to local collection efficiency. The first phase of this joint program has been completed, and additional tests are planned in order to acquire a comprehensive data base for code validation.

Figure 7 shows a computer graphics representation of the NASA icing research aircraft, a deHavilland DHC6 Twin Otter. This computer model is being used to calculate three-dimensional trajectories of water droplets about the aircraft to help in interpreting icing cloud instrument data. Selected results of trajectory analysis studies of the laser spectrometer droplet sizing instrument are shown in figure 8. The results show that significant errors can occur when the instrument is mounted beneath the main wing of the NASA icing research aircraft. This error is attributed to the three-dimensional flowfield effects on the trajectories of the water droplets. The curves indicate that, for the droplet sizes of interest (10 to 100 μm), the instrument will sense that fewer droplets per cubic meter exist than actually do exist in the "free stream" icing cloud. Similar results would be expected for any other aircraft configuration which had icing instruments located in close proximity to the aircraft surface.

A first-generation code has been developed to predict the growth of ice on a single-element airfoil. A typical comparison of the predictions of this code (called LEWICE) with data taken in the IRT on a 21 in. chord NACA 0012 airfoil is shown in figure 9. Currently evaluation studies of LEWICE are being conducted by NASA, FAA, and several companies under cooperative programs.

The LEWICE code uses a simple control volume approach for calculating local mass and energy balances which lead to local ice growth rate predictions. Such a global approach is necessary because the fundamental physics of aircraft icing are not that well understood. Fundamental in-house and university research efforts are under way to improve the basic physics understanding and incorporate this knowledge into later versions of LEWICE to improve the ice shape predictions. One example of this research is shown in figure 10.

Closeup flash pictures were taken of droplet impingement in the stagnation region of a circular cylinder. Individual cloud droplet streaks can be seen as well as water coalescence into much larger droplets and resulting movement on the surface prior to freezing.

Improved values for impact ice structural properties as well as adhesion strengths are required inputs to computer models of mechanical and thermal deicing systems. Fundamental experiments are being conducted to acquire such data, and a representative sample of the data being acquired is shown in figure 11. The figure shows adhesive shear stress as a function of airstream temperature. One important point to be gained from the figure is the considerable amount of scatter which exists with this type of data. Similar levels of data scatter have been observed by other researchers.

The current emphasis in predicting aerodynamic performance degradation due to icing is to extend and validate state-of-the-art airfoil analysis codes to predict "iced airfoil" performance. Detailed flowfield data are required to evaluate these codes, and the current approach being taken is shown in figure 12. A 21-in. NACA 0012 airfoil model was fabricated with an idealized leading edge ice accretion as shown. This initial ice accretion shape tested was meant to be generally like an ice accretion but to have well-defined cross-sectional characteristics and smooth continuous coordinates. This model was tested in the Ohio State University 4- by 5-ft low-speed wind tunnel. As the figure indicates, force and moment data were acquired as well as detailed surface pressure distributions, boundary layer profiles on both surfaces, concentrating in the vicinity of the separation reattachment zones, and flow visualization data. These data were used to compare with two state-of the-art analysis codes - the ARC two-dimensional Navier-Stokes analysis code of NASA Ames and the Interactive Boundary Layer (IBL) code of Cebeci (California State, Long Beach). The lift and drag coefficient variations with angle of attack as predicted by the codes are compared in figure 13 to the data previously shown. Generally, the agreement is judged to be good for both codes although the IBL code tends to underpredict drag at the higher angles of attack. The activity is continuing, and, in particular, measurements and comparisons are being made with more realistic ice shape geometries.

Icing instrument research is an important part of the NASA icing research program. Figure 14 shows droplet size measurements made in the Icing Research Tunnel (IRT) using various laser spectrometer probes compared with the volume median droplet sizes determined from the facility calibration developed by NACA. The wide spread of the data away from the line of perfect agreement suggests the need for improvements in the accuracy of droplet sizing instrumentation. The data taken in this test program suggested current instrumentation accuracies of no better than ±4 µm (on a volume median diameter (VMD) basis). The effect of a ±4 µm variation of VMD on ice accretion shape and resulting airfoil drag increase are shown in figure 15. The figure suggests that the effects can be significant and that the accuracy of droplet sizing instrumentation must be improved.

A more accurate measurement of icing cloud properties (i.e., liquid water content and droplet size distribution) is necessary for many icing R&D purposes. Currently it is felt that the most severe problems exist for those instruments that measure droplet sizes. As indicated, the accuracy of current optical systems appears to be no better than ±4 µm out of 20 (on a VMD basis).

The current research activities to improve current drop sizing instruments (fig. 16) include the following:

(1) Improved calibration devices

(2) Theoretical modeling of the optical characteristics of the instruments and complimentary fundamental research

(3) Comparisons of available instruments in a simple, well-documented spray

The NASA Icing Research Tunnel (IRT) is the largest refrigerated icing wind tunnel in the world (fig. 17). It has played a key role in developing technology to solve aircraft icing problems since it became operational in June of 1944. As an indication of its importance and contributions, the American Society of Mechanical Engineers (ASME) recently designated the IRT to be an international mechanical engineering landmark facility, one of only 21 such facilities in the world. A $3.6 million upgrade to the facility was recently completed to ensure that the IRT will continue to play a key role in the future in developing aircraft icing technology. Some of the key features of the new IRT are shown here. Of particular interest to the research community is the new spray bar system, which will allow a wider range of icing conditions to be provided to users. The final goal is to be able to provide complete coverage of the FAA/Icing envelopes.

Natural icing flight testing is also a key part of the aircraft icing research program. Currently, the aircraft being used for these tests is a deHavilland DHC6 Twin Otter. The prime emphasis of the flight tests has been to acquire an icing simulation data base, as indicated in figure 18. The primary parts of this data base are (1) the icing cloud properties (liquid water content (LWC) and droplet size spectra) measured by using the vast array of instruments on the aircraft, (2) main wing ice accretion shapes documented with a stereo photography system, and (3) wing section drag measured with a heated wake survey probe. This data being acquired over a wide range of natural icing conditions will be compared with IRT results from tests of a full-scale Twin Otter wing section and with icing analysis code predictions.

Studies of aircraft performance/stability and control changes due to icing are also being conducted with the Twin Otter. Representative performance and stability and control data are shown in figures 19 and 20. These data are also being compared with computer predictions.

Emphasis in the aircraft icing research program will eventually shift from the fixed wing to the rotary wing since some of the most difficult icing problems are faced by the rotorcraft community. Currently, the rotorcraft icing activities are focused on evaluating the model rotor icing test technique, that is, determining what use can be made of testing scale-model rotors in a large icing wind tunnel such as the IRT. To date, no such tests have been conducted in the U.S., and U.S. manufacturers must rely primarily on artificial/natural icing flight testing which is extremely costly and time consuming. In order to evaluate the model rotor test technique, NASA has teamed with the four major U.S. helicopter manufacturers and Texas A&M University to carry out all the activities required to test in the IRT a fully instrumented, powered-force model provided by Sikorsky and shown in figure 21. Prior to this test, several supporting test techniques must be developed, and for these preliminary activities, an OH58 tail rotor rig shown here will be used. The OH58 is a much sturdier rig and therefore should be more forgiving to any unexpected surprises which might be encountered during the initial IRT test.

Once this initial evaluation is completed, it is envisioned that follow-on tests will be conducted, especially for comparison with full-scale, natural icing flight test results. Initial full-scale rotor icing test results were acquired in the recent NASA/Army Helicopter Icing Flight Test Program. The various activities in this multiphase program are shown in figure 22. This test program was a multiphase effort to acquire unprotected helicopter rotor ice accretion and aerodynamic performance data for both hover and forward flight conditions. The techniques developed will be used in proposed future programs to acquire flight data for comparison with the scale-model rotor data which will be acquired in follow-on IRT Tests.

Now that some highlights of the NASA aircraft icing research program have been reviewed, it is appropriate to consider figure 1 and indicate the future directions of the program.

The generic activities will continue as indicated:

(1) The icing analysis codes will become more robust and sophisticated as to the problems which can be analyzed.

(2) New instrumentation concepts will be investigated which will offer improved accuracy levels over current instruments.

(3) Research will continue to look for alternate ice protection concepts which look attractive from weight, power requirement, and efficiency standpoints.

Future emphasis as related to fixed-wing aircraft will be to couple the codes together to form more comprehensive icing-effects-simulation computer models. Such models, once validated against icing flight data, could be used in pilot training simulators, for preliminary design studies, and possibly as part of certification/qualification programs.

(1) Investigations will be conducted of potential icing problems for unique military aircraft configurations of the future with emphasis on the ice protection design requirements for such aircraft.

(2) NASA is also developing jointly with the major U.S. airframe and engine manufacturers a proposed research program to investigate the ice protection requirements for the advanced propfan engine configurations which will be flying in the early 1990's. A major component of this proposed program would be natural icing flight tests of a propfan configuration, and it is felt that the so-called PTA aircraft would be the ideal research aircraft to conduct these studies.

The longer term emphasis of the NASA icing research program will shift to the helicopter, with the areas of emphasis shown in figure 1. In the shorter term, the majority of activities will be to evaluate the model rotor icing test technique.

A bibliography of icing reports generated by the NASA Aircraft Icing Research Program is included in the appendix.

APPENDIX - AIRCRAFT ICING RESEARCH PROGRAM BIBLIOGRAPHY

1980

Norment, H.G.: Calculation of Water Drop Trajectories To and About Arbitrary Three-Dimensional Bodies in Potential Airflow. NASA CR-3291, 1980.

1981

Bragg, M.B.; Gregorek, G.M.; and Shaw, R.J.: An Analytical Approach to Airfoil Icing. AIAA Paper 81-0403, Jan. 1981.

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.

Evanich, P.L.: NASA Lewis Research Center's Icing Research Program. Proceedings: Fifth Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, NASA CP-2192, D.W. Camp, W. Frost, and P.D. Parsley, eds., 1981, pp. 64-75.

Koegeboehn, L.P.: Commercial Aviation Icing Research Requirements. NASA CR-165336, 1981.

Kohlman, D.L., et al.: Icing Tunnel Tests of a Glycol-Exuding Porous Leading Edge Ice Protection System on a General Aviation Airfoil. (KU-FRL-464-1, Kansas University; NASA Grant NAG3 71) NASA CR-164377, 1981.

Kohlmann, D.L.; Schweikhard, W.G.; and Evanich, P.: Icing Tunnel Tests of a Glycol-Exuding Porous Leading Edge Ice Protection System on a General Aviation Airfoil. AIAA Paper 81-0405, Jan. 1981.

Olsen, W.: Survey of Aircraft Icing Simulation Test Facilities in North America. NASA TM-81707, 1981.

Peterson, A.A.; Dadone, L.; and Bevan, D.: Rotorcraft Aviation Icing Research Requirements: Research Review and Recommendations. (D210-11662-1, Boeing Vertol Co.; NASA Contract NAS3-22384) NASA CR-165344, 1981.

Reinmann, J.J., ed.: Selected Bibliography of NACA-NASA Aircraft Icing Publications. NASA TM-81651, 1981.

1982

Bragg, M.B.: Rime Ice Accretion and Its Effect on Airfoil Performance. NASA CR-165599, 1982.

Bragg, M.B.; and Gregorek, G.M.: Aerodynamic Characteristics of Airfoils With Ice Accretions. AIAA Paper 82-0282, Jan. 1982.

Bragg, M.B.; Gregorek, G.M.; and Shaw, R.J.: Wind Tunnel Investigation of Airfoil Performance Degradation Due to Icing. AIAA Paper 82-0582, Mar. 1982.

Bragg, M.B.; Zaguli, R.J.; and Gregorek, G.M.: Wind Tunnel Evaluation of Airfoil Performance Using Simulated Ice Shapes. NASA CR-167960, 1982.

DeWitt, K.J.; and Baliga, G.: Numerical Simulation of One-Dimensional Heat Transfer in Composite Bodies With Phase Change. NASA CR-165607, 1982.

Korkan, K.D.; Dadone, L.; and Shaw, R.J.: Performance Degradation of Propeller Systems Due to Rime Ice Accretion. AIAA Paper 82-0286, Jan. 1982. (J. Aircraft, vol. 21, no. 1, Jan. 1984, pp. 44-49).

MacArthur, C.D.; Keller, J.L.; and Luers, J.K.: Mathematical Modeling of Ice Accretion on Airfoils. AIAA Paper 82-0284, Jan. 1982.

Magenheim, B.; and Rocks, J.: A Microwave Ice Accretion Measurement Instrument (MIAMI). AIAA Paper 82-0285, Jan. 1982.

Magenheim, B.; and Rocks, J.K.: Development and Test of a Microwave Ice Accretion Measurement Instrument (MIAMI). NASA CR-3598, 1982.

Reinmann, J.J.; Shaw, R.J.; and Olsen, W.A., Jr.: Aircraft Icing Research at NASA. Proceedings of the First International Workshop on Atmospheric Icing of Structures, CRREL SR-83-17, L.D. Minsk, ed., Electric Power Research Institute, 1982, pp. 103-116. (Avail. NTIS, AD-A131869 and AD-E850387). (NASA TM-82919.)

Shaw, R.J.: The NASA Aircraft Icing Research Program. Sixth Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, NASA CP-2274, W. Frost, D.W. Camp, and L.W. Hershman, eds., 1982, pp. 50-56.

Shaw, R.J.; Sotos, R.G.; and Solano, F.R.: An Experimental Study of Airfoil Icing Characteristics. NASA TM-82790, 1982.

1983

Bragg, M.B.; and Gregorek, G.M.: An Analytical Evaluation of the Icing Properties of Several Low and Medium Speed Airfoils. AIAA Paper 83-0109, Jan. 1983.

Bragg, M.B.; and Gregorek, G.M.: Predicting Aircraft Performance Degradation Due to Ice Accretion. SAE Paper 830742, 1983.

Chang, K., et al.: Influence of Multidroplet Size Distribution on Icing Collection Efficiency. AIAA Paper 83-0110, Jan. 1983.

Chao, D.F.K.: Numerical Simulation of Two-Dimensional Heat Transfer in Composite Bodies With Application to De-Icing of Aircraft Components. NASA CR-168283, 1983.

DeWitt, K.J., et al.: Numerical Simulation of Electrothermal Deicing Systems. AIAA Paper 83-0114, Jan. 1983.

Flemming, R.J.; and Lednicer, D.A.: High Speed Ice Accretion on Rotorcraft Airfoils. Proceedings, 39th Annual Forum, American Helicopter Society, 1983, pp. 44-57.

Kohlman, D.L.; and Albright, A.E.: A Method of Predicting Flow Rates Required to Achieve Anti-Icing Performance With A Porous Leading Edge Ice Protection System. (KU-FRL-464-5 REV-A, Kansas University; NASA Grant NAG3-71) NASA CR-168213, 1983.

Korkan, K.D.; Dadone, L.; and Shaw, R.J.: Performance Degradation of Helicopter Rotor Systems in Forward Flight Due to Rime Ice Accretion. AIAA Paper 83-0029, Jan. 1983.

MacArthur, C.D.: Numerical Simulation of Airfoil Ice Accretion. AIAA Paper 83-0112, Jan. 1983.

Marano, J.J.: Numerical Simulation of an Electrothermal Deicer Pad. NASA CR-168097, 1983.

Miller, T.L.; Korkan, K.D.; and Shaw, R.J.: Statistical Study of an Airfoil Glaze Ice Drag Correlation. SAE Paper 830753, 1983.

Olsen, W.; Takeuchi, D.; and Adams, K.: Experimental Comparison of Icing Cloud Instruments. AIAA Paper 83-0026, Jan. 1983. (NASA TM-83340.)

Palko, R.L.; and Cassady, P.L.: Photogrammetric Analysis of Ice Buildup on a U.S. Army UH-1H Helicopter Main Rotor in Hover Flight. AEDC-TR-83-43, Oct. 1983. (Avail. NTIS, AD-B077844.)

Reinmann, J.J.; Shaw, R.J.; and Olsen, W.A., Jr.: NASA Lewis Research Center's Program on Icing Research. AIAA Paper 83-0204, Jan. 1983. (NASA TM-83031.)

Takeuchi, D.M., et al.: Comparison of Modern Icing Cloud Instruments. (MRI-82-FR-1862, Meteorology Research Inc.; NASA Contract NAS3-22760) NASA CR-168008, 1983.

1984

Albright, A.E.: Experimental and Analytical Investigation of a Freezing Point Depressant Fluid Ice Protection System. NASA CR-174758, 1984.

Albright, A.E.; and Kohlman, A.E.: An Improved Method of Predicting Anti-Icing Flow Rates for a Fluid Ice Protection System. AIAA Paper 84-0023, Jan. 1984.

Arimilli, R.V.; Keshock, E.G.; and Smith, M.E.: Measurements of Local Convective Heat Transfer Coefficients on Ice Accretion Shapes. AIAA Paper 84-0018, Jan. 1984.

Bernhart, W.D.; and Zumwalt, G.W.: Electro-Impulse Deicing: Structural Dynamic Studies, Icing Tunnel Tests and Applications. AIAA Paper 84-0022, Jan. 1984.

Bragg, M.B.: Predicting Airfoil Performance With Rime and Glaze Ice Accretions. AIAA Paper 84-0106, Jan. 1984.

Bragg, M.B.; Gregorek, G.M.; and Lee, J.D.: Experimental and Analytical Investigations Into Airfoil Icing. 14th Congress of the International Council of the Aeronautical Sciences, Vol. 2, B. Laschka and R. Staufenbiel, eds., AIAA, 1984, pp. 1127-1138.

Flemming, R.J.; and Lednicer, D.A.: Experimental Investigation of Ice Accretion on Rotorcraft Airfoils at High Speeds. AIAA Paper 84-0183, Jan. 1984.

Gregorek, G.M.; Bragg, M.B.; and Shilling, J.B.: Performance Analyses for Aircraft in Icing Conditions. AIAA Paper 84-0180, Jan. 1984.

Ide, R.F.; and Richter, G.P.: Comparison of Icing Cloud Instruments for 1982-83 Icing Season Flight Program. AIAA Paper 84-0020, Jan. 1984. (NASA TM-83569.)

Keith, T.G., Jr., et al.: Predicted Electrothermal Deicing of Aircraft Blades. AIAA Paper 84-0110, Jan. 1984.

Korkan, K.D.; Cross, E.J., Jr.; and Cornell, C.C.: Experimental Study of Performance Degradation of a Model Helicopter Main Rotor With Simulated Ice Shapes. AIAA Paper 84-0184, Jan. 1984.

Korkan, K.D.; Cross, E.J., Jr.; and Miller, T.L.: Performance Degradation of a Model Helicopter Main Rotor in Hover and Forward Flight With a Generic Ice Shape. AIAA Paper 84-0609, Mar. 1984.

Korkan, K.D.; Dadone, L.; and Shaw, R.J.: Helicopter Rotor Performance Degradation in Natural Icing Encounter. J. Aircraft, vol. 21, no. 1, Jan. 1984, pp. 84-85.

Lee, J.D.: Aerodynamic Evaluation of a Helicopter Rotor Blade With Ice Accretion in Hover. AIAA Paper 84-0608, Mar. 1984.

Lee, J.D.; Harding, R.; and Palko, R.L.: Documentation of Ice Shapes on the Main Rotor of a UH-1H Helicopter in Hover. NASA CR-168332, 1984.

Olsen, W.A., Jr.; Shaw, R.J.; and Newton, J.: Ice Shapes and the Resulting Drag Increase for a NACA 0012 Airfoil. AIAA Paper 84-0109, Jan. 1984.

Olsen, W.A., Jr.; Walker, E.D.; and Sotos, R.G.: Microscopic High Speed Movies Showing the Droplet Freezing Process of Icing. AIAA Paper 84-0019, Jan. 1984.

Palko, R.L., et al.: Initial Feasibility Ground Test of a Proposed Photogrammetric System for Measuring the Shapes of Ice Accretions on Helicopter Rotor Blades During Forward Flight. NASA TM-87391, 1984.

Potapczuk, M.G., et al.: Evaluation of Iced Airfoil Performance Using a Navier-Stokes Equation Solver With a Body-Fitted Curvilinear Coordinate System. AIAA Paper 84-0107, Jan. 1984.

Ranaudo, R.J., et al.: Performance Degradation of a Typical Twin Engine Commuter Type Aircraft in Measured Natural Icing Conditions. AIAA Paper 84-0179, Jan. 1984.

Schrag, R.L.; and Zumwalt, G.W.: Electro-Impulse Deicing: Concept and Electrodynamic Studies. AIAA Paper 84-0021, Jan. 1984.

Shaw, R.J.: Experimental Determination of Airfoil Performance Degradation Due to Icing. AIAA Paper 84-0607, Mar. 1984.

Shaw, R.J.: Progress Toward the Development of an Aircraft Icing Analysis Capability. AIAA Paper 84-0105, Jan. 1984. (NASA TM-83562.)

VanFossen, G.J., et al.: Heat Transfer Distributions Around Nominal Ice Accretion Shapes Formed on a Cylinder in the NASA Lewis Research Tunnel. AIAA Paper 84-0017, Jan. 1984.

Zaguli, R.J.: Potential Flow Analysis of Glaze Ice Accretions on an Airfoil. NASA CR-168282, 1984.

Zaguli, R.J.; Bragg, M.B.; and Gregorek, G.M.: Results of an Experimental Program Investigating the Effects of Simulated Ice on the Performance of the NACA-63A415 Airfoil With Flap. (AARL-TR-83-2, Ohio State Univ.; NASA Grant NAG3-28) NASA CR-168288, 1984.

Zumwalt, G.W.; and Mueller, A.A.: Flight and Wind Tunnel Tests of an Electro-Impulse De-Icing System. AIAA Paper 84-2234, July 1984.

1985

Albright, A.E.: A Summary of NASA's Research on the Fluid Ice Protection System. AIAA Paper 85-0467, Jan. 1985.

Bragg, M.B.; and Coirier, W.J.: Detailed Measurements of the Flowfield in the Vicinity of an Airfoil with Glaze Ice. AIAA Paper 85-0409, Jan. 1985.

Flemming, R.J.; and Lednicer, D.A.: Correlation of Airfoil Icing Relationships with Two-Dimensional Model and Full Scale Rotorcraft Icing Test Data. AIAA Paper 85-0337, Jan. 1985.

Flemming, R.J.; Shaw, R.J.; and Lee, J.D.: The Performance Characteristics of Simulated Ice on Rotorcraft Airfoils. Proceedings, 41st Annual Forum, American Helicopter Society, 1985, pp. 743-757.

Gregorek, G.M., et al.: NASA Twin Otter Flight Test Program - Comparison of Flight Results with Analytic Theory. SAE Paper 850924, Apr. 1985.

Hansman, R.J., Jr.; and Kirby, M.S.: Measurement of Ice Accretion Using Ultrasonic Pulse-Echo Techniques. AIAA Paper 85-0471, Jan. 1985.

Haworth, L.A.; and Graham, M.S.: Flight Tests of the Helicopter Pneumatic Deicing System. Proceedings, American Helicopter Society, 41st Annual Forum, 1985, pp. 725-733.

Hovenac, E.A.; Hirleman, E.D.; and Ide, R.: Calibration and Sample Volume Characterization of PMS Optical Array Probes. Presented at the International Conference on Liquid Atomization and Spray Systems (ICLASS), London, England, July 1985.

Kim, J.J.: Computational Particle Trajectory Analysis on a Three-Dimensional Engine Inlet. AIAA Paper 85-0411, Jan. 1985.

Korkan, K.D.; Dadone, L.; and Shaw, R.J.: Performance Degradation of Helicopters Due to Icing - A Review. Proceedings, 41st Annual Forum, American Helicopter Society, 1985.

Lee, J.D.; and Shaw, R.J.: The Aerodynamics of Rotor Blades with Ice Shapes Accreted in Hover and in Level Flight. Proceedings, 41st Annual Forum, American Helicopter Society, 1985, pp. 735-742.

Masiulaniec, K.K., et al.: Full Two-Dimensional Transient Solutions of Electrothermal Aircraft Blade Deicing. AIAA Paper 85-0413, Jan. 1985.

Mikkelsen, K.L., et al.: Icing Flight Research: Aerodynamic Effects of Ice, and Ice Shape Documentation with Stereo Photography. AIAA Paper 85-0468, Jan. 1985.

Miller, T.L.; Korkan, K.D.; and Shaw, R.J.: Analytical Determination of Propeller Performance Degradation Due to Ice Accretion. AIAA Paper 85-0339, Jan. 1985.

Norment, H.G.: Calculation of Water Drop Trajectories To and About Arbitrary Three-Dimensional Lifting and Nonlifting Bodies in Potential Airflow. NASA CR-3935, 1985.

Norment, H.G.: Three-Dimensional Airflow and Hydrometeor Trajectory Calculation with Applications. AIAA Paper 85-0412, Jan. 1985.

Potapczuk, M.G.; and Gerhart, P.M.: Progress in Development of a Navier-Stokes Solver for Evaluation of Iced Airfoil Performance. AIAA Paper 85-0410, Jan. 1985.

Shaw, R.J.; and Richter, G.P.: The UH-1H Helicopter Icing Flight Test Program: An Overview. AIAA Paper 85-0338, Jan. 1985.

Zumwalt, G.W.: Icing Tunnel Tests of Electro-Impulse De-Icing of an Engine Inlet and High Speed Wings. AIAA Paper 85-0466, Jan. 1985.

1986

Bernhart, W.D.; Gien, P.H.; and Wilson, B.K.: A Structural Dynamics Investigation Related to EIDI Application. AIAA Paper 86-0550, Jan. 1986.

Bragg, M.B.; and Coirier, W.J.: Aerodynamic Measurements of an Airfoil With Simulated Glaze Ice. AIAA Paper 86-0484, Jan. 1986.

Hansman, R.J., Jr.; and Kirby, M.S.: Real-Time Measurement of Ice Growth During Simulated and Natural Icing Conditions Using Ultrasonic Pulse-Echo Techniques. AIAA Paper 86-0410, Jan. 1986.

Hovenac, E.A.: Calibration of Droplet Sizing and Liquid Water Content Instruments: Survey and Analysis. (FAA-CT-86-19, Sverdrup Technology Inc., NASA Contract NAS3 24105) NASA CR 175099, 1986.

Hovenac, E.A.: Use of Rotating Reticles for Calibration of Single Particle Counters. LIA, vol. 58, 1987, pp. 129-134.

Ingebo, R.D.: Formation and Characterization of Simulated Small-Droplet Icing Clouds. AIAA Paper 86-0409, Jan. 1986. (NASA TM-87180.)

Jordan, J.L.; Platz, S.J.; and Schinstock, W.C.: Flight Test Report of the NASA Icing Research Airplane: Performance, Stability, and Control After Flight Through Natural Icing Conditions. (KSR-86-01, Kohlman Systems Research; NASA Contract NAS3-24547) NASA CR-179515, 1986.

Kim, J.J.: Particle Trajectory Computation on a 3-Dimensional Engine Inlet. (DOT-FAA-CT-86-1, Wichita State Univ.; NASA Grant NAG3-566) NASA CR-175023, 1986.

Kim, J.J.; and Elangovan, R.: An Efficient Numerical Computation Scheme for Stiff Equations of Droplet Trajectories. AIAA Paper 86-0407, Jan. 1986.

McKnight, R.C.; Palko, R.L.; and Humes, R.L.: In-Flight Photogrammetric Measurement of Wing Ice Accretions. AIAA Paper 86-0483, Jan. 1986. (NASA TM-87191.)

Mikkelsen, K., et al.: In-Flight Measurements of Wing Ice Shapes and Wing Section Drag Increases Caused by Natural Icing Conditions. NASA TM-87301, 1986.

Nelepovitz, D.O.; and Rosenthal, H.A.: Electro-Impulse De-Icing of Aircraft Engine Inlets. AIAA Paper 86-0546, Jan. 1986.

Olsen, W.: Experimental Evaluation of Icing Scaling Laws: A Progress Report. AIAA Paper 86-0482, Jan. 1986.

Olsen, W.; and Walker, E.: Experimental Evidence for Modifying the Current Physical Model for Ice Accretion on Aircraft Surfaces. NASA TM-87184, 1986.

Papadakis, M., et al.: An Experimental Method for Measuring Droplet Impingement Efficiency on Two- and Three-Dimensional Bodies. AIAA Paper 86-0406, Jan. 1986.

Ranaudo, R.J., et al.: The Measurement of Aircraft Performance and Stability and Control After Flight Through Natural Icing Conditions. AIAA Paper 86-9758, Apr. 1986. (NASA TM 87265.)

Ross, R.: Application of Electro-Impulse De-Icing to the NASA Lewis Altitude Wind Tunnel (AWT) Turning Vanes. AIAA Paper 86-0548, Jan. 1986.

Ruff, G.A.: Verification and Application of the Icing Scaling Equations. AIAA Paper 86-0481, Jan. 1986.

Shaw, R.J.: NASA's Aircraft Icing Analysis Program. NASA TM-88791, 1986.

Shaw, R.J., et al.: The Use of a Three Dimensional Water Droplet Trajectory Analysis to Aid in Interpreting Icing Cloud Data, AIAA Paper 86-0405, Jan. 1986.

Zumwalt, G.W.; and Friedberg, R.A.: Designing an Electro-Impulse De-Icing System. AIAA Paper 86-0545, Jan. 1986.

1987

Alexander, D.R.: Comparison of UNL Laser Imaging and Sizing System and a Phase/Doppler System for Analyzing Sprays from a NASA Nozzle. NASA CR-182437, 1987.

Bragg, M.B.: An Experimental Study of the Aerodynamics of a NACA 0012 Airfoil with a Simulated Glaze Ice Accretion. NASA CR-179897, 1987.

Cebeci, T.: Effects of Environmentally Imposed Roughness on Airfoil Performance. NASA CR-179639, 1987.

Henderson, R.A.; and Schrag, R.L.: Theoretical Analysis of the Electrical Aspects of the Basic Electro-Impulse Problem in Aircraft De-Icing Applications. NASA CR-180845, 1987.

Hovenac, E.A.: Fresnel Diffraction by Spherical Obstacles. Am. J. Phys., vol. 57, no. 1, Jan. 1989, pp. 79-84.

Hovenac, E.A.: Performance and Operating Envelope of Imaging and Scattering Particle Sizing Instruments. NASA CR-180859, 1987.

Miller, T.L.; Shaw, R.J.; and Korkan, K.D.: Evaluation of Icing Drag Coefficient Correlations Applied to Iced Propeller Performance Prediction. SAE Paper 871033, Apr. 1987.

Miller, T.L.; Korkan, K.D.; and Shaw, R.J.: Analytical Determination of Propeller Performance Degradation Due to Ice Accretion. J. Aircraft, vol. 24, no. 11, Nov. 1987, pp. 768-775.

Newton, J.E.: Icing of Flow Conditioners in a Closed-Loop Wind Tunnel. NASA TM-89824, 1987.

Oldenburg, J.R.: Analysis of Counting Errors in the Phase/Doppler Particle Analyzer. NASA TM-100231, 1987.

Olsen, W.; Van Fossen, J.; and Nussle, R.: Measured Performance of the Heat Exchanger in the NASA Icing Research Tunnel Under Severe Icing and Dry Air Conditions. NASA TM-100116, 1987.

Potapczuk, M.G.: Numerical Analysis of a NACA 0012 Airfoil with Leading-Edge Ice Accretions. AIAA Paper 87-0101, Jan. 1987. (J. Aircraft, vol. 25, no. 3, Mar. 1988, pp. 193-194).

Reehorst, A.L.; and Richter, G.P.: New Methods and Materials for Molding and Casting Ice Formations. NASA TM-100126, 1987.

Scavuzzo, R.J.; and Chu, M.L.: Structural Properties of Impact Ices Accreted on Aircraft Structures. NASA CR-179580, 1987.

Shaw, R.J.; and Reinmann, J.J.: NASA's Rotorcraft Icing Research Program. NASA/Army Rotorcraft Technology, Vol. 2, NASA CP-2495-VOL-2, 1987, pp. 802-832.

1988

Khatkhate, A.A.; Scavuzzo, R.J.; and Chu, M.L.: A Finite Element Study of the EIDI System. AIAA Paper 88-0022, Jan. 1988.

VanFossen, J.G., et al.: Measurement of Local Convective Heat Transfer Coefficients from a Smooth and Roughened NACA-0012 Airfoil: Flight Test Data. AIAA Paper 88-0287, Jan. 1988. (NASA TM-100284).

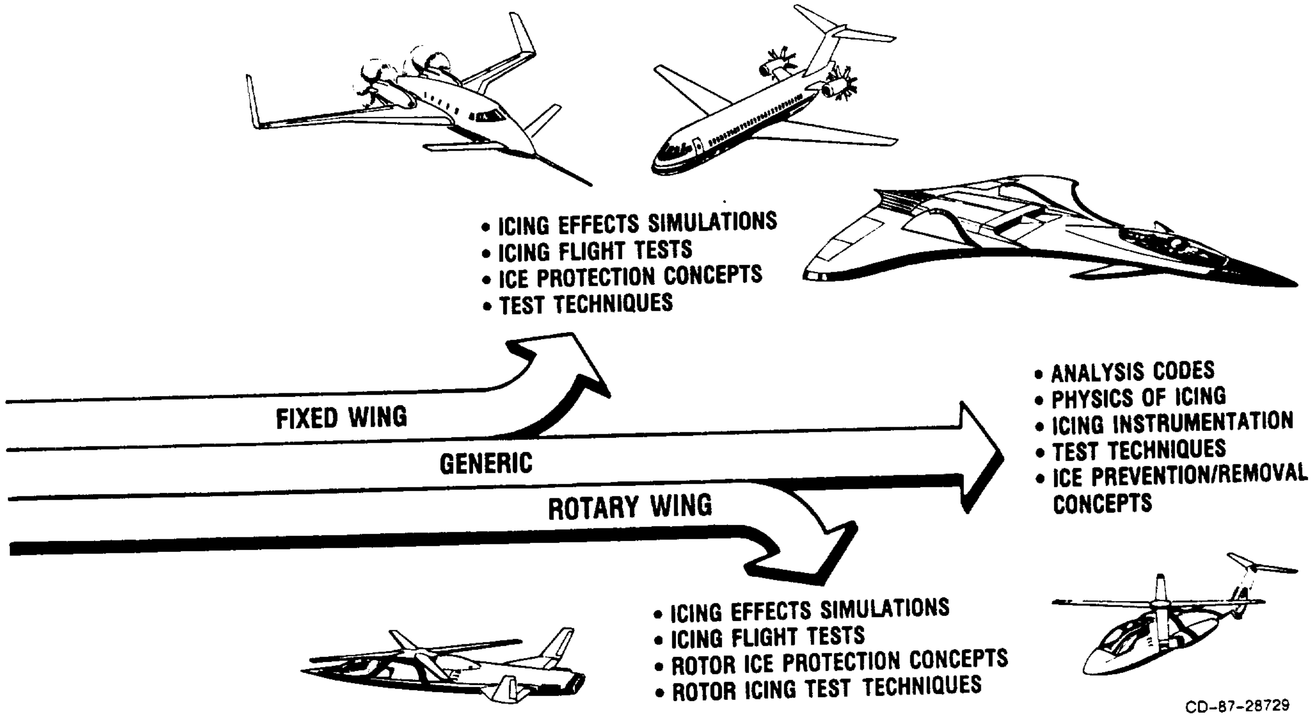

Figure 1. - Aircraft icing technology program.

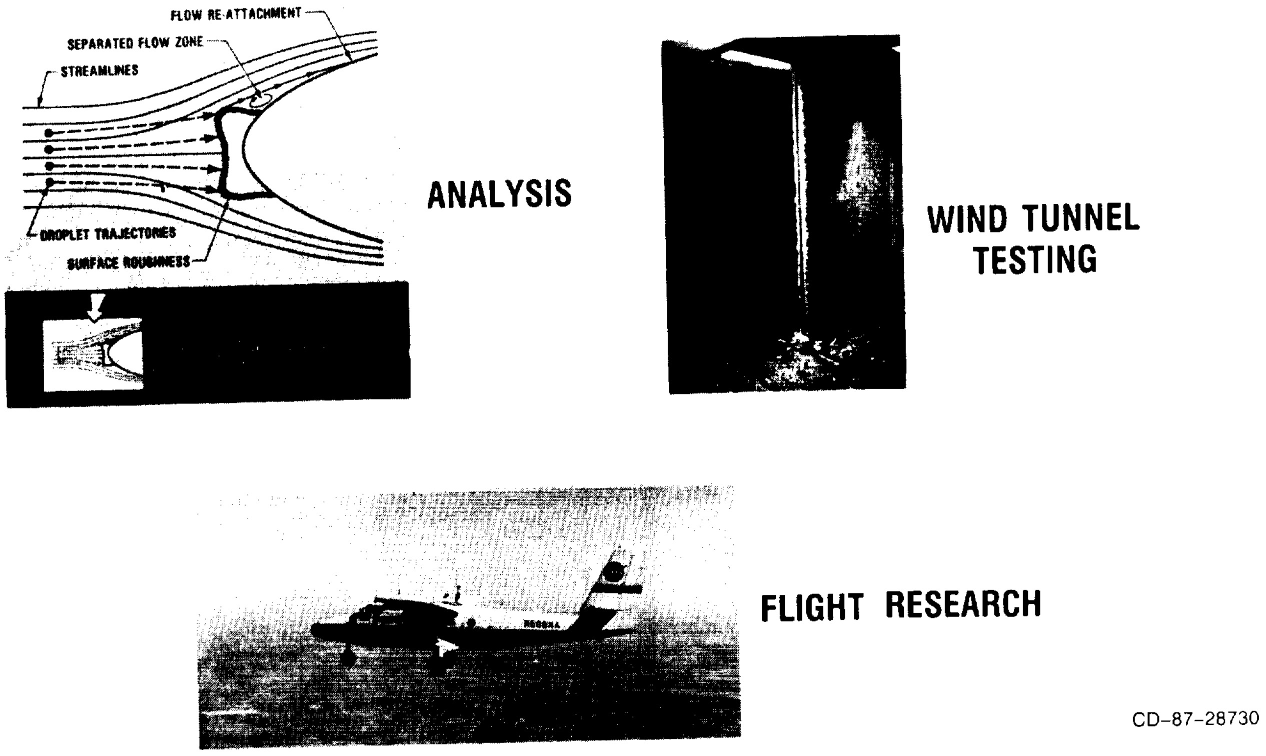

Figure 2. - Icing research.

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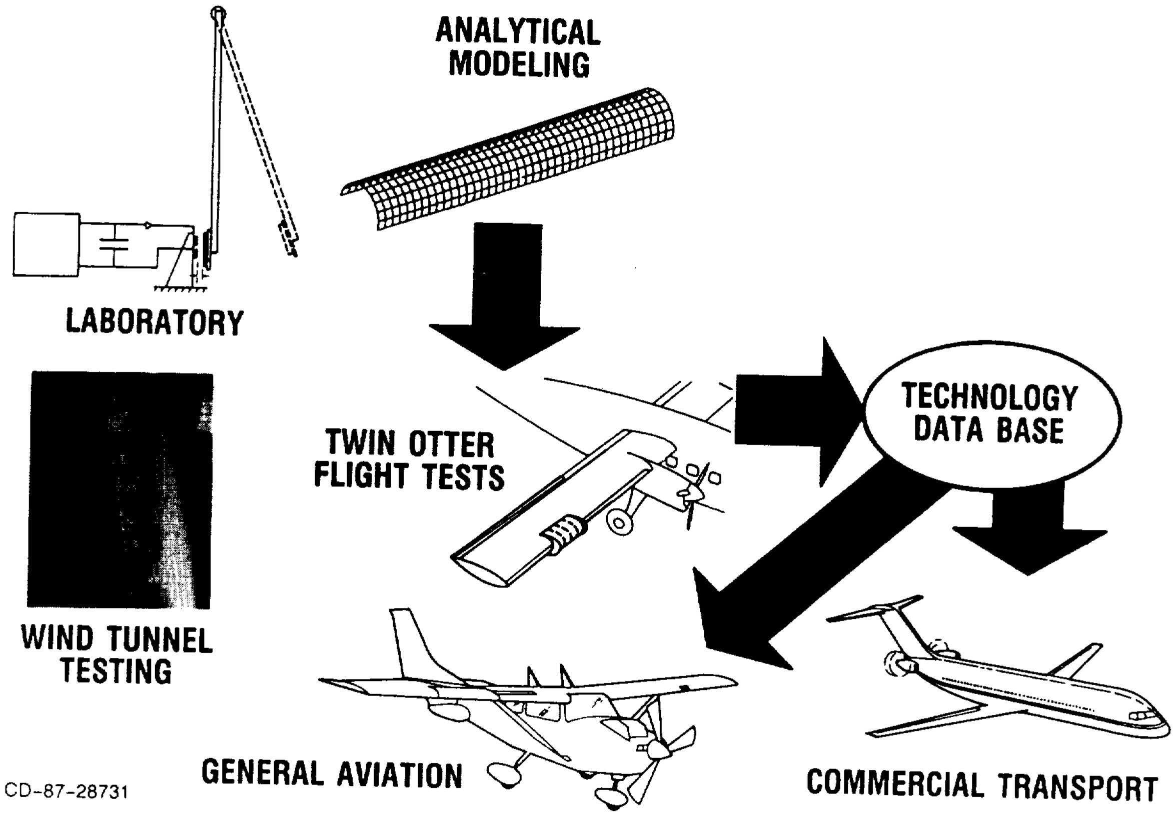

Figure 3. - NASA electromagnetic impulse deicer program.

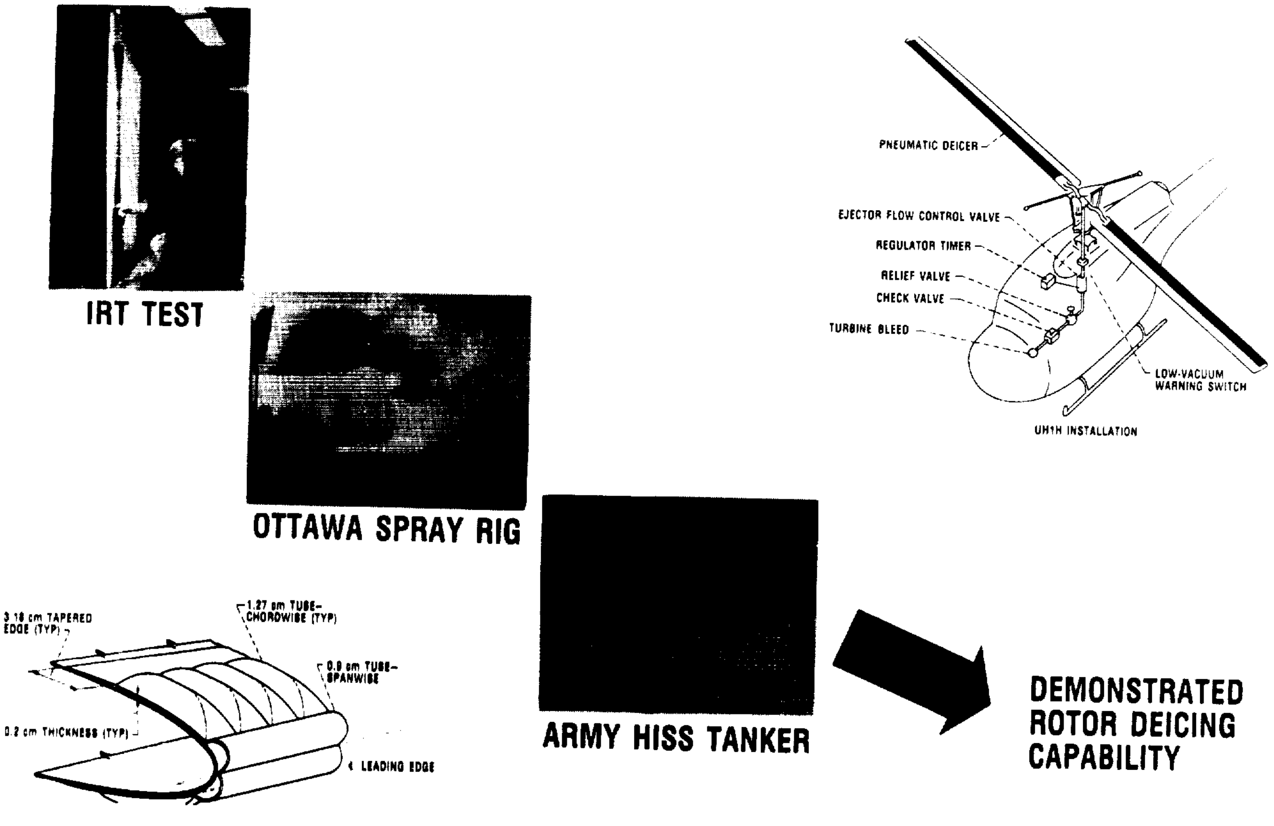

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Figure 4. - NASA/Army/industry rotor pneumatic boot program.

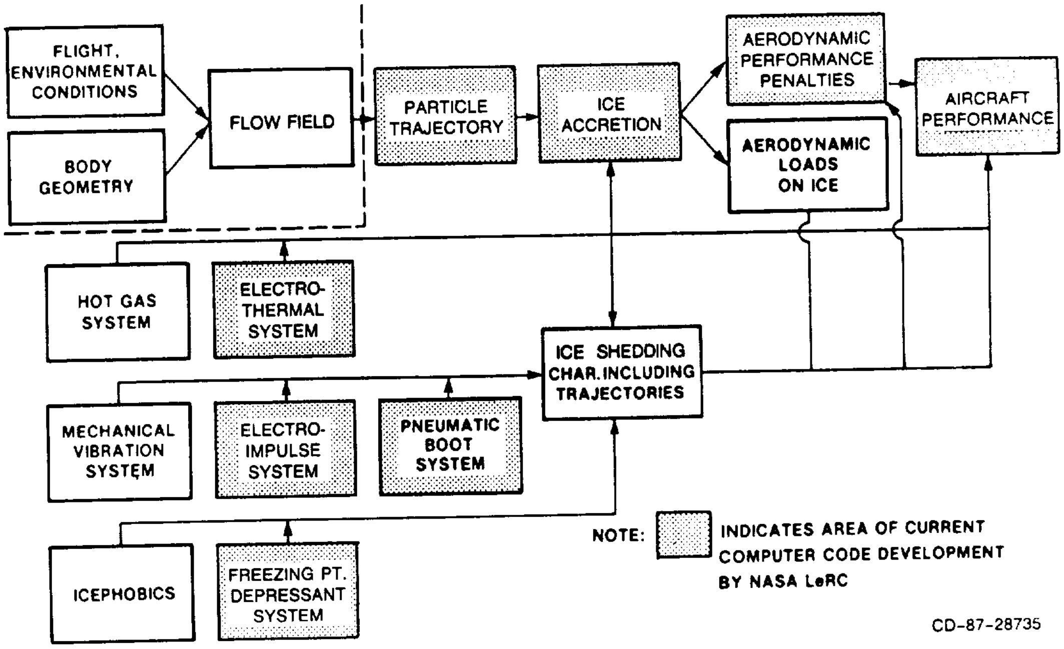

Figure 5. - Aircraft icing analysis methodology.

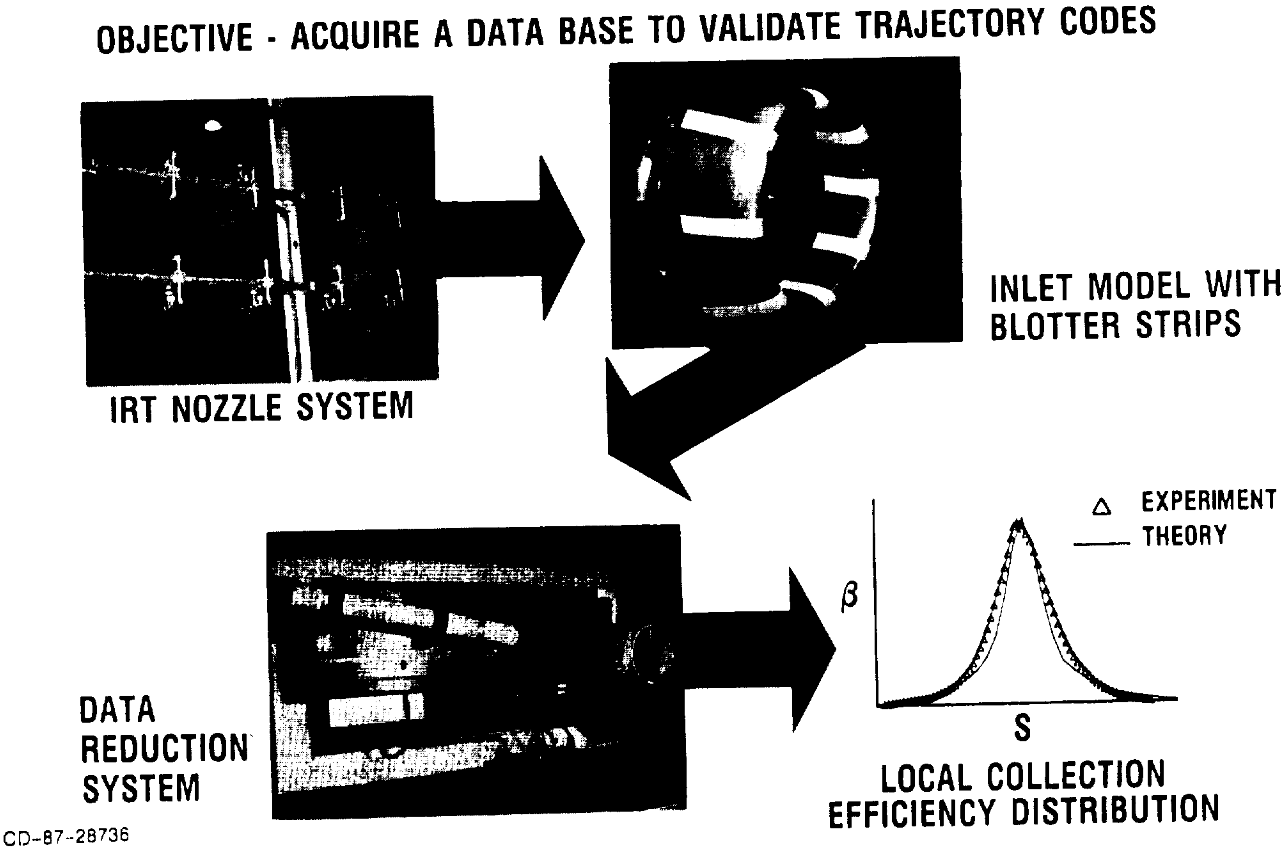

Figure 6. - NASA/FAA water droplet impingement research program.

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Figure 7. - Twin Otter trajectory analysis.

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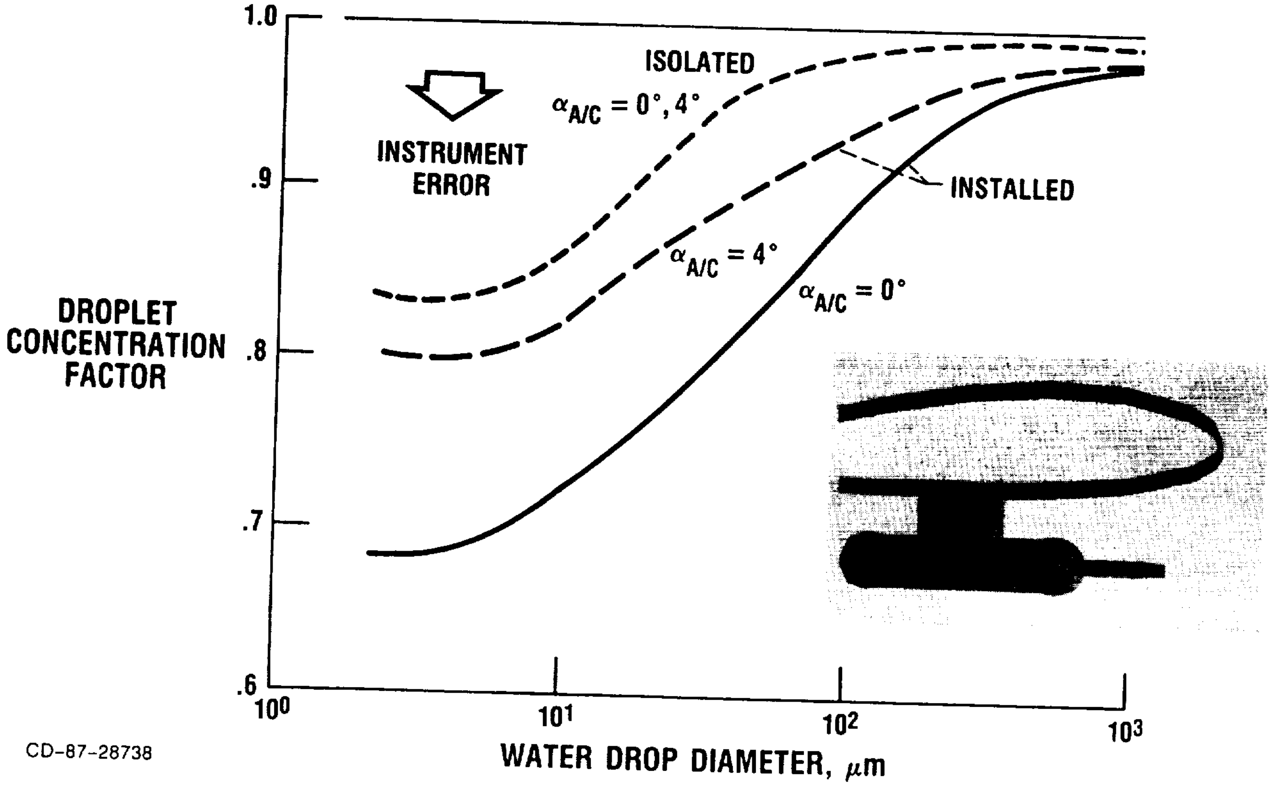

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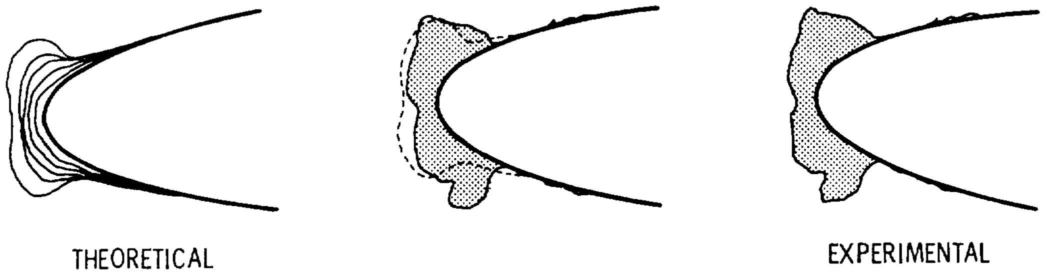
Figure 8. - Trajectory analysis for laser spectrometer.



VELOCITY, m/sec	89.40
TEMPERATURE, ^{o}C	-10.65
PRESSURE, kPa	94.20
HUMIDITY, percent	100
LWC, g/m^3	1.20
DROP DIAMETER, μm	20
TIME, sec	240

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Figure 9. - NASA airfoil ice accretion code (LEWICE) comparison of glaze ice shapes (NACA 0012 airfoil, 21-in. chord).

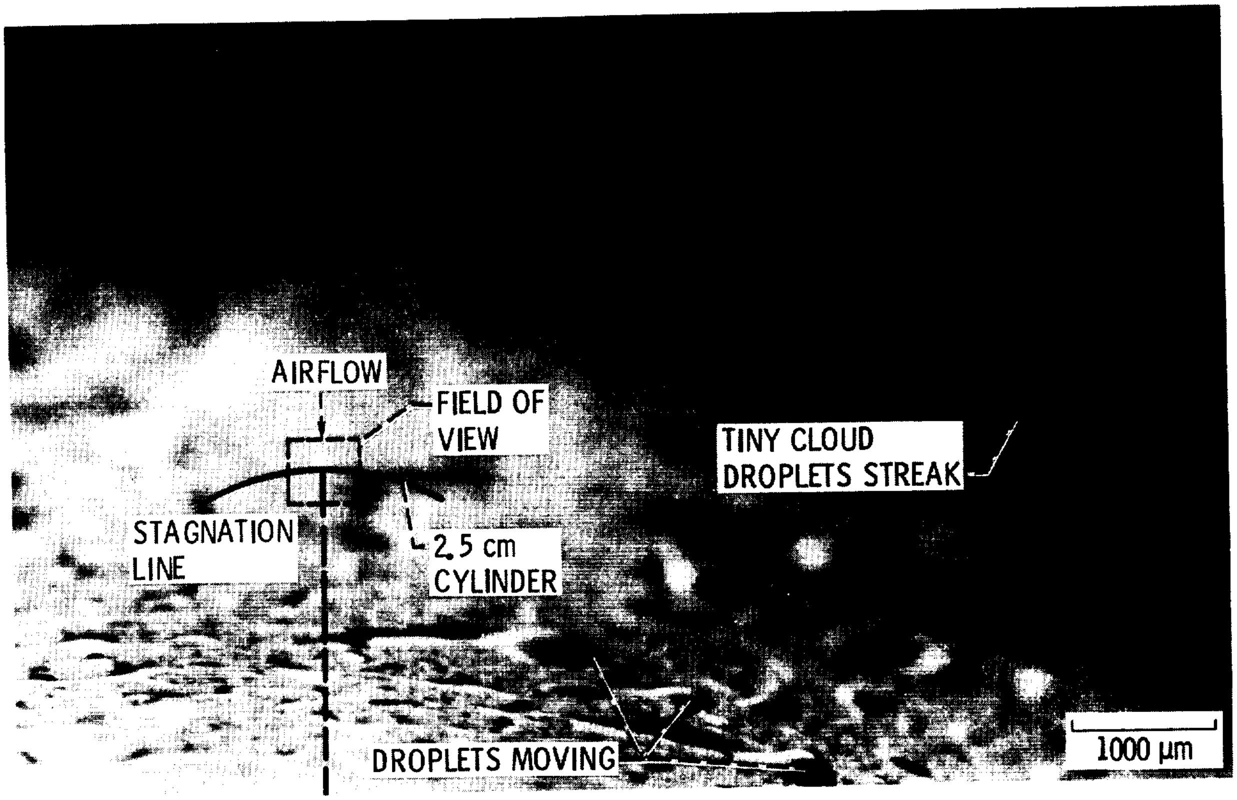

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Figure 10. - Closeup flash picture of droplet impingement.

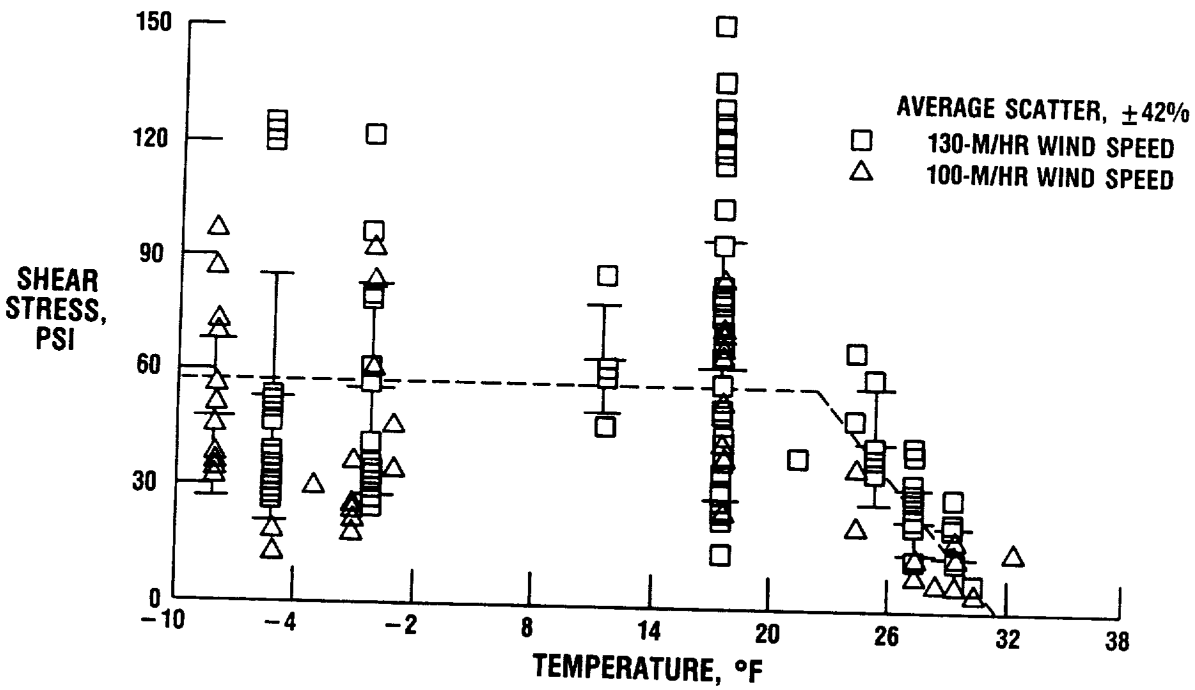

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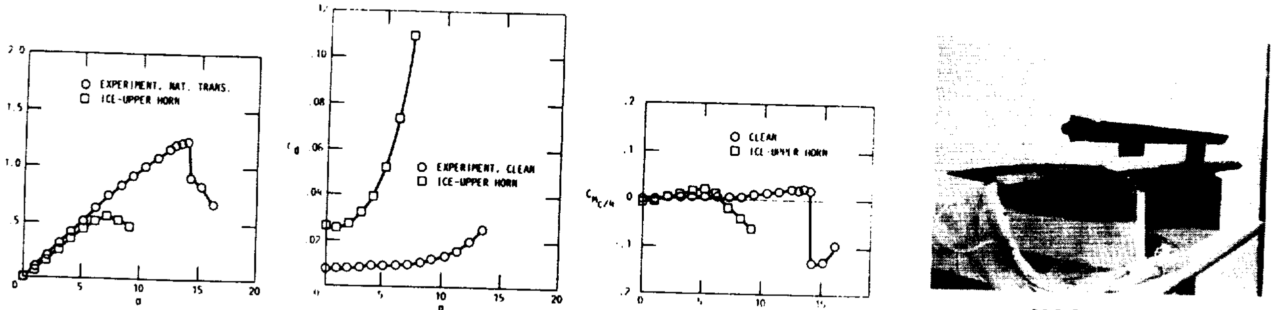
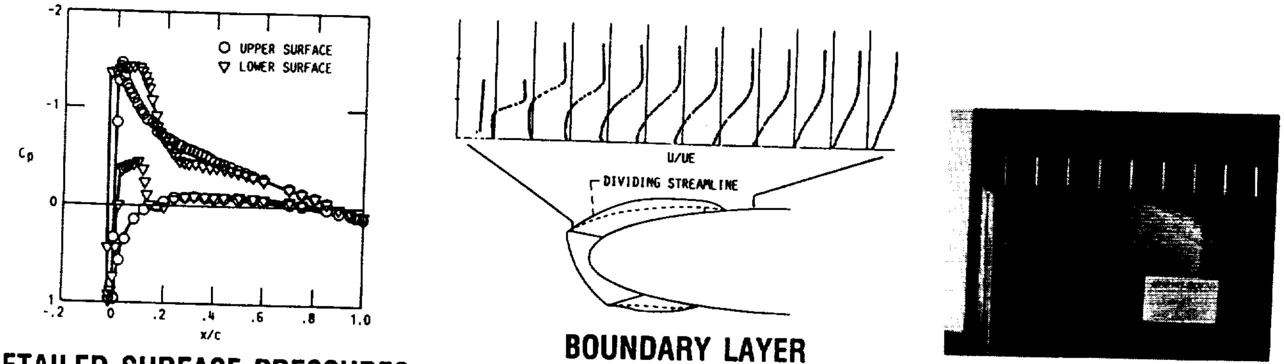
Figure 11. - Adhesive shear stress versus interface temperature.



FORCE AND MOMENT DATA

NACA 0012 MODEL



DETAILED SURFACE PRESSURES

BOUNDARY LAYER PROFILES

FLOW VISUALIZATION

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Figure 12. - Code validation studies - iced airfoil analysis.

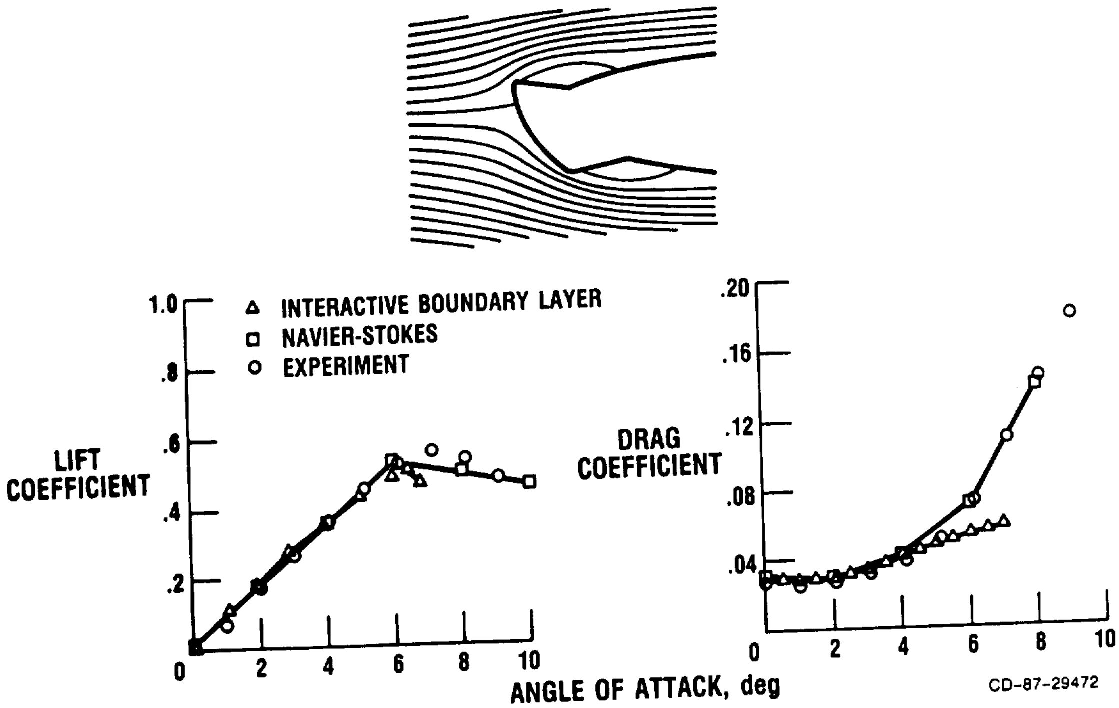

Figure 13. - Iced airfoil analysis.

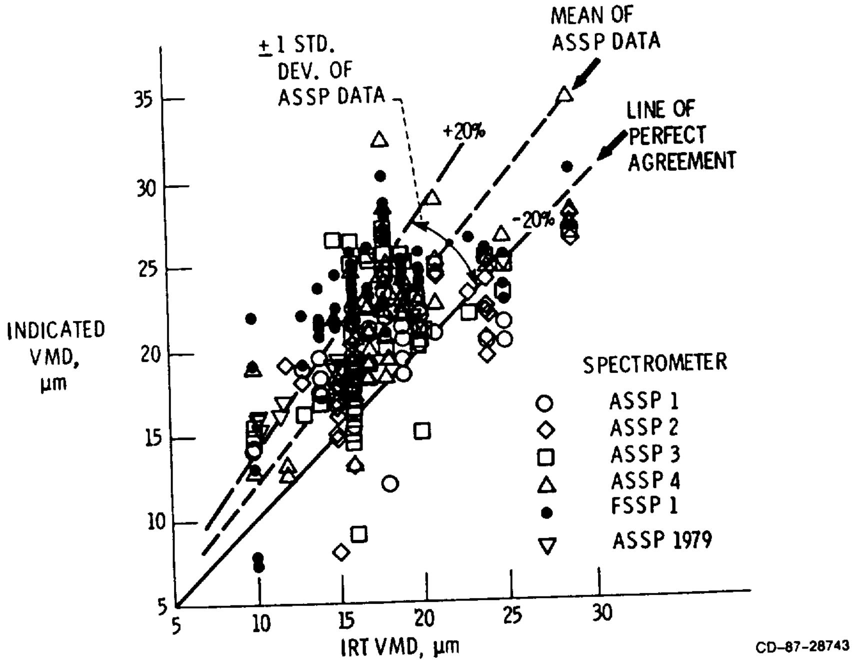

Figure 14. - Comparison of laser spectrometer drop size indications to old IRT calibration (range of conditions: VMD, 10 to 30 mm; LWC, 0.3 to 3 g/m3; velocity, 80 to 460 km/hr; ASSP and ISSP denote axial scattering and forward scattering spectrometer probes, respectively).

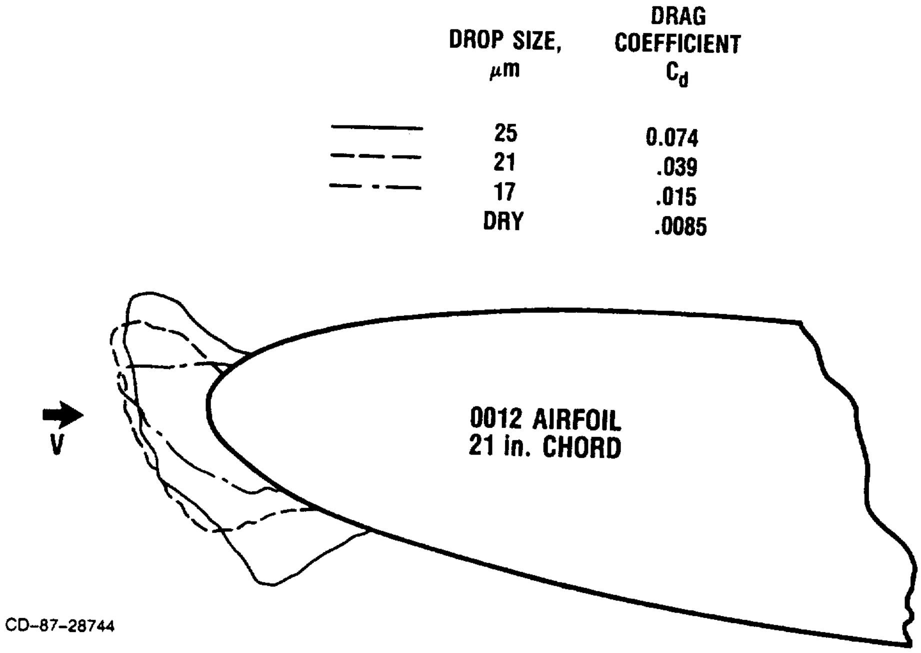

Figure 15. - Effects of drop size measurement errors.

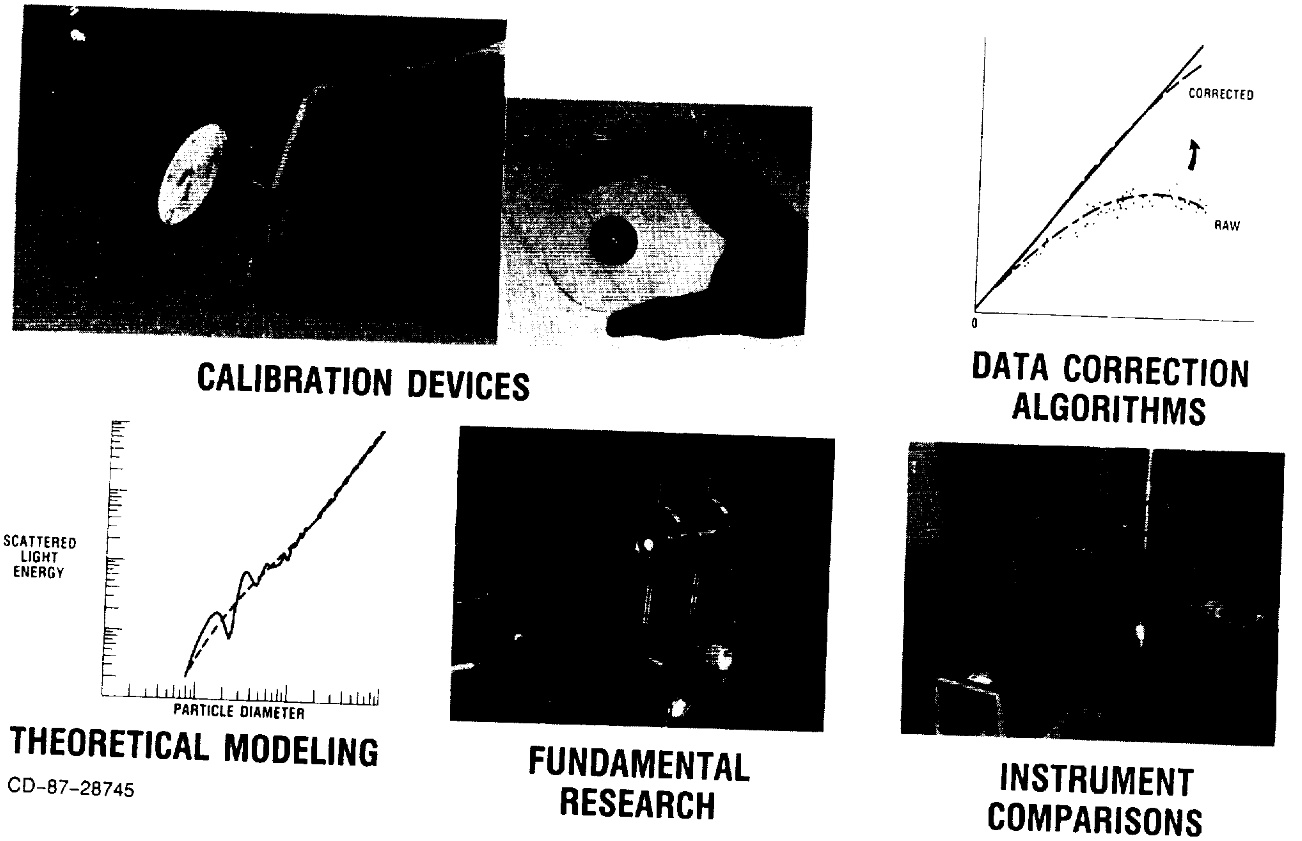

Figure 16. - Particle sizing instrumentation research.

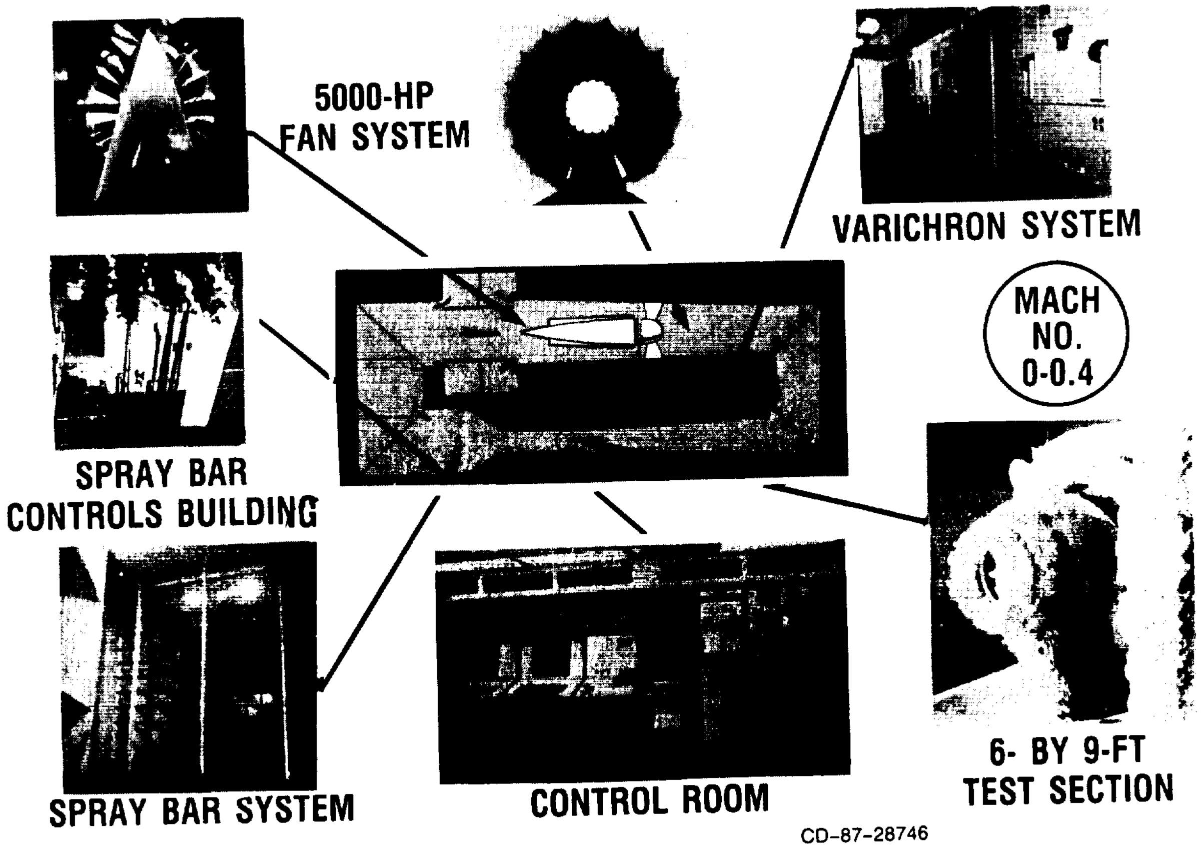

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Figure 17. - Icing Research Tunnel.

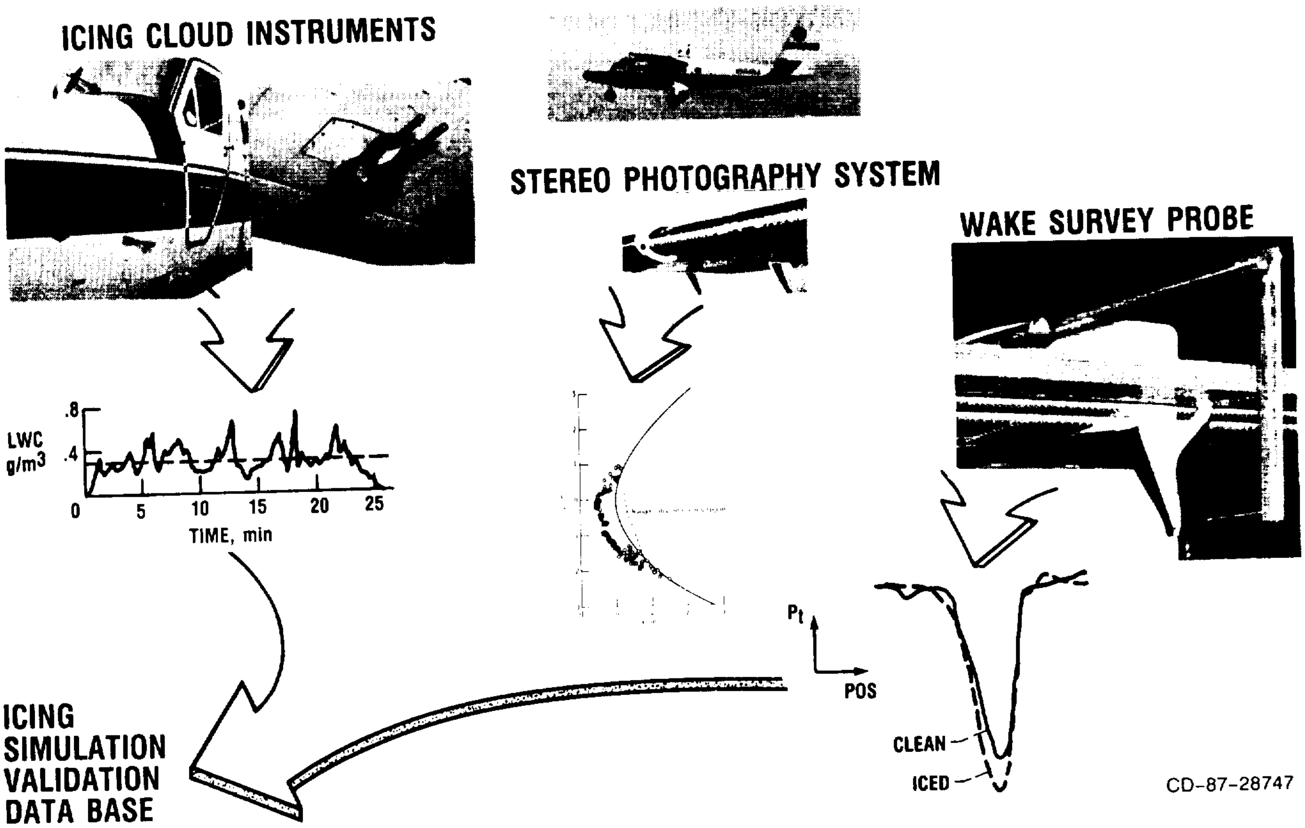

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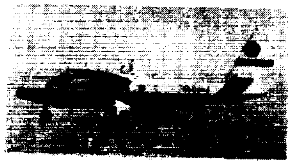
Figure 18. - Twin Otter wing icing/aeroperformance.

EXPERIMENTAL DATA BASE IS BEING ACQUIRED, RELATING AIRCRAFT PERFORMANCE DEGRADATION TO A MATRIX OF MEASURED NATURAL ICING CONDITIONS



NASA DHC-6 TWIN OTTER ICING RESEARCH AIRCRAFT

GLAZE ICING ENCOUNTER

VMD - 13 μm ICING TIME - 26 min
LWC - 0.31 g/m^3 STATIC TEMP. - -4 °C

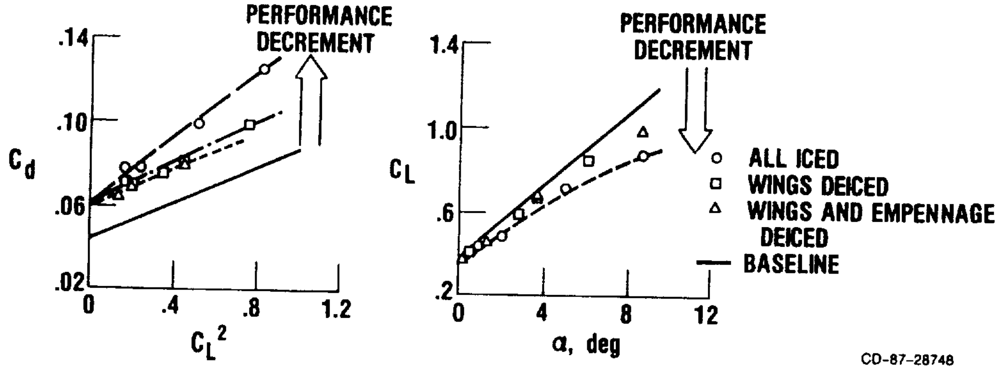


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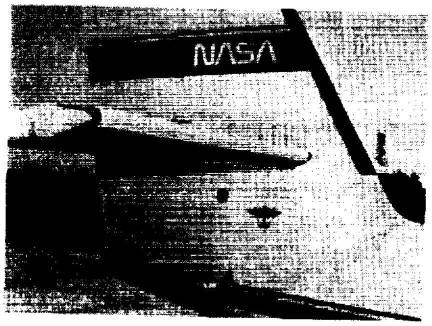
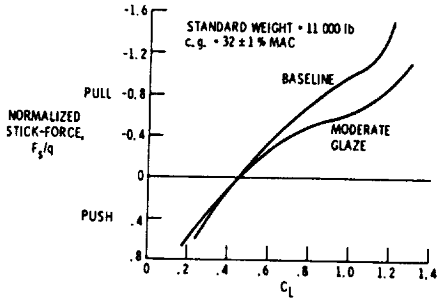
Figure 19. - Aircraft performance in natural icing.

OBJECTIVE: EMPLOY STATIC LONGITUDINAL FLIGHT TEST METHODS TO A DHC-6 AIRCRAFT WITH AN ARTIFICIAL ICE SHAPE ATTACHED TO THE HORIZONTAL TAIL PLANE TO MEASURE THE CHANGE IN STATIC MARGIN

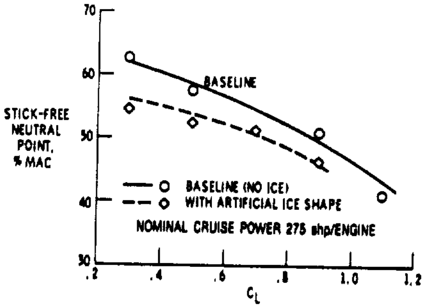
RESULTS: A REDUCTION IN STATIC MARGIN WAS MEASURED THROUGHOUT THE NORMAL FLAPS-UP CRUISE ENVELOPE



ARTIFICIAL MODERATE GLAZE ICE SHAPE ATTACHED TO HORIZONTAL TAIL



VARIATION IN NORMALIZED CONTROL FORCE FOR THE "ICED" VERSUS BASELINE TAIL



REDUCTION IN STICK-FREE STATIC MARGIN DUE TO TAIL ICE

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Figure 20. - Reduction of aircraft static longitudinal stability due to icing.

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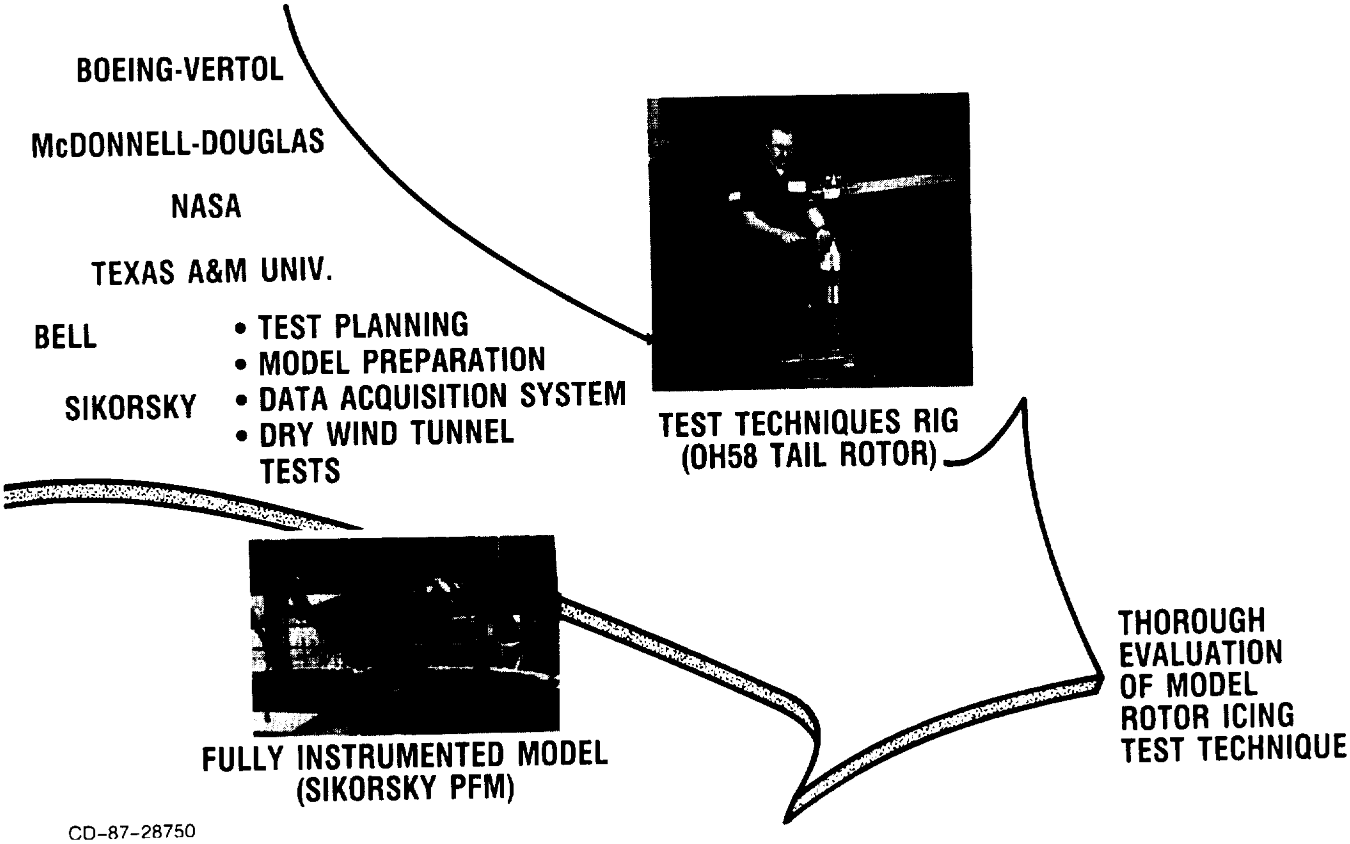

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Figure 21. - Model rotor icing program.

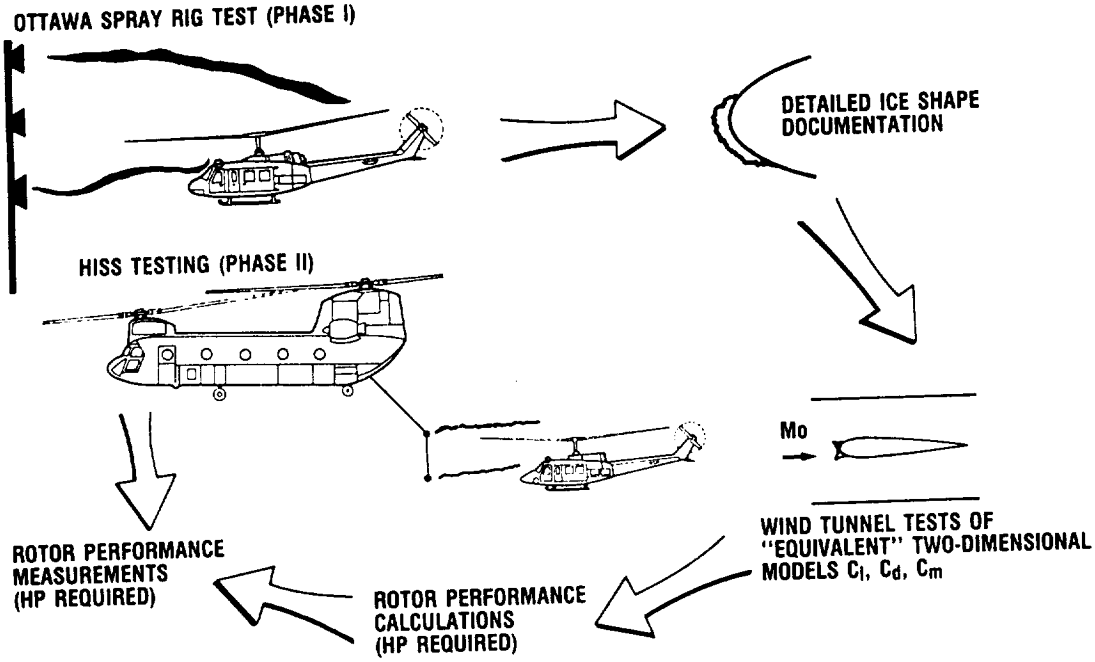

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Figure 22. - Helicopter icing flight test program.