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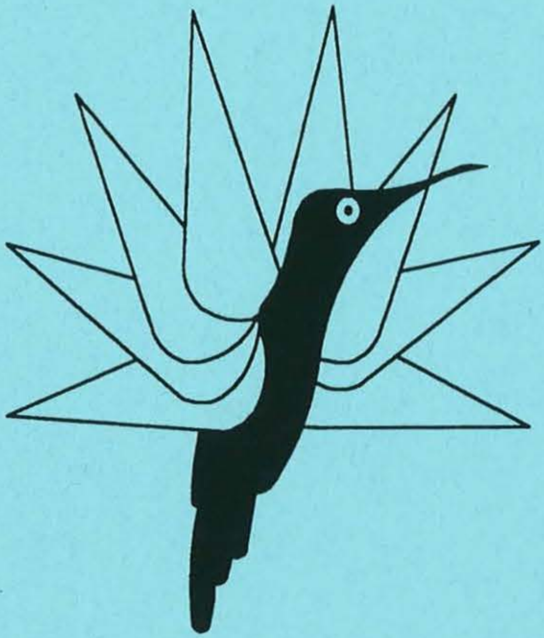

ROLE OF WIND TUNNELS AND COMPUTER CODES IN THE CERTIFICATION AND QUALIFICATION OF ROTORCRAFT FOR FLIGHT IN FORECAST ICING

BY

ROBERT J. FLEMMING
SIKORSKY AIRCRAFT DIVISION, UNITED TECHNOLOGIES CORPORATION
STRATFORD, CONNECTICUT, USA

RANDALL K. BRITTON
NYMA, INC.
BROOK PARK, OHIO, USA

THOMAS H. BOND
NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO, USA

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Robert J. Flemming, Sikorsky Aircraft Division, United Technologies Corporation

Randall K. Britton, NYMA, Inc.

Thomas H. Bond, NASA Lewis Research Center

Abstract

The cost and time to certify or qualify a rotorcraft for flight in forecast icing has been a major impediment to the development of ice protection systems for helicopter rotors. Development and flight test programs for those aircraft that have achieved certification or qualification for flight in icing conditions have taken many years, and the costs have been very high. NASA, Sikorsky, and others have been conducting research into alternative means for providing information for the development of ice protection systems, and subsequent flight testing to substantiate the air-worthiness of a rotor ice protection system. Model rotor icing tests conducted in 1989 and 1993 have provided a data base for correlation of codes, and for the validation of wind tunnel icing test techniques. This paper summarizes this research, showing test and correlation trends as functions of cloud liquid water content, rotor lift, flight speed, and ambient temperature. Molds were made of several of the ice formations on the rotor blades. These molds were used to form simulated ice on the rotor blades, and the blades were then tested in a wind tunnel to determine flight performance characteristics. These simulated-ice rotor performance tests are discussed in the paper. The levels of correlation achieved and the role of these tools (codes and wind tunnel tests) in flight test planning, testing, and extension of flight data to the limits of the icing envelope are discussed in this paper. The potential application of simulated ice, the NASA LEWICE computer code, the Sikorsky Generalized Rotor Performance aerodynamic computer code, and NASA Icing Research Tunnel rotor tests in a rotorcraft certification or qualification program are also discussed. The correlation of these computer codes with wind tunnel test data is presented, and a procedure or process to use these methods as part of a certification or qualification program is introduced.

1.0 Introduction

Many rotorcraft manufacturers have initiated the process to obtain United States Federal Aviation Administration (FAA) certification for their products for flight in forecast icing. The guidelines for the certification of a helicopter, including certification for flight in icing, have been established by certification authorities with one thing in mind - the safety of the public. Requirements generally stipulate that a helicopter be safe for all expected flight conditions. For most of the requirements established for certification, the manufacturer can set up a test program that covers the full range of expected conditions, and thereby can confirm that the requirements are met. To certify an aircraft for flight in forecast icing, the manufacturer seeks to find and fly in worst case icing conditions. But this search is difficult for two reasons. First, the certification icing envelope covers conditions that occur at the extremes of known natural cloud conditions, which are unlikely to be located during a reasonable length flight test program. Second, if a location for severe icing conditions is forecast, the helicopter flight time to reach these conditions may be too long to allow the test to take advantage of the forecast severe icing condition.

The difficulty in obtaining icing data is evident upon examination of test site statistics. The US Army has been conducting rotorcraft and fixed wing icing flight tests in Minnesota and Ottawa over the past 16 icing seasons. Figure 1 shows the summation of the number of days rotorcraft were on site. Figure 2 shows the average number of flight hours actually spent in icing for each day the aircraft was on site. These rotorcraft averaged 0.14 hours of artificial icing time per day on site, and averaged 0.15 hours of natural icing time per day on site, for a total of only 0.29 hours of icing time per day the aircraft were on site. The maximum artificial icing rate for a test program was 0.24 hours per day. The maximum natural icing rate was 0.65 hours per day. The amount of icing time achieved during a test is, of course, a function of weather conditions, but it is also a function of the maturity of the ice protection system and the daily "mission" readiness of the helicopter. The highest icing test hours (artificial + natural icing) in a season (29.7 hours) were achieved in 1984 by a US Navy/Sikorsky CH-53E that was being tested without an ice protection system. Six other test programs were able to test in icing for 16 hours or more in a single season. Two UH-60A test programs were able to find in excess of 18 hours of natural icing in a single season. These statistics reinforce the need to have validated codes and ground test methods available to complement limited data aquired during the flight program.

The operational adequacy of several components of a helicopter must be shown to obtain clearance for flight in forecast icing. These components include engines and air induction systems, airspeed systems, windshields, tail surfaces, and rotors. This paper will only address rotor ice accretion and ice protection. However, the methods addressed herein may also be applied to propellers, tilt rotors operating in both helicopter and propeller modes, and ducted tail rotors, when the ice prediction methods described are properly coupled to aerodynamic models for these devices.

Most rotorcraft companies have gathered insufficient natural icing flight test data to permit FAA certification. To date only Eurocopter has brought the certification process to a conclusion, with certification of the Super Puma by the Direction Generale de l'Aviation Civile (DGAC) in 1983 and certification by the FAA in 1984[1]. The flight test program started with the Puma in the late 1970s, and continued with the Super Puma in 1981. Super Puma certification occurred after 53 flight hours in natural icing conditions[2]. The estimated costs for the Super Puma icing certification are $20 million over the nine year period that includes both Puma and Super Puma testing. Large cost projections and limited market estimates have forced companies to reassess the value of an icing certification. All too often the certification plan has been suspended or abandoned. However, an icing certification program conducted today should use the analytical methods and experience now available to supplement natural icing data, more than offsetting the cost inflation that has occurred since the Super Puma certification flight test program. If these codes are used to reduce hardware design iterations and flight test time, program costs are estimated to be between $12 million and $18 million, depending on the extent of the application of prior technology in the design and the extent of the use of analytical methods in the certification process.

Military qualification (the term "qualification" as used here is the military equivalent of certification) of rotorcraft for flight in icing has been slightly more successful. This is primarily due to three reasons. First, the production quantity for a military rotorcraft type is generally higher than that for a civil rotorcraft, permitting the amortization of deice system development and test costs over a larger number of rotorcraft. Secondly, the qualification envelopes are generally set to less severe conditions that can more easily be found in nature. Thirdly, the military has relied on artificial (tanker) icing to augment limited natural icing test points. Artificial icing facilities and nozzle technology have undergone significant improvements, overcoming earlier concerns that these facilities produce icing clouds that differ significantly from naturally occurring clouds. Fortunately, artificial icing tends to be more severe than natural icing, and if the test aircraft can fly acceptably behind a spray rig or a tanker, it should be able to work successfully in a natural cloud.

The US Army/Sikorsky BLACK HAWK was qualified by the US Army for flight in icing conditions after a short prototype deice system evaluation in 1976 and a three-season qualification flight program in 1979, 1980 and 1981[3]. The BLACK HAWK qualification included 24.2 hours of icing tests in artificial icing and 25.8 hours in natural icing. (Other icing tests of the BLACK HAWK have occurred during subsequent years to gather data for new aircraft components and to determine characteristics with the deice system inoperative.) The US Navy/Sikorsky Seahawk flew an additional 28.4 icing hours for qualification. The US Army/McDonnell Douglas Apache was qualified following icing flight tests during four icing seasons (1982, 1985, 1986 and 1987). The Apache qualification included 18.8 hours of icing tests in artificial icing and 29.2 hours in natural icing[4]. The methods available now to assess the adequacy of an ice protection system were not available for these two test programs. While sufficient data were gathered to support qualification, the new methods would have provided added confidence in the process and reduced the time and cost to qualify.

While the western world has not embraced the application of deicing systems to rotorcraft, Russian helicopters have consistently been equipped with rotor ice protection systems. All Mil Design Bureau helicopters have had ice protection systems available[5]. Qualification has been achieved by demonstrating the system in available icing test conditions. The Russians, French, and Americans have shown that the fabrication of ice protection systems are technologically feasible. The problem preventing widespread use on a wider variety of rotorcraft is a combination of low projected market quantities and high certification costs.

Researchers in many countries have been conducting studies in forecasting, cloud characterization, computer ice accretion predictions, and computer deice system codes, especially over the past 16 years. During this time, data have been gathered in flight and in icing tunnels to provide a base for use in code correlation. Wind tunnel tests by ONERA, RAE(now DRA), Sikorsky and NASA have added substantially to the understanding of rotor icing. It is now time to show that predictive methods for ice accretion and deicing can produce trends and absolute values to the high confidence level that manufacturers and certification authorities need to allow the codes to supplement available natural icing data. The time and financial benefits for a reduction or elimination of natural icing tests in a certification test program are obvious. The search for naturally occurring super cooled clouds is, in itself, an expensive process. The recently completed Canadian Atlantic Storms Project (CASP) has found that the conditions in a cloud vary tremendously. Areas of high liquid water content change as an aircraft moves through the cloud. Time (and luck) are critical to finding the desired conditions in nature. Finding the steady-state icing conditions necessary to confirm a prediction can be very difficult. The FAA funded a study in 1985 to survey the feeling of the aircraft industry to the need and value of natural icing flight tests. A significant number of respondents cited concern for the ability to find the right flight test conditions to support a certification plan. While flight in natural icing conditions received significant support, other methods of substantiation were endorsed. This paper does not advocate the elimination of test flights in natural clouds for new rotor ice protection systems. Natural icing test data should be used for validation whenever possible during the qualification or certification process. The paper, however, will show that progress in artificial and simulated ice testing and code correlation has been made, and that these methods can be an integral part of a certification program plan. There are many operational and development rotorcraft that can benefit from methods that reduce the cost and time to certify or qualify a helicopter for flight in forecast icing. These include the Bell 214ST and Bell four-bladed models, the Bell/Boeing V-22 Osprey, the Sikorsky Wide Chord BLACK HAWK, S-92 and S-76, and the NH-90, EH-101, Super Puma MK II, and Tiger in Europe. This paper discusses the process for integrating codes and two dimensional and three dimensional wind tunnel results with certification natural icing data. It also presents results from several NASA-sponsored research projects that deal with model rotor testing and computer validation.

2.0 Alternative Approaches to Natural Icing Flight Testing

For the purposes of this paper the terms "artificial icing" and "simulated icing" will be defined as follows: artificial ice is real ice which has been created from a spray rig of some type (tanker, icing wind tunnel, etc), simulated ice is wood, plastic, or epoxy castings. Flight testing in naturally occurring clouds has long been the standard for rotor ice protection system certification. Other methods have been used to support the certification of fixed airfoil surfaces and other aircraft components, but these have not yet been applied to a rotor FAA certification program. Research at NASA has been directed toward the substantiation of alternative methods, including artificial icing tests of two-dimensional and three-dimensional scale models, full-scale and model-scale rotor tests in dry tunnels with simulated (plastic) ice, and rotor ice accretion and performance predictions using computer codes.

2.1 Calibration and Validation of Computational Methods

The current icing research program in the United States contains computational and experimental elements. Emphasis has been placed on the calibration and validation of computational methods, while improving ground and flight test techniques. Recent emphasis has been placed on the acquisition of rotary wing icing test data, and the comparison of that data with codes such as the LEWICE[6] and Sikorsky Generalized Rotor Performance (GRP)[7] and Boeing Helicopters B-65 codes. In its basic form LEWICE is used for two-dimensional airfoils, and much of the data used for correlation has come from fixed wing airfoil tests. However, application to rotary wing airfoils and blade sections have been successful.

Icing committees operating within technical societies such as the Society of Automotive Engineers and the American Helicopter Society have been working to establish data bases of available computational methods, available icing test facilities, and ice protection methods. Continuing advances in computer speed and computational methods will make first principles (Euler and Navier Stokes) calculation of rotor aerodynamics feasible, and with that will come the capability of calculating the effects of ice accretion, deicing, and residual ice on a complete rotor.

Tests of airfoils in icing tunnels was the first step in the development of rotorcraft icing rotor performance methods. ONERA and NASA conducted steady and oscillating airfoil icing tests of rotorcraft airfoils. These tests provided data that formed the foundation of rotor performance prediction methods[8,9]. The Reference 9 correlations have been studied by many researchers, and they reasonably replicate the rotor and airfoil wind tunnel data.

2.2 Proposed Certification Process

The proposed certification process combines the elements of the existing certification process with elements supported by current research initiatives. The preliminary design process can now include results from the LEWICE code and rotor performance codes, enhancing confidence for the success for the certification plan. Design trades and system optimization that were previously included during flight tests can now be started using the theoretical methods. Early prototype system flight tests as conducted on the BLACK HAWK and Apache should no longer be necessary. Sensitivities for icing severity on vehicle performance can be made early in the system design, and the baseline system parameters (power density, coverage required, cycle order, on time, and off time(s)) can be established analytically. The codes can be used to predict worst case icing conditions, both for certification cases of an operating deice system with one engine inoperative, and for 15 minutes of flight with the deice system inoperative. With the worst case performance and ice shapes established, the next steps in the validation process are dry air flight tests of the deice system and ground and flight tests with simulated ice shapes installed on the rotor blades. Acceptable tolerances for the codes need to be established at this time, remembering that the data from artificial and natural icing testing will contain random scatter. In general, performance test scatter for flight in icing will be larger than that found for dry air testing, but the resulting data can still be acceptable for icing correlation. Use of codes can be of special value when changes to an existing ice protection system or rotor geometry are made. In these cases increments can be calculated with high expectations of success.

Simulated ice test data can provide initial power correlation data for the rotor performance code. Aircraft flight performance tolerances "with known ice" can be established as a baseline for the artificial and natural icing test data. Completion of the dry air testing can be followed by natural icing tests, or a combination of natural and artificial icing tests. It can be expected that a significant portion of the certification envelope will not be available during the icing test program. The code must then be validated and aligned based on available data and the established tolerances, and then these codes can be used to show that the rotorcraft can operate to the extremes of the icing envelope.

Because of the size of facilities, many tests will need to use sub scale models and constraints may result in models that may not be fabricated to strict geometric scaling. Scaling laws have been offered by several researchers[10,11]. While tests and theoretical exercises have shown that scaling an electrothermal deicing system is not practical[12], scaling may be practical for some conditions for ice accretion characteristics, and may be practical for pneumatic and electromechanical deicing systems. Publicly available full-scale icing data to validate scaling laws is scarce, but these data form the foundation for validation of wind tunnel techniques and rotor codes. Since full-scale test data are scarce, adequacy of wind tunnel methods is best determined using the rotor performance code as a bridge, comparing the degree of correlation of full-scale data with the correlation of the sub-scale data. This process is a key element in the Sikorsky research program, and is fundamental to the success of NASA initiatives.

Confirmation could be obtained at a higher confidence level if a significant quantity of high quality research (high accuracy with reduced scatter) data were available. Sikorsky has used published US Army UH-60A BLACK HAWK qualification data and data acquired for comparable scaled conditions in the NASA Lewis Research Center Icing Research Tunnel (IRT) in 1993. A direct model-scale to full-scale comparison was not feasible because of model geometry constraints and spray nozzle capabilities. The IRT droplet diameter was generally higher than the scaled flight test conditions, and the LWC was higher for a few conditions. For example, a typical flight test liquid water content was .5 g/m^3 with a droplet diameter of 20 microns. Using the scaling relations of Reference 10 and the geometric data, the wind tunnel model target conditions were .62 g/m^3 and 6 microns, respectively. Tunnel spray constraints results in this condition being run at .62 g/m^3 and 15 microns, respectively.

3.0 Full Scale Artificial Icing Data

Full scale artificial icing data taken behind a fixed wing tanker may not provide valid data due to the small size of the cloud produced. These tankers are designed to ice a component of an aircraft, not the complete aircraft. The National Research Council of Canada Helicopter Icing Spray Rig (HISR) can provide useful data, but is limited to very low wind velocities, where rotor wake effects may be significant. The YCH-47D HISS tanker can produce a large spray, and has recently produced droplets with reasonable diameters, but wake turbulence from the tanker aircraft makes the acquisition of performance data unrealistic. The Mi-6 helicopter tanker produces a large spray, but the cloud quality is not known to the authors. Use of full-scale artificial icing data for performance correlation is very limited. Ice shapes obtained in the HISR can be used for correlation because time between shape measurement and icing is small. Loss of ice during shutdown or flight to a test center may erode the ice and limit the usefulness of post flight ice shape data from tanker tests.

4.0 Simulated Ice Test Data

Simulated ice has been used for years for airfoils on wings and tail surfaces and for nacelles, and has been used by helicopter companies for empennage and nacelle certification characteristics. Ratvasky and Ranaudo[13] have utilized the simulated icing technique to investigate the effects of tail surface icing on the stability and control characteristics of the NASA DH-6 Twin Otter icing research aircraft. Simulated glaze ice shapes, constructed from styrofoam were attached to the leading edges of the horizontal and vertical stabilizers. The actual ice shapes were determined from photographs taken of real ice on the tail of the airplane. They found that tail ice significantly affected some of the stability and control parameters while having no affect on others. The researchers concluded that the techniques employed permitted an accurate evaluation of the effects of moderate glaze tail ice on the stability and control characteristics of the aircraft. However, we know of no full-scale test data acquired using ice shapes on a rotor. NASA and Sikorsky tested simulated ice in the large test section of the United Technologies Research Center (UTRC) Large Subsonic Wind Tunnel (LSWT) in October 1993. The ice shapes were formed from molds produced on the same rotor blades during tests in April and May 1993 in the NASA IRT. The results from this test showed the effects of a learning curve in the production of representative molds. We found that the time of tunnel and rotor shutdown after ice accretion to be very important, with agreement much better when the tunnel and rotor shutdown was very quick. Slower shutdowns are thought to have caused sublimation and shedding of ice shape detail, critical to the production of a shape for the measurement of an accurate torque rise. The test data for the better of the conditions is given in Figure 3. The other two configurations tested showed the effects of ice loss prior to the molding of the ice.

The sensitivity of airfoil performance on ice shape lift and drag has been determined during tests at the Ohio State University[14]. These tests showed the ice shape detail to be very important, but that a geometric increase in shape size could overcome this loss.

5.0 Types of Model Scale Ice Accretion Tests

5.1 Model Rotorcraft Airfoil Tests

In 1985, a 3-phase model scale icing wind tunnel test program was completed by Flemming and Lednicer[15] where icing effects on the performance of 2-D helicopter airfoils were investigated. A significant database over a wide range of Mach number and angle of attack for a variety of icing conditions was obtained. The test program was conducted in the Canadian National Research Council's High Speed Icing Wind Tunnel and the Ohio State University 6 x 22 Transonic Airfoil Facility. The database consisted of both artificial (ice accreted in an icing wind tunnel) and simulated (castings made from ice molds) icing. Two-dimensional relationships for performance degradation (lift, drag, and moment coefficients) as well as ice thickness as a function of icing condition were formulated from this data. These relationships have been incorporated as a subroutine into several rotorcraft hover and forward flight performance prediciton codes.

5.2 OH-58 Tail Rotor Tests

Historically, shed-ice particles have been a problem for aircraft, particularly rotorcraft. Because of the high particle velocities involved, damage to a fuselage or other airframe component from a shed-ice impact can be significant. Design rules for damage tolerance from shed-ice impact are not well developed because of a lack of experimental data. Thus in 1992, the NASA Lewis Research Center (LeRC) began an effort to develop a database of impact force and energy resulting from shed ice[16]. This effort consisted of a test of NASA LeRC's Model Rotor Test Rig (MRTR) in the IRT. Both natural shedding and forced shedding were investigated. Forced shedding was achieved by fitting the rotor blades with Small Tube Pneumatic (STP) de-icer boots manufactured by BF Goodrich. The impact energy values were obtained using the Impact Energy Measurement System (IEMS) developed in cooperation between NASA and the University of Toledo. The IEMS is a combination of a sensor plate which can measure force-time traces due to an impact, and an imaging system which can be used to estimate the particle's size, velocity, and trajectory prior to impact. The energy absorbed by the sensor plate is derived by manipulation of the force-time trace recorded and estimation of the particle's incoming kinetic energy. For this test, the sensing plate was mounted flush against the tunnel wall and had a total sensing area of 18" X 36". The plate consisted of 3 Force Sensing Resistors (FSR), each 18" X 12". Two high-speed imaging devices were used to obtain the particle trajectory information. The two cameras were mounted in such a way as to have viewing planes orthogonal to each other. Thus, a complete 3-D trajectory of the particle could be obtained. In addition, the cameras also provided information about the particle velocity and size. Once the volume of the particle had been estimated based on the imaging information, the mass was calculated using an approximation for ice density. During the course of testing, peak impact forces of up to 9000 Newtons were observed against 0.032" thick 6061-T6 Aluminum sheets covering the FSR plates.

5.3 1989 and 1993 Powered Force Model (PFM) Tests

A heavily instrumented sub-scale model of a generic helicopter main rotor was tested in the NASA LeRC IRT in September and November 1989. The four bladed rotor had a diameter of 1.83 m (6 ft) and the 0.124 (4.9 in) chord rotor blades were specifically fabricated for this experiment. The rotor blade form was a NACA 0012 airfoil, with a -10° linear twist and a taper ratio of 1. The instrumented rotor was mounted on a Sikorsky Aircraft Powered Force Model (PFM), which enclosed a rotor balance and other measurement systems. The model rotor was exposed to a range of icing conditions that included variations in temperature, liquid water content, and median droplet diameter, and was operated over ranges of advance ratio, shaft angle, tip Mach Number, and weight coefficient to determine the effects of these parameters on ice accretion. In addition to strain gage and balance data, the test was documented with still, video, and high speed photography, ice profile tracings, and ice molds. The test data quality was found to be excellent, and ice accretion prediction methods (LEWICE) and rotor performance prediction methods reproduced most of the performance trends observed in the test[17]. However, after studying the results from the 1989 test and comparing them to predictions, it became clear that certain test conditions still needed investigation. Therefore, a re-entry of the PFM in the IRT in 1993 was instituted in order to expand upon the current rotorcraft sub-scale model experimental database[18]. For this test, the rotor blades were 0.175 scale UH-60 blades which were truncated to 1.86 m (6.09 ft) diameter in order to meet size constraints imposed by the IRT. The major areas of interest included expansion of the test matrix to include a larger number of points in the FAA AC 29-2 icing envelope, inclusion of a number of high power rotor performance points, close examination of warm temperature operations, operation of the model in constant lift mode, and testing for conditions for icing test points in the full-scale helicopter database. The expanded database has allowed further and more detailed examination and comparison with analytical models. Figure 4 shows a mapping of the meteorological conditions of the 1993 test. This is compared to the previous tests in 1989 and the FAA AC 29-2 Icing Envelope. It can be seen that this test filled in a significant portion of the envelope not acquired during the 1989 test.

Repeatability has traditionally been a problem in natural icing flight testing because of the lack of control over meteorological conditions. Indeed, droplet distribution and concentration can vary widely under the same initial conditions. A major advantage of a facility such as the IRT is that cloud conditions within the test section can be controlled with a reasonable repeatability. The main rotor lift during the icing encounter was controlled in two ways for this test; constant collective mode and constant lift mode. In the constant collective mode, the collective pitch of the rotor was set at the beginning of the icing spray and held constant during the icing event. While the rotor was iced up and the rotor lift decreased, the pilot maintained trimmed rotor moments using cyclic control, but took no action to keep lift or propulsive force constant. In the constant lift mode, the collective pitch of the rotor was increased automatically during the icing spray to maintain a constant lift throughout the icing event. Figure 5 shows good repeatability of torque for a constant collective condition which was repeated three times. Repeatability was also very good for the constant lift condition, as shown in Figure 6. Figure 7 shows a torque rise comparison between two runs in which the only difference is the lift control mode of the rotor. The constant lift mode has a higher torque rise for the same condition because of the increase in collective pitch required to offset the effect of icing on lift.

All types of ice, including beak ice, were observed during this test. As with any rotating system, the local velocity increases along the span with maximum velocity at the tip. This type of variation affects the local ice accretion on a rotor blade in two ways. First, the velocity of incoming water droplets relative to the local blade station increases with span. Thus, it would be expected that the local ice shape would, in the absence of shedding, grow larger in a linear fashion along the span of the blade. This indeed holds true, as long as local conditions are within the rime ice regime. Secondly, as the velocity increases, the effects of aerodynamic heating become an important factor and can be significant at full scale tip speeds. This has the effect of increasing the local temperature along the radius of the blade.

One of the main areas of concern for this test was that of temperature effects, particularly near freezing. Tests at various temperatures were performed for both the constant lift and constant collective control modes. Figure 8 shows the torque rise as a function of icing time for a temperature range of -25 °C to -12 °C with the rotor in the constant collective mode. It can be seen that the torque rise increases as temperature increases. As the temperature increases, the accreted ice shape on the outer portion of the rotor blades changes from rime to glaze, increasing the performance penalties. The observed boundary between rime ice and higher-drag glaze ice is shown in Figure 9. Here, the type of ice at various radial locations has been plotted as a function of temperature. The transition location from rime to glaze along the outer portion of the blade moved inboard as temperature increases. This is further illustrated in Figure 10, which shows ice tracings taken at a spanwise extent of 90% for two different temperatures. The -25 °C tracing was clearly a rime shape while the -12 °C tracing was glaze. So, for this temperature range the torque rise was mainly a function of ice type transition location. Figure 11 shows the torque rise as a function of time for a temperature ranging from -12 °C to -2 °C with the rotor in constant collective mode. For this temperature range it can be seen that the torque rise decreases as temperature increased, the opposite of Figure 8. The torque rise decreased because, in this temperature range, the radial extent of icing decreased as the temperature approached that of freezing. Less ice was accreting on the rotor, reducing the performance penalties. This boundary is shown in Figure 9 where the spanwise extent of ice decreased from 92% to 35% as the temperature increased from -12 °C to -2 °C. So, for this temperature range the torque rise was mainly a function of icing radial extent. Thus, there is a transition from rime, to mixed, to glaze, to beak ice along the radius of the blade. This is demonstrated in the ice profiles shown in Figure 12 for a temperature of -12 °C. Here, ice profiles were taken from the same run at three different radial locations. The transition of ice type can clearly be seen. Figures 8 and 11 indicate that, for this test configuration the "worst" case temperature in terms of torque rise was -12 °C. This agrees with the 1989 PFM test, which indicated a "worst" case temperature of between -15 °C and -10 °C.

After three entries in five years, a sizeable amount of sub-scale model rotor icing data has been collected. Analysis of this data has shown it to be of high quality. This test program has also demonstrated the feasibility of performing rotorcraft testing in an icing wind tunnel, like the IRT.

6.0 Computer Codes

6.1 LEWICE

The numerical analysis code, LEWICE[6], which has been developed by the NASA Lewis Research Center predicts the theoretical ice shape which accretes on a component of interest (usually an airfoil) subjected to an icing condition for a given amount of time. The analysis consists of a four step process which determines the flowfield, water droplet impingement characteristics, heat transfer processes, and ice accumulation on the component. The physical model of ice accretion is patterned after the Messinger runback model[19]. In general, the LEWICE analysis has been found to predict the rime case very well. Historically, it has always been more difficult to model the glaze ice condition. This is because the local heat and mass transfer must be taken into account for this condition. The complex task of predicting heat transfer coefficients as well as local surface roughness values usually makes for a less precise prediction of the ice shape than in the rime condition. This is true for the LEWICE analysis.

The first official release of LEWICE 1.0 to U.S. industry and academia occurred in May 1990, although many preliminary, undocumented versions had been given out prior to that. The most recent version, LEWICE 1.3 was officially released in July 1993 and contains many modifications to the original. Many of the changes were made so that the code could run more time steps and thus longer simulations, with more consistency in the predicted ice shapes. Additional improvements were made to the heat transfer prediction, the ice density correlation, and the runback model. Water shedding, ice shedding, and anti-icing heat requirements were added, along with more user-friendly output, both graphically and in text form.

Application of LEWICE to a rotor blade, with a varying local velocity and angle of attack, takes some special consideration. The current technique is to azimuthally average (average over the entire 360° arc of the blade passage) the velocity and angle of attack at the blade station of interest. Because of the very high accretion rates associated with rotorcraft (relatively small chord airfoils moving at high velocities), it is critical to use an accurate icing time as input into LEWICE. If the above concerns are properly taken into account, application of the LEWICE analysis to rotorcraft test data has generally yielded representative results[20]. Predictions in the rime ice case show good agreement with the experimental data, with less accurate predictions seen in the glaze ice case. This is illustrated in Figures 13 and 14.

6.2 B65 & GRP

Basic to any analysis of the effects of icing on a helicopter is the ability to predict main rotor performance. To date, the current effort has revolved around two very similar performance codes: Sikorsky Aircraft's GRP code and Boeing

Helicopter's B65 code. Both these codes are forward flight rotor analyses using a lifting line model. Previous independent comparisons have shown that the two codes usually agree very well with each other.

6.3 Icing Subroutine Correlation

An icing subroutine which has been linked to GRP and B65 has been used to predict the changes in the rotor performance due to icing. This subroutine makes use of a rotorcraft icing prediction method based on correlation studies as described in References 9 and 15. The method can be broken down into two regimes. The first regime exists prior to the onset of rotor shedding, thus limiting the analysis to ice accretion only. The second regime exists after the onset of rotor shedding. Shedding is a somewhat random phenomenon making correlation in this regime difficult.

The correlation predicts (among other things) incremental rotor lift ($\Delta C_L/\sigma$) and incremental rotor torque ($\Delta C_Q/\sigma$). Depending on the lift control mode the collective pitch can be either held constant at the predicted clean rotor trim solution (constant collective) or allowed to increase so that lift remains constant at the predicted clean rotor trim solution (constant lift). Figure 15 shows a comparison between the experimental and predicted torque rise for a constant collective condition. It can be seen that the comparison is excellent early in the icing encounter (<40 sec). As the onset of shedding begins (>40 sec), the correlation slightly overpredicts the torque rise. Figures 16 and 17 compare the predicted temperature trending to the experiment. The current correlation slightly overpredicts the warm temperature cases at an icing time of 20 seconds. The correlation is in good agreement at 40 seconds, but is optimistic at higher icing times. Current research is directed toward correlation improvements.

7.0 Conclusions

NASA and Sikorsky rotorcraft icing research has come a long way during the past 12 years, with considerable progress made using powered rotor models over the past six years. The two-dimensional rotorcraft airfoil test program provided basic data for the formation of relationships for incremental lift, drag and pitching moment, and for ice thickness and ice mass. The relationships have been incorporated in rotorcraft performance codes to predict torque rise, and the geometric data has been used in LEWICE correlation work to confirm the accuracy of that code's formulation. Existing full-scale research-quality rotor icing data is very scarce, and thus the emphasis was placed on use of sub-scale models to validate ice accretion, shedding and performance data. Data were acquired over a wide range of icing conditions, with the rotor operated in both constant lift and constant collective flight modes. A test was conducted to validate cast simulated ice bonded to rotor blades for performance runs, but with mixed results to date. The wind tunnel data appear to provide good correlation data, and the code predictions are correlating well, but further correlation with full-scale flight data is desired. These analytical and experimental tools are at a stage of maturity in which they could be used in a certification process. The next steps in the rotorcraft research program will be to gain acceptance of the research project test and code results, so that they may be used to reduce the cost of development and certification of future programs, providing a fleet of helicopters that will provide enhanced all-weather safety.

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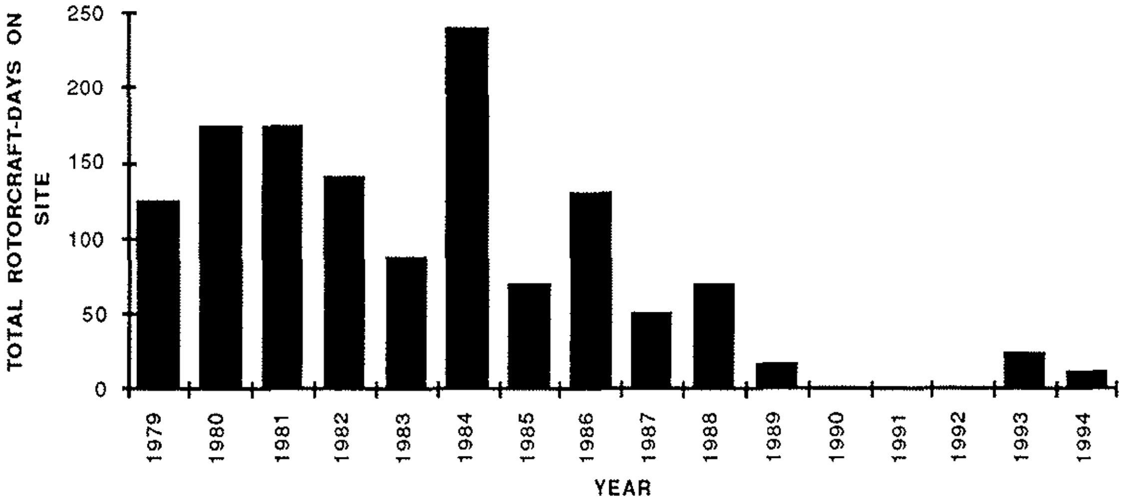

Figure 1. Summation of U.S. Army site data for rotorcraft.

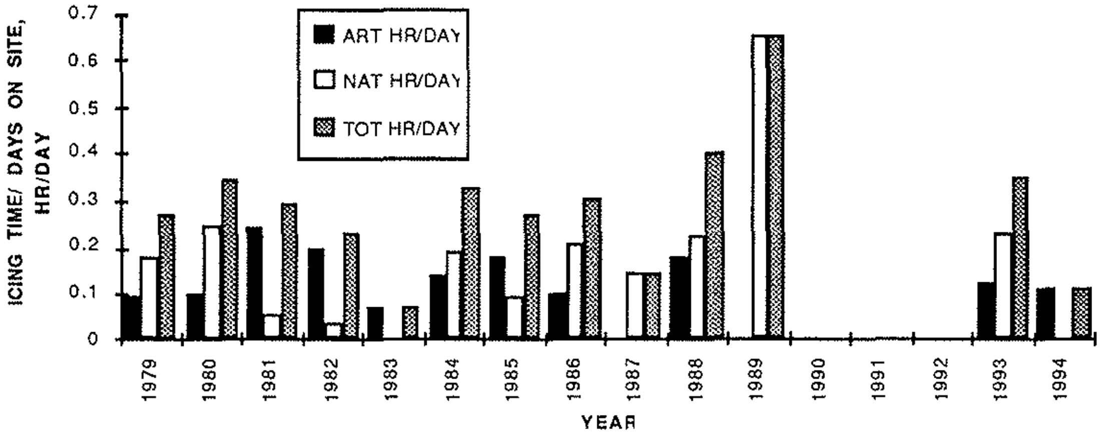

Figure 2. Summation of average U.S. Army flight test hours.

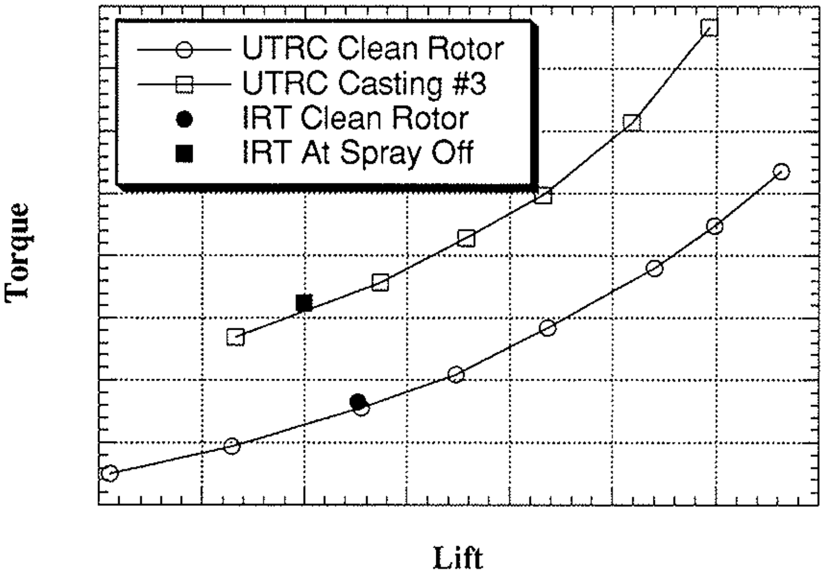

Figure 3. Test data for molding process.

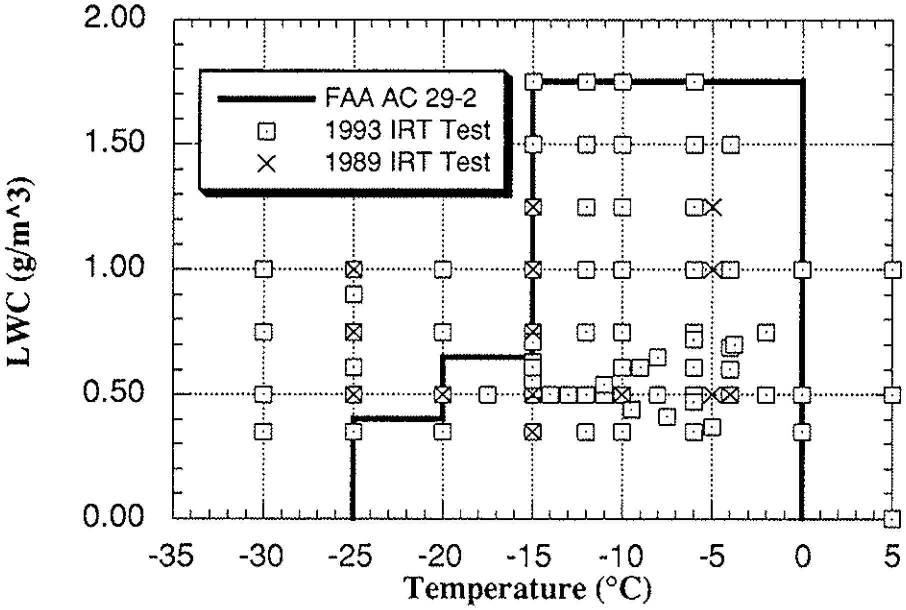

Figure 4. Icing test points for 1989 and 1993 tests.

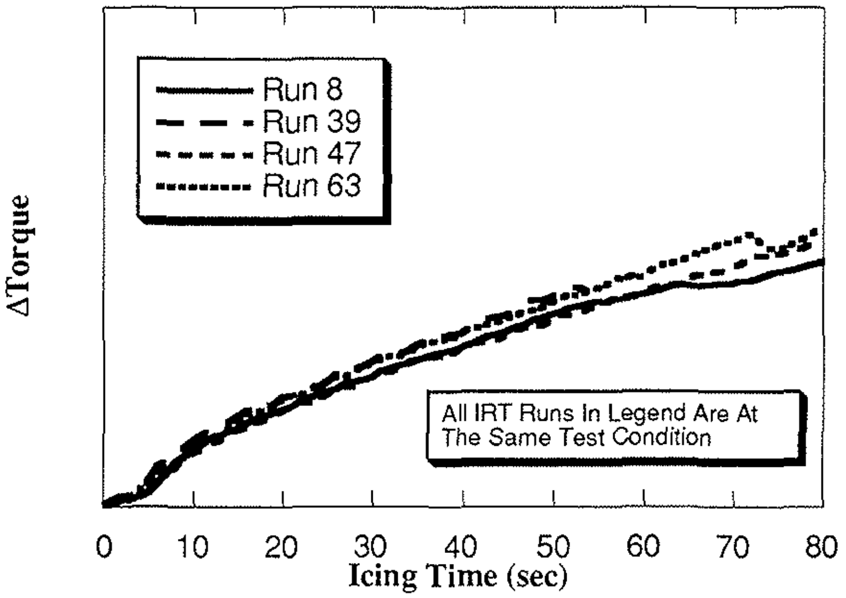

Figure 5. Torque rise repeatability for constant collective mode.

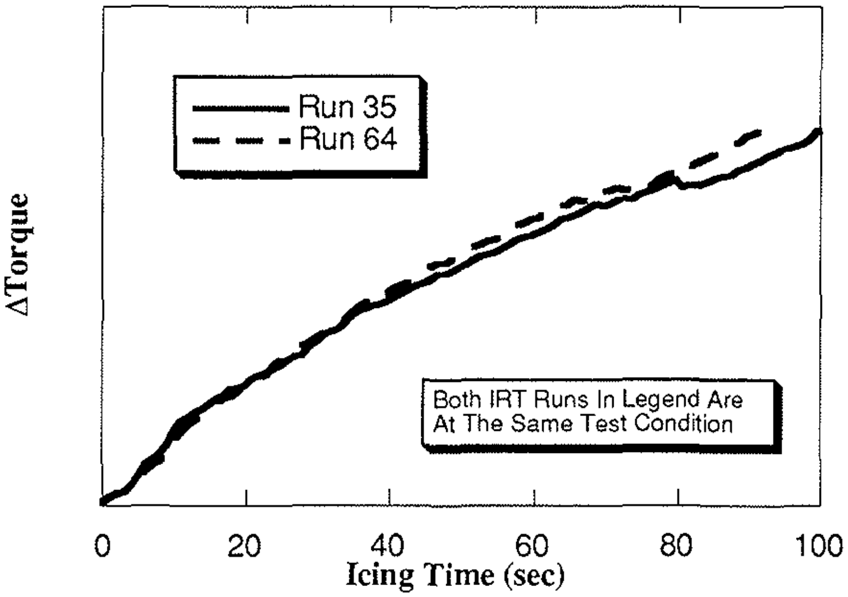

Figure 6. Torque rise repeatability for constant lift mode.

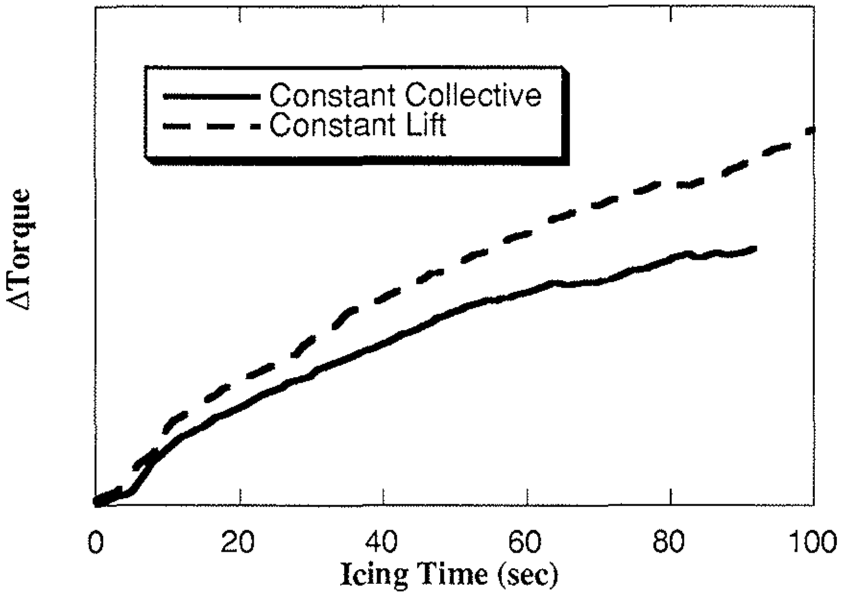

Figure 7. Torque rise comparison between constant lift and constant collective mode.

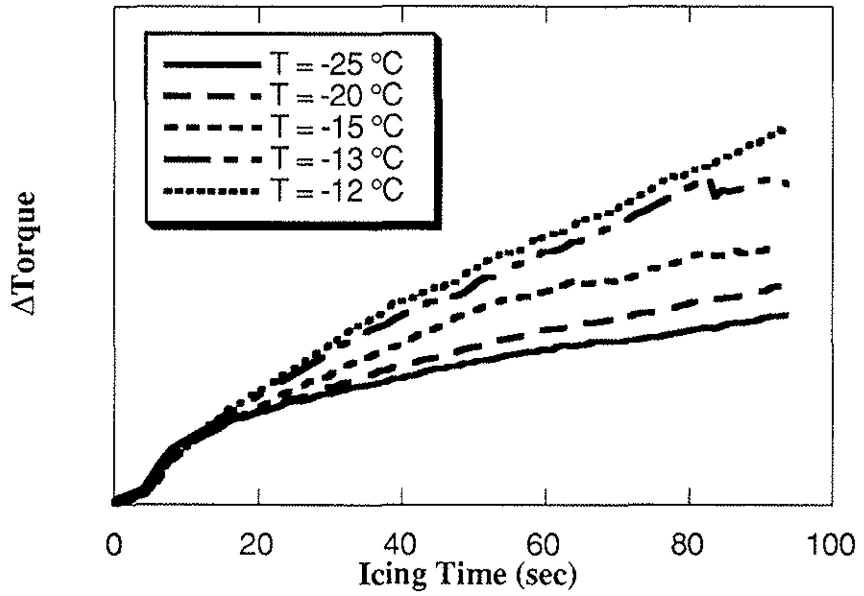

Figure 8. Torque rise trend with "cold" temperatures (constant collective mode).

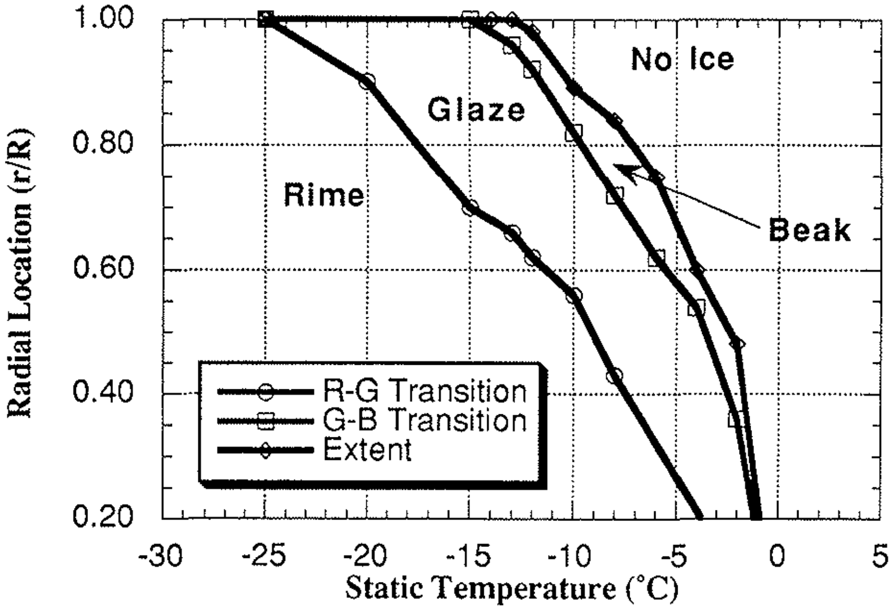

Figure 9. Experimental ice type and extent for LWC = 0.5 g/m³ (constant collective mode).

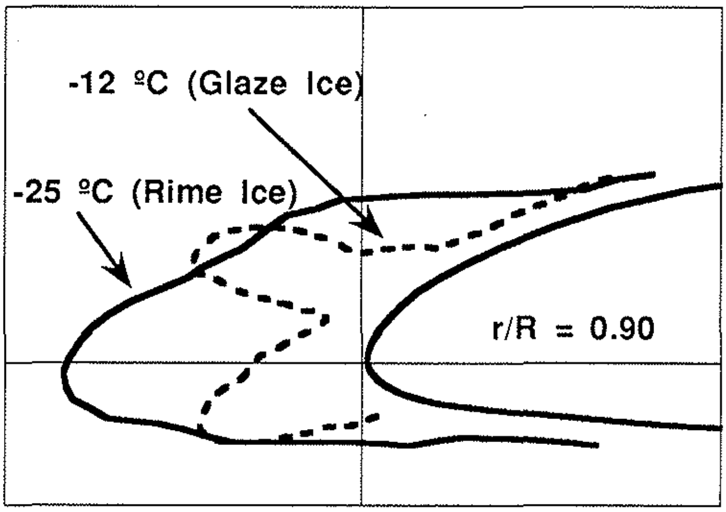

Figure 10. Ice shape tracing comparison at 90% radial location (constant collective mode).

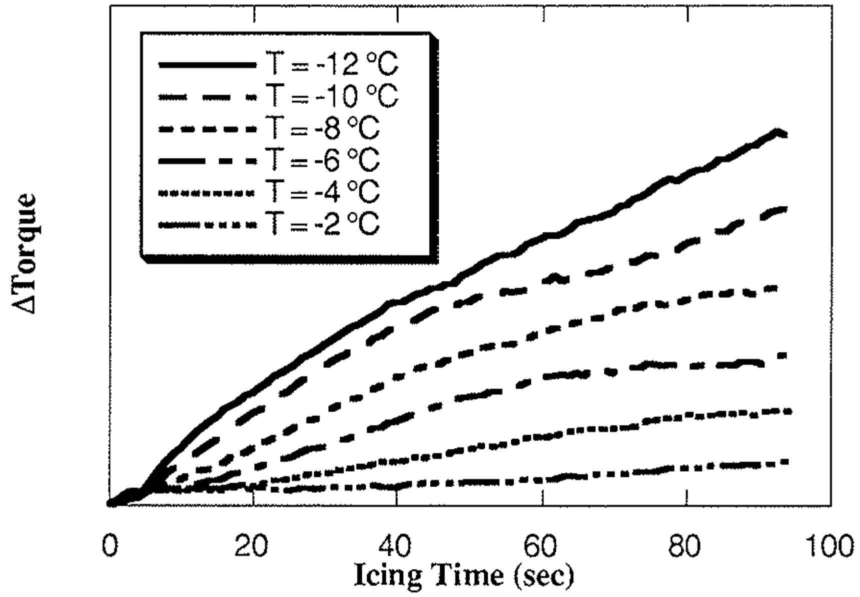

Figure 11. Torque rise trend with "warmer" temperatures (constant collective mode).

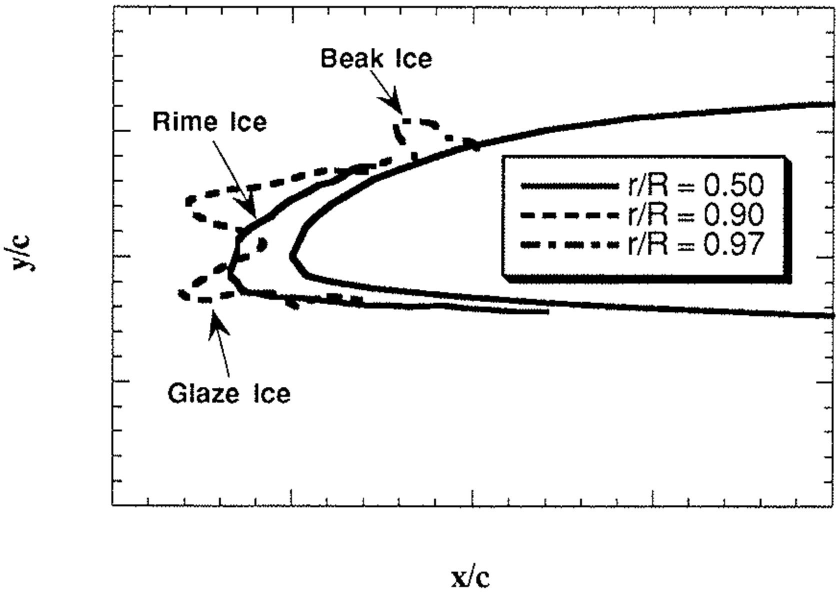

Figure 12. Ice Tracings at several radial locations at a temperature of -12 °C demonstrating transition from Rime to Glaze to Beak ice.

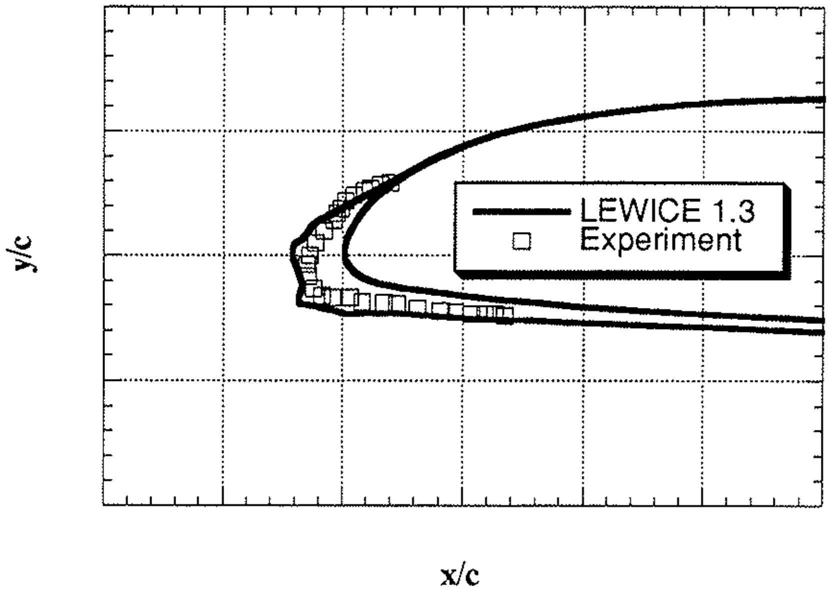

Figure 13. Comparison between LEWICE 1.3 and experiment for a Rime ice case.

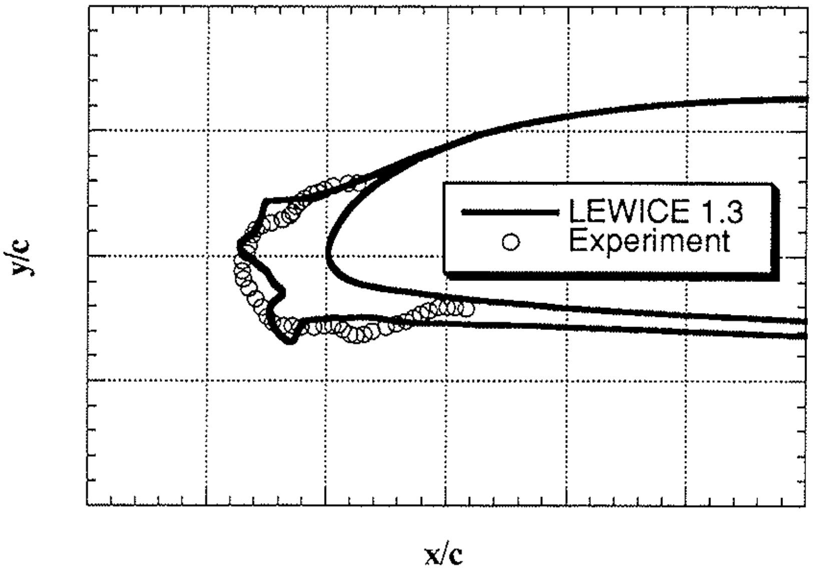

Figure 14. Comparison between LEWICE 1.3 and experiment for a Glaze ice case.

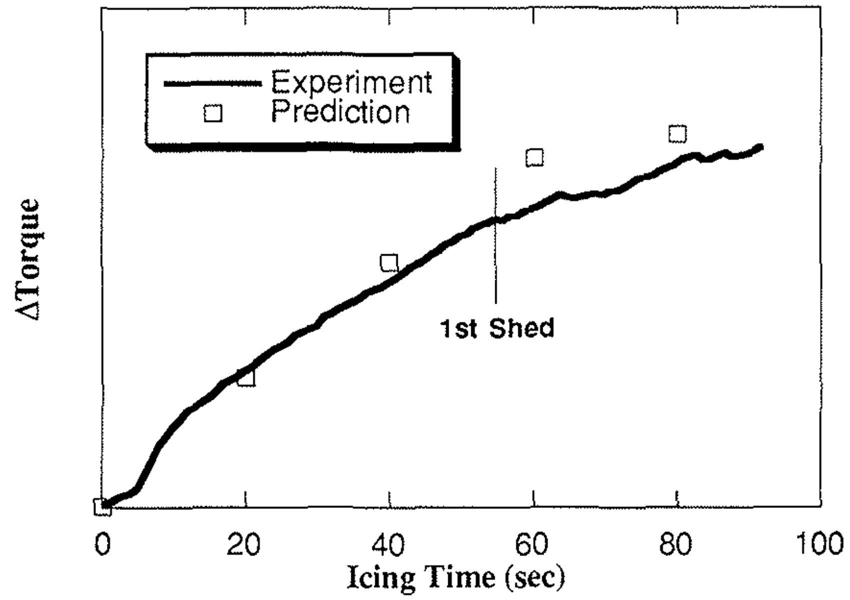

Figure 15. Comparison between experiment and prediction for torque rise (constant collective mode).

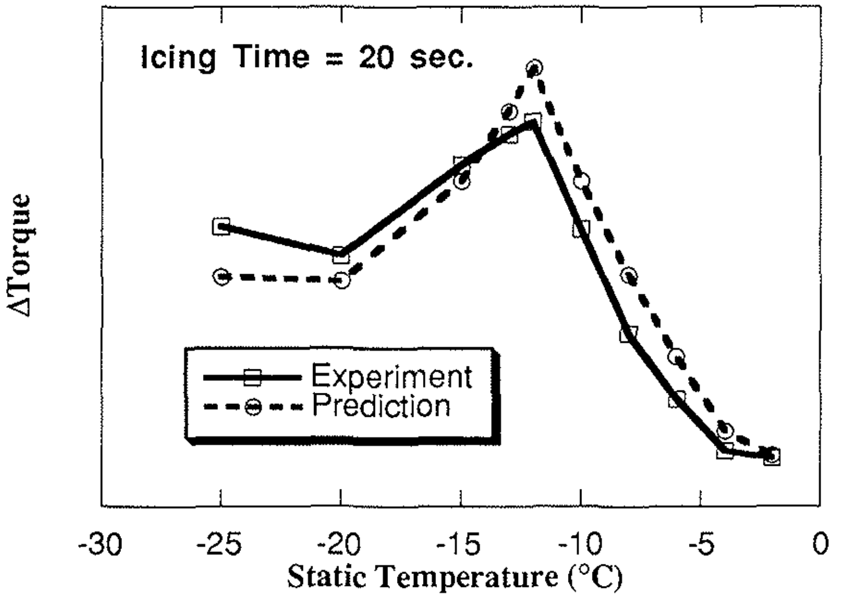

Figure 16. Comparison between experiment and prediction for torque rise as a function of temperature for an icing time of 20 seconds (constant collective mode).

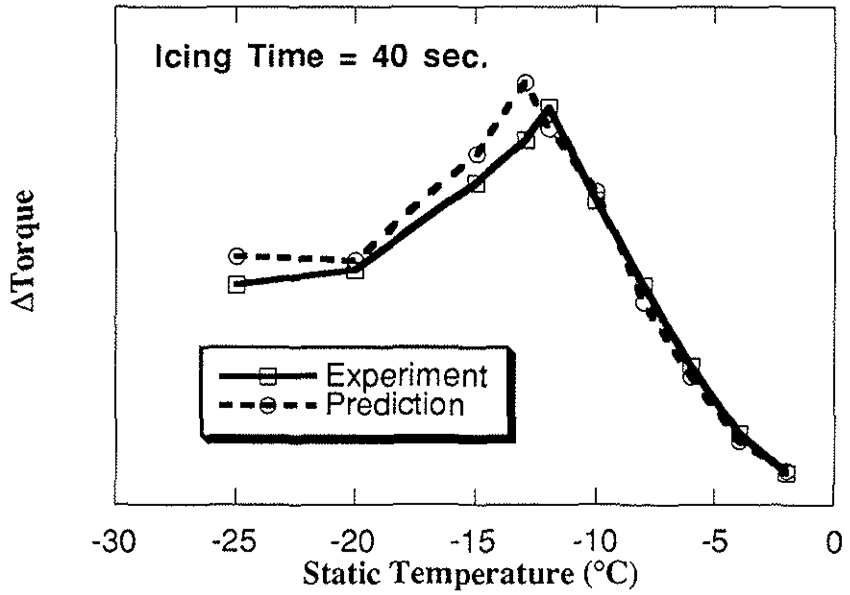

Figure 17. Comparison between experiment and prediction for torque rise as a function of temperature for an icing time of 40 seconds (constant collective mode).