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NASA's ROTORCRAFT ICING RESEARCH PROGRAM

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SUMMARY

The objective of the NASA aircraft icing research program is to develop and make available icing technology to support the needs and requirements of industry for all weather aircraft designs. While a majority of the technology being developed is viewed to be generic (i.e. appropriate to all vehicle classes), vehicle specific emphasis is being placed on the helicopter due to its unique icing problems. In particular, some of the considerations for rotorcraft icing are indicated in figure 1. The NASA icing research program emphasizes technology development in two key areas: ice protection concepts and icing simulation (analytical and experimental). The NASA research efforts related to rotorcraft icing in these two technology areas will be reviewed in this paper.

ICE PROTECTION CONCEPTS

Currently, the only rotor ice protection system being employed on operational military and civilian helicopters is the electrothermal deicing system. While the electrothermal concept has been shown to be capable of effectively deicing rotors, the weight and power requirements have caused the industry to seek other concepts. NASA research efforts have focused on two concepts: pneumatic boot and electro-impulse deicers.

PNEUMATIC BOOT

The pneumatic boot is probably one of the oldest of all ice protection concepts with its use on fixed wing aircraft dating back to at least the 1930's. The application of the pneumatic boot concept to the helicopter rotor was studied by Lockheed under an Army contract in the 1970's (ref. 1) and rejected, primarily on materials concerns. Specifically, it was felt that the pneumatic boot would not withstand the service dynamic environment of the helicopter rotor. It was feared that the boots might be damaged or completely torn off by the high levels of centrifugal forces. Also, it was felt that the rain/erosion characteristics of the neoprene rubber, from which the boots would be constructed, would be unacceptable. Concern was also expressed about the possible aerodynamic performance degradation of the rotor due to the presence of the boots especially when the tubes were inflated. These concerns were sufficient to eliminate the pneumatic boot from further consideration at that time.

However, the B.F. Goodrich Company, the only company marketing pneumatic boots in this country, subsequently investigated other candidate materials for boot construction and became convinced that a polyurethane material (trade name Estane) would solve several of the aforementioned problems. Furthermore, the possible simplicity, light weight, low power consumption and low cost of a rotor pneumatic boot deicing system justified pursuing a technology development program. Based on these considerations, NASA and B.F. Goodrich conducted a joint program in 1979 to investigate the deicing capability and aerodynamic performance of candidate pneumatic boot designs. The results of that test program conducted in the NASA Icing Research Tunnel (IRT) are given in reference 2.

The wind tunnel model used in the test (fig. 2) was a 6 ft span segment of a full scale UH1H rotor blade. Of the three pneumatic boot configurations tested, the one judged to be the most effective at removing ice is shown in figure 3. This configuration had two spanwise tubes surrounding the leading edge and chordwise tubes aft of the leading edge tubes on both the suction and pressure surfaces.

Deicing performance of this configuration for representative rime and glaze icing conditions is shown in figure 4. The drag levels as measured by a translating wake survey probe indicated large drag increases relative to clean model levels due to the ice accretions (80 to 171 percent) and drag increases of 21 to 52 percent due to the residual ice left after one boot inflation.

The results of this preliminary, proof-of-concept test were encouraging enough that a joint NASA/Army/Bell/B.F. Goodrich program was established to conduct the required flight tests to further evaluate the feasibility of the pneumatic boot concept for rotor deicing. This flight testing effort has been conducted in several phases: flight loads survey performance and handling qualities tests, hover icing (artificial), forward flight icing (artificial and natural), and rain and sand erosion testing.

Clear air and icing flight tests were conducted by the Army Engineering Flight Activity (Edwards Air Force Base) while Bell Helicopter Textron instrumented the set of rotor blades to which had been affixed the pneumatic boot deicers provided by B.F. Goodrich. The system as installed on the JUH-1H weighed only 30 lb and consisted of only six major components: pnuematic deicer, regulator-reliever shut-off valve, timer, rotary union, hose and flap assembly, and ejector flow control valve to keep the deicers deflated. Figure 5 shows a schematic of the JUH-1H helicopter with the key pneumatic deicer components indicated.

Hover icing tests were conducted in the Canadian National Research Council's Ottawa Spray Rig (fig. 6) while the forward flight icing tests were conducted behind the Army's Helicopter Icing Spray System (HISS) tanker (fig. 7). Natural icing flight tests were conducted in the general vicinity of Duluth, MN. Sand and rain erosion tests were conducted at Fort Rucker, Alabama by the Army Aviation Development Test Activity (USAAVNDTA). Limited artificial rain erosion flight tests were conducted at Edwards Air Force Base, CA by the Army Aviation Engineering Flight Activity (USAAEFA).

The deicing capability of the deicer configurations tested on the JUH-1H was judged to be satisfactory for the range of light thru moderate icing conditions tested. Structual loads measured during flight tests were all within acceptable endurance limits except the main rotor pitch link axial load which exceeded the limit by 20 percent. This was not judged to be critical. No unusual dynamic responses were noted and handling qualities of the JUH-1H were essentially unchanged by installation of the pneumatic boots. However, significant hover and level flight performance degradation due to pneumatic boot installation effects of the JUH-1H was measured. A summary of the flight test efforts is given in reference 3.

As already indicated, the ability of the Estane material to withstand the sand and rain erosion environment of the rotor was a key issue regarding feasibility of the pneumatic boot deicer. Ten hours of sand erosion testing at Fort Rucker and 6 hours of artificial rain erosion testing behind the HISS tanker failed to result in any detectable erosion. However, 10 hours of flying in natural rain of varying intensity required four separate blade repairs due to pitting and chunking of the Estane material. These repairs were required in the outer span region of the blades. This region was covered by a layer of Estane and was not protected by an active pneumatic deicer, but rather relied on self shedding for deicing.

The preliminary results from the NASA/Army/Industry program suggest that the pneumatic boot deicer is a feasible alternate rotor ice protection system. However, additional field testing appears to be needed to gain more experience with the erosion problems including the practicality of making repairs in the field before final conclusions can be drawn.

ELECTROMAGNETIC IMPULSE DEICER

The electromagnetic impulse deicer (EIDI) is a potentially attractive system for low weight, low power consumption, highly reliable and efficient deicing of aircraft components. The EIDI concept, while first suggested as early as 1937, had not been adequately developed to allow industry to consider incorporation in current or future aircraft designs. However, NASA sponsored an intensive 4 year joint effort with industrial and university partners to develop the required technology base for the EIDI concept. This activity was completed in 1986. Reference 4 summarizes the NASA industry university program for EIDI technology development.

The basic principles behind the operation of the EIDI system are shown in figure 8. Flat-wound coils made of copper ribbon wire are placed just inside the leading edge of a wing's skin with a small gap separating skin and coil. Either one or two coils are placed at a given spanwise station, depending on the size of the leading edge. Two methods of supporting coils are shown: support by the front spar or from a beam attached to the ribs. Also, mounting to the skin itself is sometimes used.

The coils are connected by low resistance, low inductance cables to a high voltage capacitor bank, and energy is discharged through the coil by a remote signal to a silicon-controlled-rectifier ("thyristor"). Discharge of the capacitor through the coils creates a rapidly forming and collapsing electromagnetic field which induces eddy currents in the metal skin. The fields resulting from current flow in the coil and skin create a repulsive force of several hundred pounds magnitude, but for a duration of only a fraction of a millisecond. A resulting small amplitude, high acceleration movement of the skin acts to shatter, debond and expel the ice. Two or three such "hits" are performed sequentially, separated by the time required to recharge the capacitors, then ice is permitted to accumulate until it again approaches an undesirable thickness.

The EIDI system is lightweight and uses a small amount of electrical energy (about 200 J per foot). For fixed-wing aircaft, system weights are comparable to those for pneumatic deicers, and the power used is about equal to the landing light power. The power required is about one percent of that used by a hot gas anti-icing system, or about 10 percent of an electrothermal system.

The ability of the EIDI system to efficiently deice the many fixed wing icing components which were tested in the IRT suggested that the system might also be used to deice helicopter rotors. In order to provide a preliminary evaluation of this hypothesis, a midspan section of an AH1 Cobra rotor blade was reworked to include EIDI coils and the resulting model was tested in the IRT (fig. 9). The Cobra blade section was of all composite design and had a chord of 31 in., but for these tests the leading edge was made of sheet metal, and attached only at its upper and lower surface extremeties.

Acceptable deicing characteristics (as shown in fig. 10) were observed for a configuration which had mini-coils located every 8 inches on the pressure surface. Coils placed adjacent to the upper or suction surface did not yield such satisfactory deicing results either when tested alone or in conjunction with selected lower surface coils.

While these initial fixed position airfoil de-icing tests gave satisfactory deicing results, several design related problems became apparent. In particular, the rotor leading edge abrasion shield must be free to move in a normal direction in order to expel ice so bonding of the shield to the composite nose would have to be restricted to well downstream of the nose on the upper and lower surfaces. Space must also be found forward of the rotor main spar to run the required number of insulated wires to the coils as well as for the coils themselves. Also, the delicate aeroelastic balance of the rotor must not be upset by inclusion of the EIDI system.

These concerns strongly suggest that the incorporation of EIDI into a helicopter rotor must be done as either part of a redesign of an existing rotor or design of a new system. That is, the EIDI is not an add-on system for helicopter rotor blades. Thus the development of the required technology cannot be accomplished so readily as it was for fixed wing aircraft where retrofitting of EIDI was an acceptable approach.

In the future, it is hoped that a joint NASA/Army/industry/university consortium can be established which will develop the required technology base. It is envisioned that a series of IRT tests will be initially required followed by hover icing tests at the Ottawa Spray Rig and forward flight icing tests, in both artificial and natural conditions.

ICING SIMULATION

The rotorcraft icing community is severely lacking in available validated simulation techniques (both experimental and analytical) to investigate icing problems for research and development, design, or certification/qualification purposes. A major goal of the NASA rotorcraft icing research effort is to develop and validate the required simulation techniques. The following section describes the various research efforts, the results of which will contribute to this goal.

AIRFOIL PERFORMANCE IN ICING

Prior to the NASA icing research program, the vast majority of the airfoil performance-in-icing data was acquired in the IRT by NACA researchers in the 1944 to 55 time period. The IRT has a maximum test section velocity of 300 mph ($M \approx 0.4$) which does not allow the high speed icing studies needed by the rotorcraft community to be conducted. It is well known that the outer span regions of helicopter rotors contribute significantly to the overall lift and drag and thus a knowledge of rotor outer span icing characteristics is essential. A first step to gaining this understanding is to understand the high speed icing characteristics of airfoil sections which are representative of outer span sections. Also, it should be noted that the airfoil geometries tested by NACA researchers in the IRT were primarily for fixed wing applications.

In order to begin to acquire the required airfoil high speed icing data base, NASA sponsored an extensive research program in the Canadian National Research Council's (NRC) 12 by 12 in. high speed icing wind tunnel. At the time of this program, the NRC wind tunnel was the only operational high sped icing wind tunnel in North America.

This program, which was conducted by Sikorsky Aircraft and The Ohio State University and is discussed in reference 5, involved testing several different subscale airfoil geometries over a wide range of aerodynamic and environmental conditions. Figure 11 shows the main airfoil geometries tested. The NACA0012 airfoil represented a first generation rotor airfoil while the VR-7 SC1095, SC1094 R8, and SC1012 R8 represented second generation airfoil contours. The SSC-A09 and circulation control sections were chosen to represent advanced airfoil designs.

A large amount of airfoil icing performance and ice accretion shape data was acquired for Mach numbers from 0.3 to as high as 0.7. In addition to airfoil force and moment levels, measurements were also made of surface pressure distributions for some of the models.

Figure 12 shows some typical data gathered during the test program. Changes in airfoil lift and moment coefficients are shown as a function of icing time. For all airfoil configurations, increases in drag coefficient were large while the changes in lift and pitching moment coefficients were smaller (but certainly not insignificant).

Data such as that shown in figure 12 was used to formulate correlation equations for changes in airfoil lift and moment coefficients as functions of aerodynamic, environmental, and airfoil geometric variables. These correlation equations gave predictions which agreed with the experimental data to within about 30 percent.

These two-dimensional airfoil icing correlation equations were then used along with appropriate rotor performance analysis codes to predict rotor performance in icing for the S-76, UH-1H, and UH-60A aircraft and to compare the predictions with available icing flight data. Predictions were made for torque rise levels for both hover and forward flight conditions. The results are shown in figure 13. Appreciable scatter existed in the results, although the general agreement was judged to be better for the hover condition. Generally, the predicted torque rise levels for forward flight conditions were less than the observed values.

It is difficult to evaluate the shortcomings of the analysis from these limited comparisons since the quality of the flight data can be questioned. The data was gathered during programs for which the main goal was to evaluate ice protection system performance rather than to acquire rotor performance-in-icing data. It is felt that dedicated flight test programs must be conducted to acquire quality code validation data. Also, shedding of ice, especially from the outer span region of the rotor, is felt to be a key aspect of rotor icing. The prediction methodology had only a very simple treatment of this complex phenomenon, and no information about shedding was contained as part of the reported experimental results. Again, future flight test programs must adequately document the shedding characteristics.

In 1985, Fluidyne Engineering Corporation (Minneapolis, MN) began operation of a 22 by 22 in. transonic icing wind tunnel (fig. 14). This is an atmospheric total pressure facility which relies on ambient conditions to provide proper air temperature. NASA has initiated a series of tests in this facility to acquire larger chord rotorcraft airfoil icing data. First phase of testing involved acquiring ice accretion shapes for a NACA0012 section for Mach numbers up to 0.6 while follow on testing will involve acquisition of ice shapes and resulting section drag levels. Eventually, tests will be conducted with other representative airfoil sections.

Lower speed icing studies of the NACA0012 airfoil (21 in. chord) have been conducted in the NASA IRT (ref 6). These studies are also aimed at acquiring airfoil ice accretion and resultant drag increase levels.

An oscillating rig mechanism for the IRT has been fabricated and will be used in future tests to assess the importance of pitch oscillation on ice accretion and resultant aero degradation levels.

MODEL ROTOR ICING

While two-dimensional airfoil icing data is a required part of a comprehensive rotor icing data base, data is also required for actual rotors operating in the icing environment. This data would include ice accretion shapes, ice shedding characteristics, and resultant rotor loads. Natural and artificial icing flight tests of full scale helicopters is the most obvious way to acquire such data, but flight testing is an expensive, manpower intensive effort and it is not realistically possible to be able to acquire data for "worst" icing conditions.

A more desirable approach to acquiring such rotor icing data would be through icing wind tunnel tests of properly scaled model rotors. This approach would allow systematic exploration within the icing envelopes of liquid water content, droplet size, and ambient temperature to determine areas of increased rotor sensitivity to icing. To date the only model rotor icing tests conducted have been done by the French (ref 7). The French claimed their results, when compared with natural icing flight test data, showed that meaningful ice accretion and aero performance data could be acquired but the value of electrothermal deicer data was questioned.

Model rotor icing tests could be a valuable test technique not only for icing R&D purposes but also for icing certification purposes. However, for either application, the simulation approach must be validated by comparison with full scale flight data.

In order to develop this model rotor icing test technique, NASA, the four major helicopter companies, and Texas A&M University have formed a consortium to plan and carry out model rotor icing tests in the IRT. The first model to be tested will be a fully instrumented Powered Force Model (PFM) provided by Sikorsky (fig. 15). The rotor diameter will be 6 ft and the airfoil section will be NACA0012. The initial tests of the PFM are tentatively scheduled for late 1987. Follow on tests would involve a properly scaled model rotor to allow direct comparisons to be made with data acquired from a complementary flight test program. It is envisioned that this proposed flight test program would likely be a joint NASA/Army venture.

One issue which must be addressed as part of the model rotor icing effort is what icing scaling relations to apply between full scale and model scale tests. The issue of icing scaling is a key one within the entire icing community since icing research facilities do not exist which allow testing of either full scale components or complete aircraft (model or full-scale) over the complete range of desired conditions. Current NASA efforts with regard to scaling are to concentrate on improving the understanding of the fundamental physics of ice accretion and to conduct comparison tests of the several scaling laws that have been published in the literature. Improvement in the formulation of ice accretion modeling should allow improved scaling relations to be developed.

Another desirable approach to acquiring rotor aero performance-in -icing data is to conduct dry wind tunnel tests of model rotors to which have been affixed to the leading edge representative artificial ice shapes. Initial attempts to explore this simulation approach have involved model helicopter tests in the Texas A&M 7 by 10 low speed wind tunnel (fig. 10). A two-dimensional glaze like ice accretion was affixed to the rotors and resulting rotor loads measured for a variety of hover and forward flight conditions. Typical forward flight test results shown in figure 17 indicate large increases in required torque were experienced relative to the clean rotor levels. The results also indicate that the ice shape covering the final 15 percent span of the rotor makes a large contribution to overall performance degradation.

Supporting two-dimensional airfoil tests were conducted in the Texas A&M 7 by 10 wind tunnel to measure local section performance degradation due to the ice shape. Overall results of both the two-dimensional airfoil and model rotor tests are reviewed in reference 8.

Follow on testing of this model helicopter is currently underway to investigate the importance of using more detailed artificial ice shapes. Simulated asymmetric ice shedding cases are also being studied.

The artificial ice shape testing approach offers another potentially attractive simulation testing technique if it can be properly validated. The ice shapes could be determined by analytical predictions, available experimental data and/or personal judgement. Data acquired could be useful for validating analytical prediction methodologies and for providing data to support qualification/certification programs.

FULL SCALE HELICOPTER ICING

As previously indicated, icing flight testing is a very expensive and time consuming test technique, and validated simulation approaches are preferable. However, some icing flight testing is required to develop the necessary validation data base. These test programs must be dedicated to acquiring such data rather than the data being acquired as a by product of a program aimed at some other goal, such as, development of an ice protection system.

NASA and the Army have completed the first such flight program called the Helicopter Icing Flight Test (HIFT) program (refs. 9 and 10). The overall HIFT program has been a multi year effort which has involved several other organizations Bell Helicopter Textron, Fluidyne Engineering Corporation, Hovey and Associates, and The Ohio State University.

The major elements of the HIFT program and how they are related are shown in figure 18. Phase I flight tests were conducted in the Canadian NRC'S Ottawa Spray Rig while Phase II flight tests were conducted behind the Army's HISS tanker. For each Phase of the flight testing, ice was allowed to accrete on the unprotected rotors of the test aircraft, a UH-1H, and resultant aero performance degradation was measured. The test aircraft was then landed with care so as to minimize the ice shed from the rotors during shut down. Rotor ice accretions were then measured along the span primarily using two techniques - ice shape tracings and silicone molds.

Ice shape tracings recorded along the span of the rotor for flight E of the Phase I hover tests are shown in figure 19 while figure 20 shows one of the silicone molds acquired for the same flight. The increase in horsepower required to sustain hover flight for the icing of flight E was 96-HP which was about a 17 percent increase over the clean rotor value. Summaries of the ice shape documentation efforts for the two phases of flight testing are given in references 11 and 12.

The silicone molds acquired from Flight E were then used to make detailed epoxy castings of the ice accretions such as the one shown in figure 21. Full scale UH1H rotor sections, with these castings affixed to the leading

C-4

edge were tested in the Fluidyne dry transonic wind tunnel to measure rotor sections drag increases due to the artificial ice shapes. The results of these tests are shown in figure 22. These results were then used along with Bell rotor performance codes to predict the rotor degradation. The comparisons for Flight E shown in figure 23 indicated good agreement existed between measured and predicted performance degradation.

For the forward flight tests (phase II), one flight test point has been chosen for follow-on testing and analysis. The wind tunnel tests have been completed and the rotor performance degradation predictions will soon be made.

The HIFT program has demonstrated that it is possible to acquire rotor ice accretion/aero-performance data for hover and forward flight icing. Future test programs should incorporate in-flight ice shape documentation in addition to the ground documentation techniques employed in the HIFT program. one such flight system might be the hub mounted video camera system developed by the Army as part of the rotor pneumatic boot program already discussed. Such a system could document when and where ice shedding occurred during the test flights.

ROTOR ICING ANALYSIS

The major efforts in rotor icing analysis are in the areas of rotor aero performance degradation and electrothermal de-icing performance.

Initial aero performance predictions were accomplished through joint NASA/Boeing-Vertol/Texas A&M studies to predict Boeing Chinook front rotor degradation due to rime icing (refs. 13 and 14). The intent of this initial study was to determine whether it was feasible to predict rotor performance in icing using a purely theoretical approach. In particular, a droplet trajectory code, an airfoil performance degradation correlation expression, and a rotor performance code were coupled to form an analysis methodology. Initial studies were done for hover icing (ref. 13) and then extended to forward flight conditions (ref. 14). The droplet trajectory code used was that developed by Bragg (ref. 15).

Figure 24 shows the predictions for horsepower required to maintain a constant value of rotor thrust coefficient for two different assumed radial extents of icing (85 and 100 percent). The figure show the important contribution of the rotor outer span to overall rotor degradation. These results clearly show that a comprehensive rotor icing performance methodology must be able to predict radial extent of icing. Also these results suggest the importance of being able to handle rotor ice shedding, especially in the outer span region.

The hover icing predictions were encouraging enough to extend the predictions to forward flight conditions. This conclusion was primarily on the basis that the performance degradation levels predicted were reasonable, especially when compared to reported values for other helicopters. Unfortunately, no data was available at the time for Chinook performance in icing.

For the hover icing analysis, it was possible to take advantage of the rotor axial symmetry so that droplet trajectory and airfoil performance anzlyses had to be performed only as a function of radial position and not also as a function of azimuthal position. However, for the forward flight analysis it was necessary to account for the azimuthal dependence.

Initially, trajectory and airfoil performance calculations were performed for 13 radial locations for each 15^{o} increment of rotor disk (24 total azimuthal locations). This matrix of information was then input into the forward flight performance code and rotor degradation predicted. A simplified approach was also investigated which involved calculating average section Mach number and angle-of-attack for each radial location on the rotor. These average conditions were then used as inputs into the trajectory and airfoil performance analyses. The resultant array of airfoil degradation levels were then input into the rotor performance code to make the final prediction. While the number of calculations required for this simplified approach was far less than for the detailed analyses, the results differed by no more than 5 percent in predictions of horsepower required to sustain level flight.

Figure 25 shows the predictions of horsepower required (referenced to the no ice value) using the detailed analytical approach. Four different assumed radial extents of icing are shown, and again the importance of the outer span icing is evident. Sikorsky employed this same basic analytical approach in the studies already mentioned. Improvements on the initial NASA/Boeing-Vertol/Texas A&M methodology were in the areas of predictions of spanwise extent of icing, prediction of ice shedding, and use of general airfoil correlations rather than just a rime icing correlation.

The major conclusion to be reached from the rotor icing analysis efforts completed is that it appears to be possible to develop a comprehensive rotor icing analysis methodology which will predict with reasonable accuracy the rotor degradation levels to be expected from ice accretions. Current NASA efforts are aimed at developing such a comprehensive methodology, the main elements of which are shown in figure 26. In the near term, correlations will be used to predict airfoil degradation due to icing while in the longer term it is envisioned that these correlations will be replaced by codes which predict the actual ice accretion distribution on the rotor and the resultant section changes in lift, drag, and moment coefficients. These codes are currently being developed and validated by NASA as part of the aircraft icing research program. Also, ongoing fundamental research (both analytical and experimental) in the area of ice structural properties should provide some guidance in the development of the ice shedding module.

While this rotor icing analysis methodology will certainly require significant computational resources, it is felt that it will be a fundamentally correct methodology which will not be based on extensive use of correlations which can always be questioned when "new" or different rotor configurations are investigated.

Again, it must be emphasized that additional high quality icing flight test data must be acquired to validate this rotor icing analysis methodology. Currently, the data being used is that provided through the HIFT program as well as unprotected British RAF Chinook data provided by the British Royal

Aircraft Establishment (RAE) through the joint NASA/RAE studies on helicopter icing.

The other analysis effort has been the development and validation of a series of transient heat conduction codes which model the electrothermal deicer. Figure 27 gives the important characteristics of the six different codes developed to date and how they differ from one another. As the table suggests, the codes vary greatly in complexity and therefore, in the size of computer required. Codes 1 and 2 which model the electrothermal deicer on a one-dimensional, time varying basis can be run on a personal computer. Code 6 which analyzes the complete two-dimensional geometry, including the variable thickness ice layer and the many layers of the airfoil geometry requires a supercomputer (i.e. a Cray 1S or XMP) to achieve reasonable run times. A unique feature of all codes is that they treat the melting of the ice through a phase change routine.

Currently, the code predictions are being compared with electrothermal deicer data from icing wind tunnel and helicopter natural icing flight tests. These comparisons are aimed at providing a better understanding of how accurately the various codes can predict electrothermal deicer performance for the various levels of modeling complexity.

References 16 to 20 give detailed descriptions of the individual electrothermal deicer codes.

CONCLUDING REMARKS

This paper has reviewed the accomplishments to date of NASA research efforts related to helicopter icing. Some suggestion has also been given as to future planned efforts. The two major areas of concentration will continue to be developing advanced rotor ice protection concepts and developing/validating rotor icing analytical and experimental simulation methodologies. The development of advanced ice protection concepts will provide the helicopter industry with alternatives to the electrothermal system which is viewed by many to be two expensive and too heavy and to require too much power. Validated analytical and experimental simulation methodologies are tools needed by the industry to increase their understanding of the rotor icing problem and to reduce time and cost associated with icing certification/qualification. In order to accomplish a timely transfer of this icing technology, most of the research efforts are performed jointly with industry through either formal contracts or co-operative programs.

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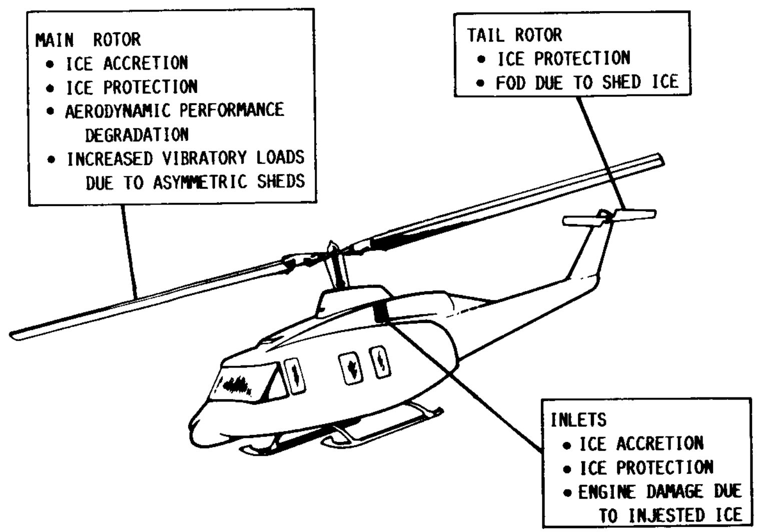

FIGURE 1. - MAJOR ROTORCRAFT ICING CONSIDERATIONS.

FIGURE 2. - PNEUMATIC BOOT ON ROTOR SECTION MODEL INSTALLED IN 6x9 FT NASA LEWIS ICING RESEARCH TUNNEL.

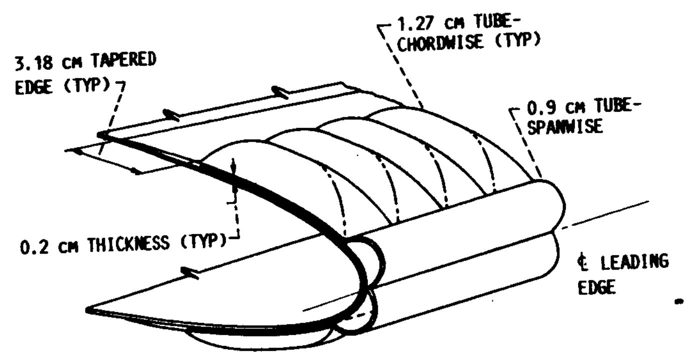

FIGURE 3.- TYPICAL CROSS SECTION OF INSTALLED DEICER (INFLATED).

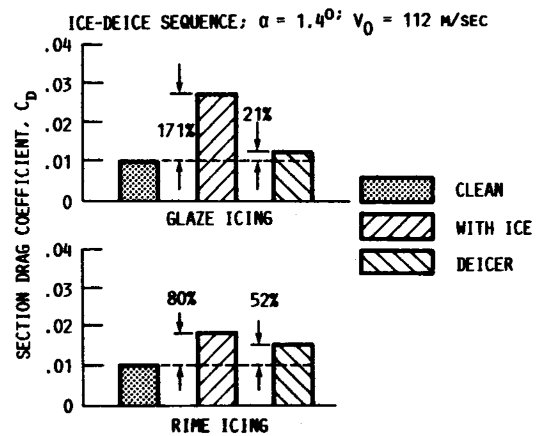

FIGURE 4. - SECTION DRAG OF HELICOPTER ROTOR MODEL WITH PNEUMATIC BOOT.

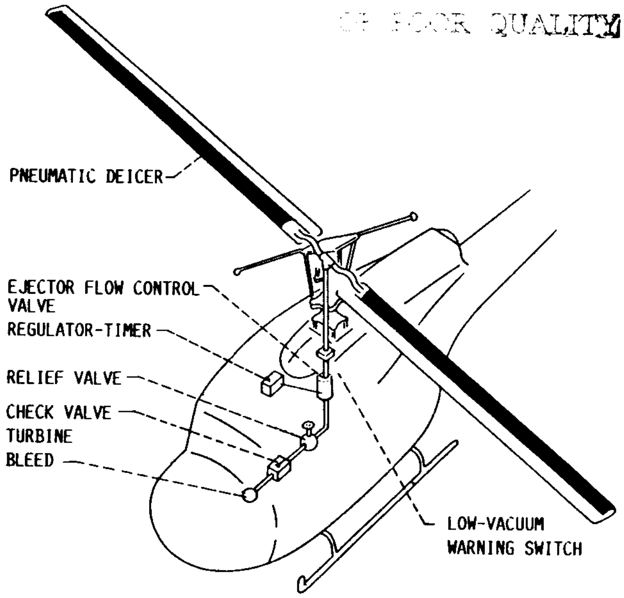

FIGURE 5. - MAIN ROTOR APPLICATION OF PNEUMATIC DEICER.

FIGURE 6.- CANADIAN NATIONAL RESEARCH COUNCIL'S OTTAWA SPRAY RIG.

FIGURE 7.- ARMY'S HELICOPTER ICING SPRAY SYSTEM (HISS) TANKER.

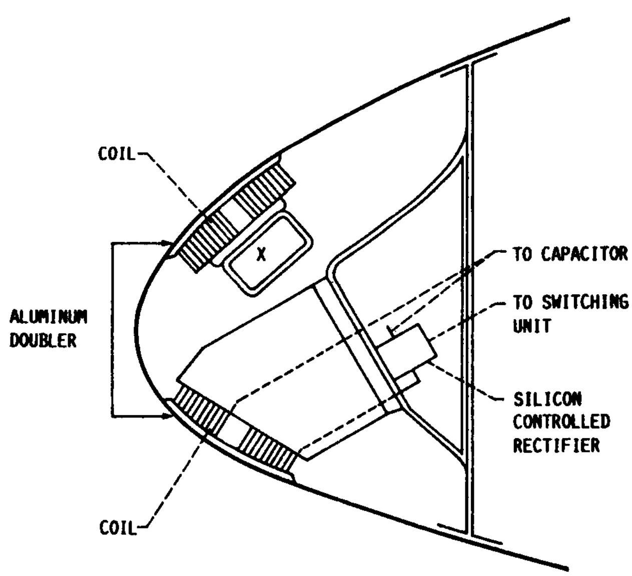

FIGURE 8.- EIDI IMPULSE COILS IN A LEADING EDGE.

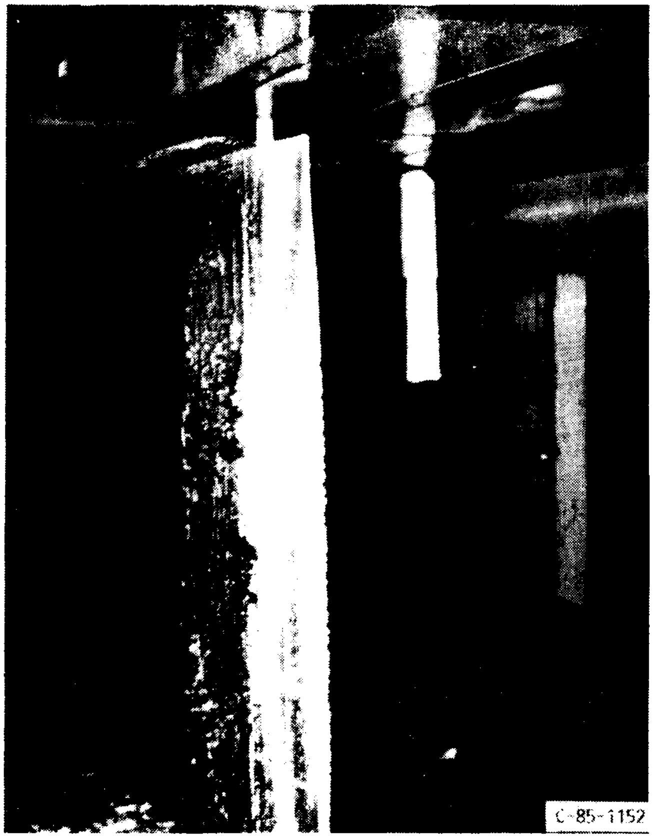

FIGURE 9.- AH1 CORBA ROTOR SECTION IN NASA IRT WITH LEADING EDGE ICE ACCRETION.

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FIGURE 10.- AH1 COBRA ROTOR SECTION AFTER ACTIVATION OF EIDI SYSTEM.

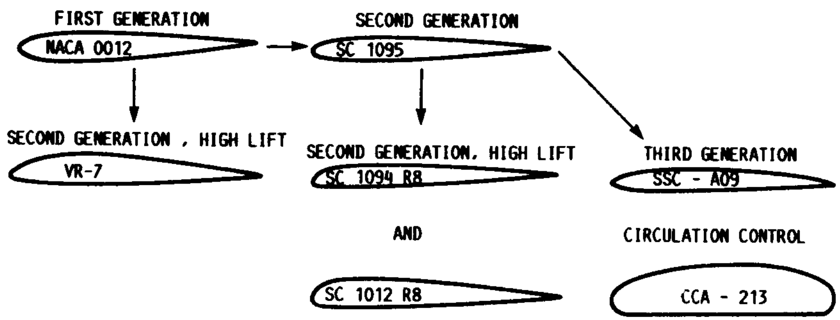

FIGURE 11.- ROTOR AIRFOIL GEOMETRIES TESTED IN CANADIAN NATIONAL RESEARCH COUNCIL'S HIGH SPEED ICING WIND TUNNEL.

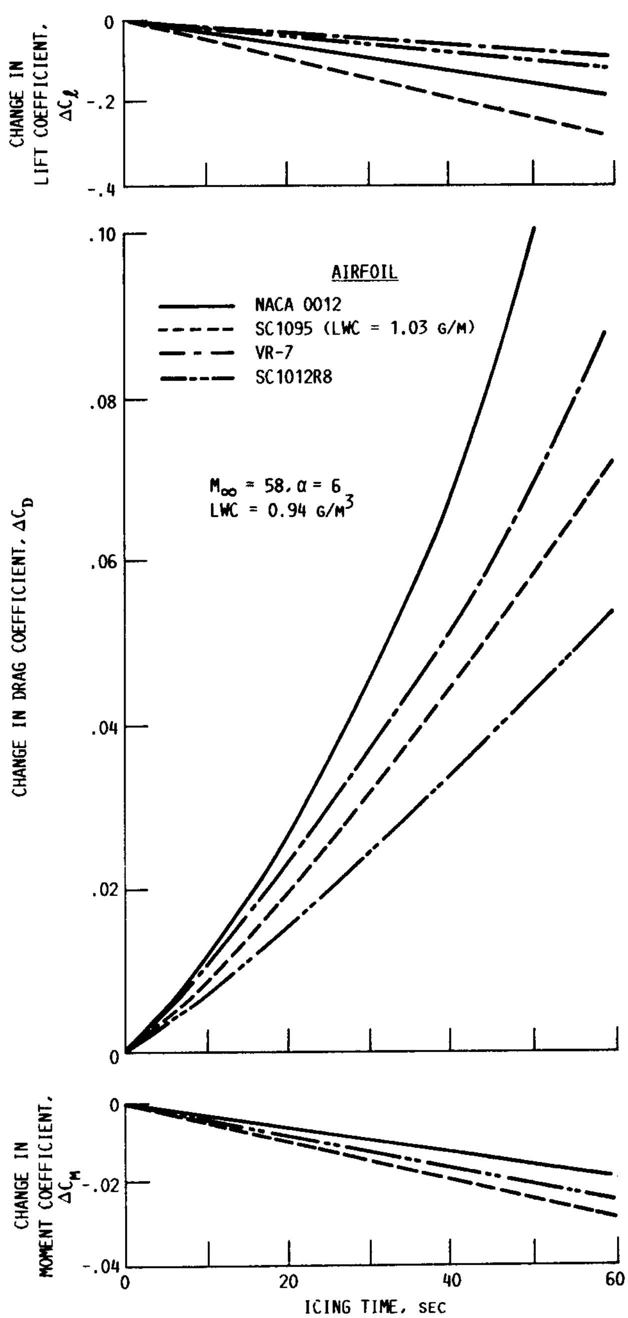

FIGURE 12.- EFFECT OF ICING TIME AT AN ANGLE OF ATTACK OF 6 DEGREES AT HIGH MACH NUMBERS.

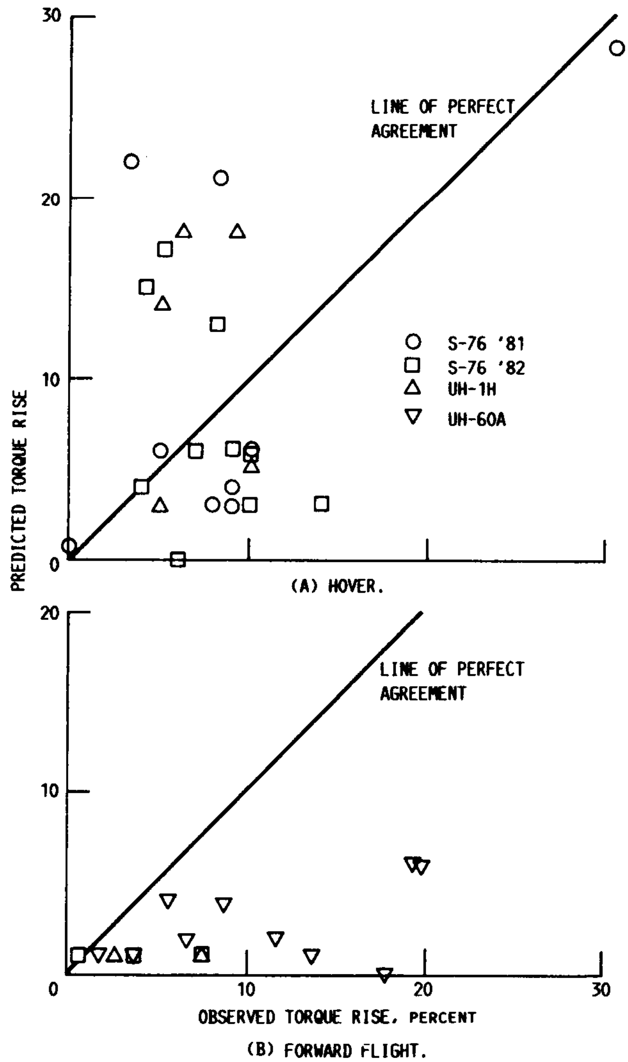

FIGURE 13.- COMPARISON OF PREDICTED AND MEASURED TORQUE RISES FOR HOVER AND FORWARD FLIGHT ICING CONDITIONS.

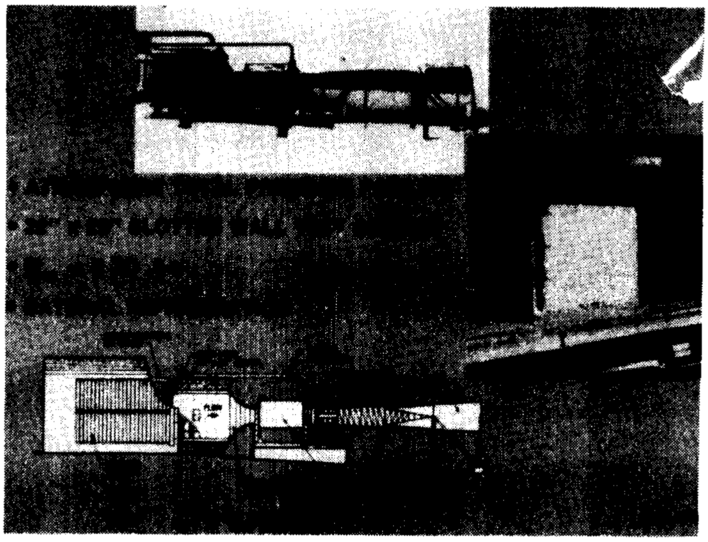

FIGURE 14.- FLUIDYNE HIGH SPEED ICING WIND TUNNEL.

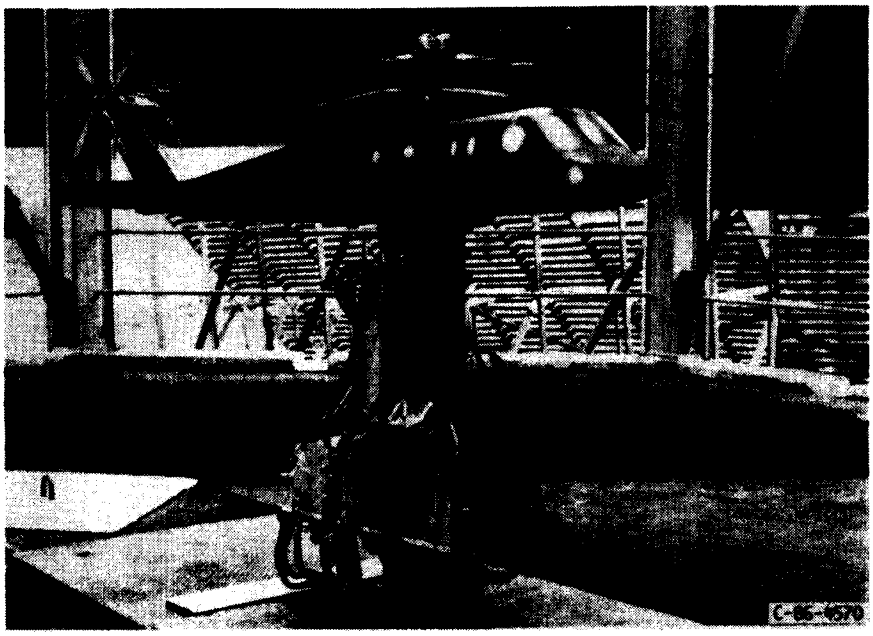

FIGURE 15.- SIKORSKY POWERED FORCE MODEL TO BE TESTED IN NASA IRT.

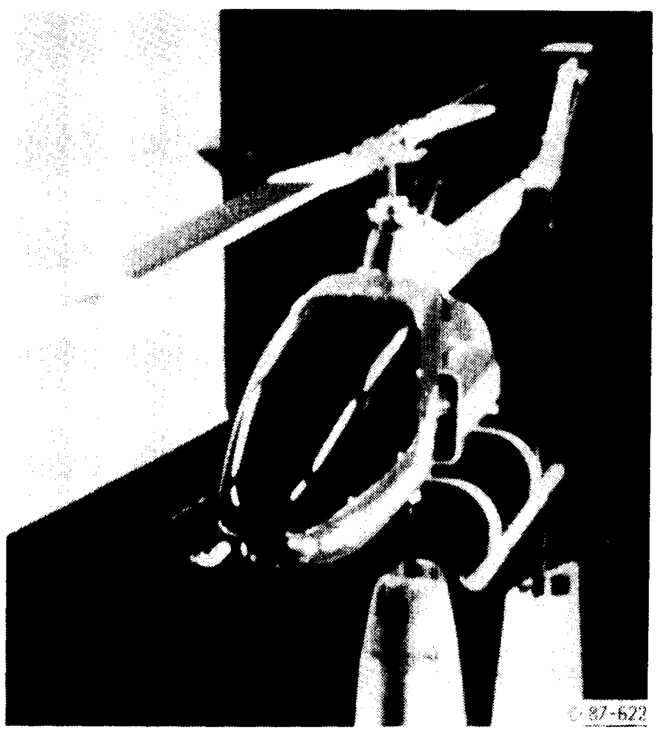

FIGURE 16.- MODEL HELICOPTER INSTALLED IN TEXAS A & M 7x10 LOW SPEED WIND TUNNEL.

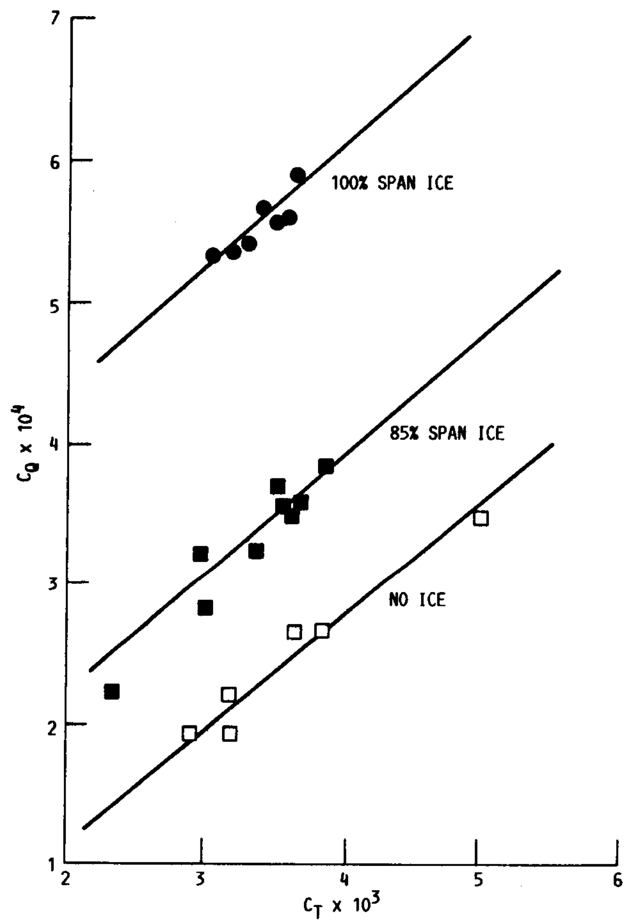

FIGURE 17.- VARIATION OF TORQUE COEFFICIENT VERSUS THRUST COEFFICIENT FOR VARIOUS SPANWISE ADDITIONS OF GENERIC ICE: FORWARD-FLIGHT CONDITION.

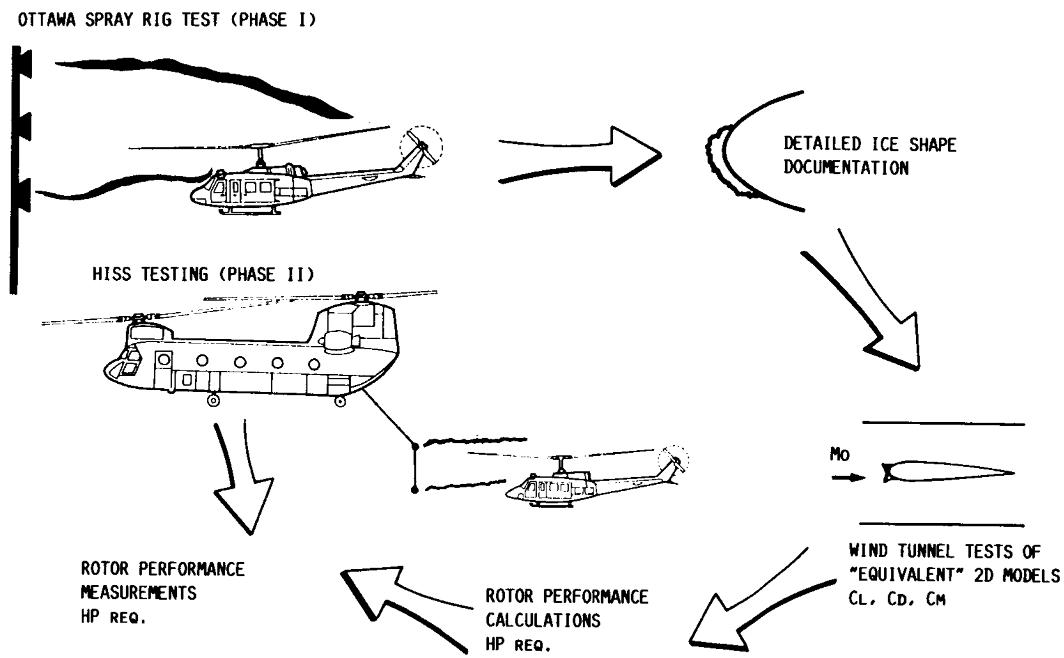

FIGURE 18.- ELEMENTS OF HELICOPTER ICING FLIGHT TEST PROGRAM.

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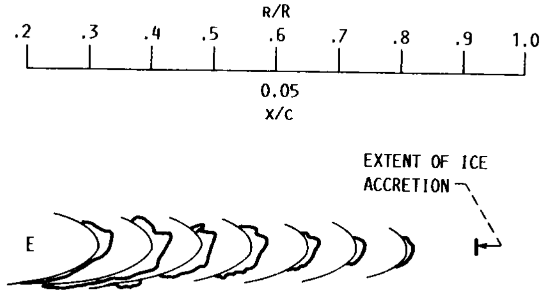

FIGURE 19.- SPANWISE VARIATION IN ROTOR ICE SHAPES FOR FLIGHT E OF PHASE I TESTING.

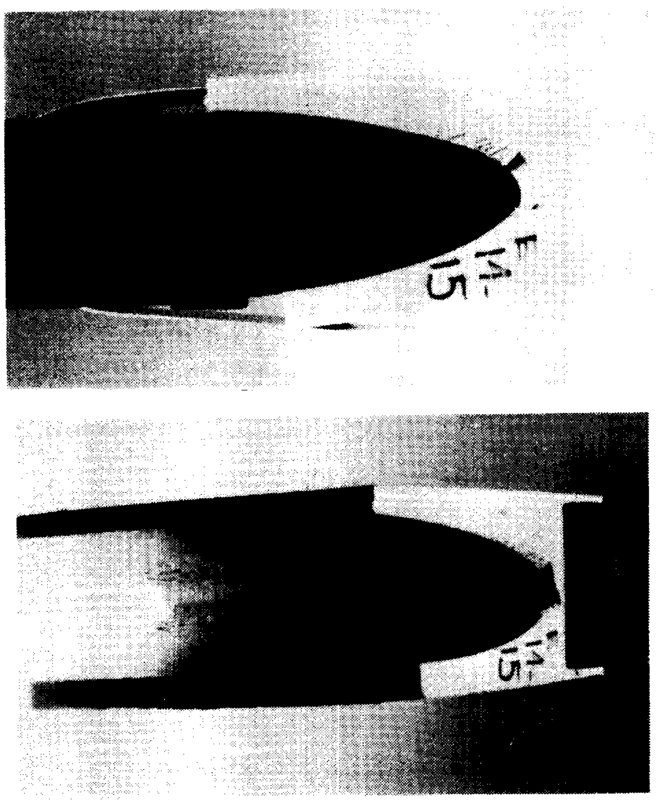

FIGURE 20.- TYPICAL MOLDS OBTAINED OF ICE FORMATION FOR FLIGHT E.

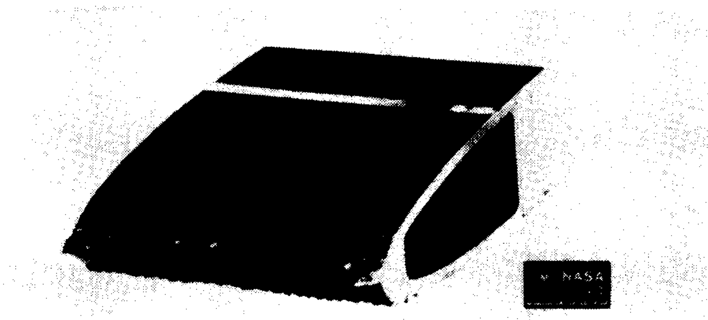

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FIGURE 21.- EPOXY CASTING AFFIXED TO UH-1H ROTOR SECTION.

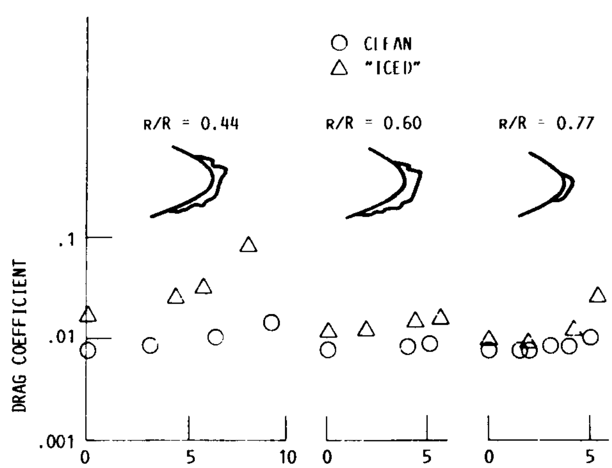

FIGURE 22.- DRY WIND TUNNEL RESULT FOR "ICED" AIRFOIL PERFORMANCE.

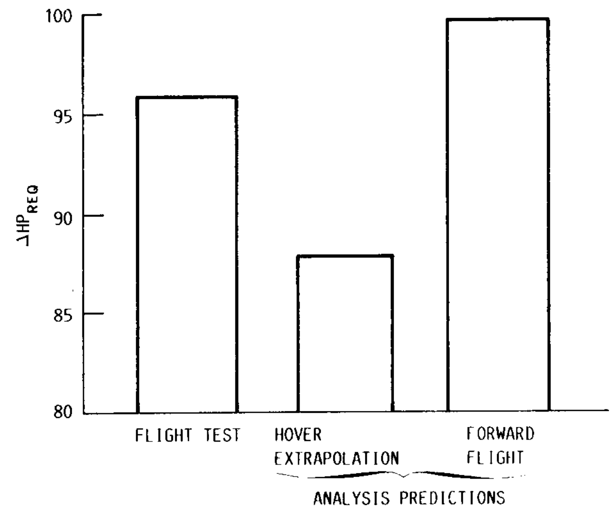

FIGURE 23.- UH-1H ROTOR PERFORMANCE DEGRADATION DUE TO ICING FOR FLIGHT E - EXPERIMENTAL AND PREDICTED.

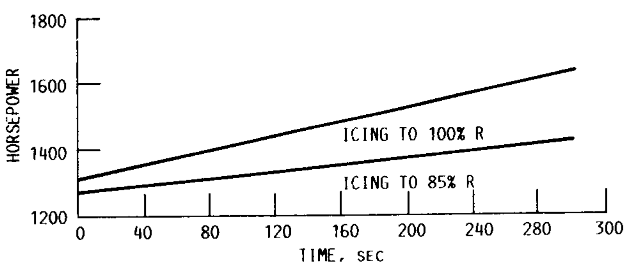

FIGURE 24.- HORSEPOWER REQUIRED TO MAINTAIN A C_T OF 0.004 AS A FUNCTION OF ICING TIME - CH47D HELICOPTER ROTOR BLADE, HOVER CONDITION.

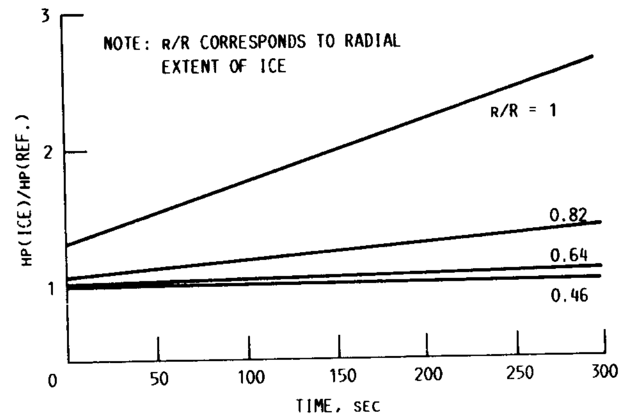

FIGURE 25.- HORSEPOWER REQUIRED WITH RIME ICE ACCRETION TO MAINTAIN A PROPULSIVE FORCE OF 1460 LB AND THRUST OF 20 750 LB (HP (REF.) = 1990, FRONT ROTOR) (360° AVERAGE - 15° SEGMENT).

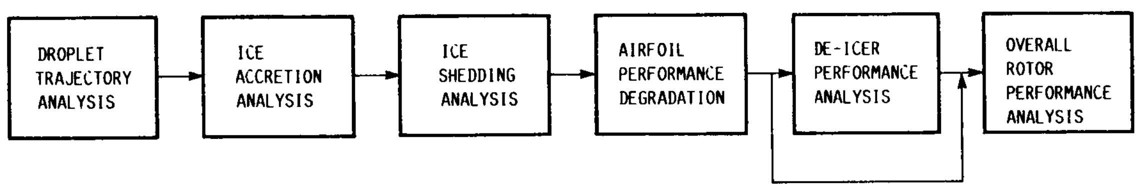

FIGURE 26.- ELEMENTS OF COMPREHENSIVE ROTOR ICING ANALYSIS METHODOLOGY.

GEOMETRY	ICE THICKNESS	NUMBER OF HEATERS	PHASE CHANGE
1. ONE DIMENSIONAL	CONSTANT	ONE	APPROXIMATE
2. ONE DIMENSIONAL	CONSTANT	ONE	WEAK ENTHALPY
3. TWO DIMENSIONAL (RECTILINEAR)	CONSTANT	ONE	WEAK ENTHALPY
4. TWO DIMENSIONAL (RECTILINEAR)	CONSTANT	VARIABLE	WEAK ENTHALPY
5. TWO DIMENSIONAL (RECTILINEAR)	VARIABLE	ONE	WEAK ENTHALPY
6. TWO DIMENSIONAL (EXACT)	VARIABLE	MULTIPLE	WEAK ENTHALPY

FIGURE 27.- ELECTROTHERMAL DEICER CODES.