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NASA's Aircraft Icing Analysis Program

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Abstract

An overview of the NASA ongoing efforts to develop an aircraft icing analysis capability is presented. Discussions are included of the overall and long term objectives of the program as well as current capabilities and limitations of the various computer codes being developed. Descriptions are given of codes being developed to analyze two and three dimensional trajectories of water droplets, airfoil ice accretion, aerodynamic performance degradation of components and complete aircraft configurations, electrothermal deicer, fluid freezing point depressant antideicer and electro-impulse deicer. The need for bench mark and verification data to support the code development is also discussed, and selected results of experimental programs are presented.

Introduction

The aircraft icing problem has long been researched and studied. Reports exist in the literature which trace icing research activities back as early as the late 1920's. Since then research into the aircraft icing problem has been an almost ongoing effort at varying levels of intensity by a number of government and private research organizations both in the United States as well as in many other countries. A common thread which binds these various activities is that for the most part they have been experimental in nature. The majority of these programs have been aimed at studying the performance of various ice protection systems, although some limited attempts have been made to develop icing analysis capabilities.

The current NASA Aircraft Icing Research Program which was started in 1978(1) seeks to take advantage of available computational fluid dynamics capabilities and develop a series of compatible computer codes which will address the fundamental icing problems. Once these initial codes are developed, additional codes will then be developed to broaden and enhance the capabilities. The computer codes will be thoroughly evaluated by comparison with appropriate verification data. The development of these computer codes and the acquisition of the required verification data bases are two major goals of the NASA aircraft icing research program.

Once these various computer codes have been developed and adequately validated, they will provide the aircraft designers and certifiers with tools which should help to reduce the time and, therefore, the cost for the development and certification of aircraft with the required ice protection.

Reference 2 presented the overall icing analysis plan which was developed and the status of the various computer codes at that time (1984). This report can be viewed as an update of that document.

Symbols

C_D, C_L	aircraft drag and lift coefficients
C_d, C_l, C_m	airfoil drag, lift, and moment coefficients
c	airfoil chord
LWC	icing cloud liquid water content, g/m^3
MVD	icing cloud median volume droplet diameter, μm
T_1, T_2, T_3	electrothermal deicer temperatures, °C
T_{oo}	free stream temperature, °C
t	time, sec
U/U_e	boundary layer velocity ratio
V_{oo}	free stream velocity, m/sec
$\frac{x}{c}, \frac{y}{c}$	nondimensional coordinates
α	angle-of-attack

Overall Objectives

The long range objective of the NASA aircraft icing analysis program is to develop a capability to predict the details of an aircraft icing encounter for both fixed and rotary wing vehicles. Figure 1 suggests four uses which could be made of such an analytical capability. Namely, the analysis could be used to predict aircraft performance and handling qualities changes due to icing on unprotected and de-iced components and to determine ice protection system performance. In addition, the analysis could be used to design ice protection systems for various applications and perhaps even be used to design components which are insensitive to icing.

A majority of the current code development/verification efforts are directed toward the two-dimensional airfoil problem. Once the capability to analyze the two-dimensional airfoil has been developed and the accuracy verified, it will serve as the basis for developing a fundamental analytical capability for treating wings, propellers, helicopter rotors, and complete aircraft configurations.

Obviously a large number of computer codes are required in order to develop an overall aircraft icing analysis capability. Figure 2 shows the codes required and some (but by no means all) of the interfaces required to develop a unified methodology.

The shaded boxes in Figure 2 indicate those computer codes currently under development and verification. As the figure indicates, there are many computer codes which are not currently being developed. While available resources certainly limit the number of codes which can be developed concurrently, another, even more significant, limitation is a lack of knowledge of appropriate fundamental physics on which to base computer models. For example, the lack of understanding of basic structural and fracture properties of impact ice make it difficult to develop a code which models the pneumatic boot, one of the oldest of all ice protection systems.

Thus, before computer codes can be developed to treat various aspects of the aircraft icing problem, a series of basic modeling experiments first must be conducted in order that the key physical elements be incorporated in any subsequent mathematical models which are formulated. This work is currently underway in several areas such as determining the mechanical properties of impact ice.[3].

Figure 2 also points out that an integral part of the icing analysis methodology under development is the aerodynamic analysis of both individual components and even complete aircraft configurations. Since these codes have historically been developed for analysis of aerodynamic performance in nonicing environments, their use to study icing problems will require that significant modifications and improvements be made. Obviously, the more robust and accurate these codes are, the more robust and accurate the icing analysis methodology will be.

The development of an aircraft icing analysis methodology requires that a large number of supporting benchmark (modeling) and verification experiments be run. The experiments require a wide range of ground and flight test facilities. Laboratory tests are required to do some of the most fundamental experiments while icing wind tunnel tests are needed to acquire data such as ice accretion, aero performance, and ice protection system performance for selected components. Dry wind tunnel tests are needed to look at the detailed flowfield characteristics about airfoils with artificial leading edge ice accretions. Flight tests are required, both in simulated and natural icing environments, to determine overall aircraft performance and handling qualities changes.

The following sections of the paper will discuss in detail the particular icing codes being developed as indicated in Figure 2.

Discussion of Icing Computer Codes

Water Droplet Trajectory Analysis

A knowledge of the water droplet trajectories about any component provides the first indication of that component's sensitivity to icing. NASA is sponsoring the development of a family of droplet trajectory codes which can handle a wide variety of geometries, from simple two-dimensional airfoils to complete aircraft configurations. Table 1 summarizes the various trajectory codes being developed and the geometries which can be handled. As the table suggests, the codes use various flowfield analysis methods. Two different techniques are used to pass flowfield information to the trajectory routine. The direct solution approach solves for the flowfield at each point along each trajectory and the grid generation approach calculates the velocity at the point of interest by interpolating on the two or three dimensional grid generated by the flowfield solver.

There are advantages and disadvantages to both approaches. The direct solution approach can be more expensive computationally, especially as the number of trajectories computed increases. However, this approach frees the user from having to worry about generating a grid which adequately resolves the flowfield acceleration near the body surface. In addition, the direct solution approaches tend to have more difficulty computing the flowfield around a body such as an airfoil which has a leading edge ice accretion. Such calculations are required as part of an ice accretion analysis as will be discussed later. The grid generation approach can handle airfoils with leading edge ice accretions, but the development of an acceptable grid requires care and skill on the part of the analyst.

All the trajectory codes indicated in Table 1 use a predictor-corrector approach to integrate the droplet equations of motion. Different droplet drag coefficient expressions are used by the various codes, but these differences are judged to not have a significant effect on the calculation of droplet trajectories.

Historically, water droplet trajectory codes have been evaluated by comparisons with available airfoil collection efficiency data obtained experimentally by NACA.[9] In general, the codes appear to be in reasonably good agreement with the experimental results which may themselves be subject to some appreciable errors. However, this database is limited in scope and in particular, is confined to low speed studies of airfoil sections of interest to the aviation community in the 1940 to 1955 time period. Also, no experimental data had been available for inlet configurations of interest.

An experimental program has been initiated to acquire a comprehensive collection efficiency database for a wide variety of modern airfoil and inlet geomerties which are of interest to the aviation community. The experimental approach, a variation on the dye tracer technique developed by NACA, is discussed in Reference 10.

The major difference from the NACA technique is that a laser reflectance technique is used to determine the local collection efficiency distribution curves from the blotter paper strips which have been placed at various locations on the test model. The NACA approach was to dissolve out the dye from small samples of the blotter paper strips and then perform a colorimetric analysis of each resultant water-dye mixture. Figure 3 shows a close-up photo of a quarter scale Boeing 737-300 inlet model in the NASA Icing Research Tunnel (IRT) with a series of blotter strips attached at various circumferential locations. The laser set-up used to determine the collection efficiency distribution is shown in Figure 4. A Helium-Neon laser is used to provide the coherent light source. The amount of light reflected from the blotter can be related to the local amount of dye on the blotter. The dye was dissolved in the spray water prior to being feed through the spray nozzles. This dye concentration is directly related to local collection efficiency. This automated data reduction procedure allows a much larger quantity of data to be reduced relative to the labor intensive method which had to be employed by NACA researchers.

Figure 5 shows measured collection efficiency data for the NACA 65_2-015 airfoil for two angles of attack (0° and 8°). Also shown are predicted collection efficiency curves. The results are in close agreement for the 0° angle-of-attack case while some differences are noted for the 8° case.

Initially, drop impingement tests will be conducted in the NASA Icing Research Tunnel (IRT) using large number of airfoil and inlet models. Once these tests are completed, follow-on tests will be conducted in a high speed icing wind tunnel to quantify the effects of flowfield compressibility on droplet trajectories. Previous analytical studies conducted jointly by NASA and the British RAE[11] have indicated that compressibility becomes important only for the smallest dropsizes. However, this analytical result must be verified experimentally.

Some current applications of the trajectory analysis codes will be mentioned. Figure 6 shows selected results of three-dimensional trajectory analysis[8] for the nose region of the NASA icing research aircraft, a deHavilland Twin Otter. The purpose of this study was to look at the effects of the flowfield on droplet trajectories and therefore, on the measurements of icing cloud liquid water content as measured by various instruments located on the aircraft. The results are shown in the form of concentration factor as a function of droplet diameter. Concentration factor indicates the number of droplets per unit volume at the measurement station ratioed to the number of droplets of that size per unit volume in the free stream cloud. As the figure indicates, for the selected location, the instrument sees more water droplets per unit volume than actually exist in the cloud especially, for a range of droplet sizes between about 20 and 200 μm and thus would indicate a liquid water content somewhat higher than the freestream value. This analysis is being used to help in interpreting icing cloud data currently being acquired and to assist in future placement of instruments.

An indepth study of airfoil collection efficiency characteristics has been investigated using the two-dimensional trajectory code of Reference 4. Some 30 different airfoil geometries were analyzed for a wide variety of velocity and angle-of-attack conditions for a range of water droplet sizes. The results were used to form a computational database to investigate the effects of airfoil design parameters such as leading edge radius, camber, and maximum thickness on collection efficiency.[12] In addition, correlation expressions have been developed to allow quick estimates to be made of airfoil collection efficiency characteristics for geometries other than those analyzed.

The three-dimensional trajectory analysis code discussed in References 6 and 7 is being applied to inlet configurations which have flowfields which are highly three-dimensional in nature. The initial results[13] are highly encouraging and indicate complex inlet geometries can be analyzed for icing sensitivity.

Airfoil Ice Accretion

The NASA airfoil ice accretion analysis code which is called LEWICE is an extension of the work of Lozowski et al.[14] and Ackley and Templeton.[15] The LEWICE code predicts the ice growth rate distribution (and thus ice shape) around the leading edge of the airfoil by locally solving the quasi-steady energy balance equation first proposed by Messinger.[16] The energy balance accounts for the governing heat and mass transfer processes thought to occur during the icing process. These terms include convection to the free stream, latent heat release due to freezing, sublimation (or evaporation), and aerodynamic heating. A more detailed discussion of the LEWICE code is given in Reference 17.

The four major elements of the LEWICE code are (1) a potential flow panel code to calculate the airfoil flowfield, (2) a two-dimensional water droplet trajectory code,[5] (3) an energy balance routine, and (4) integral boundary layer routine to predict heat transfer distributions. The LEWICE code is constructed so that the flowfield and droplet trajectory calculations are repeated at user specified time intervals as the ice accretion grows on the airfoil leading edge. This updating process attempts to account for the effect of the leading edge ice accretion on the airfoil flowfield and thus, on the changes in airfoil collection efficiency characteristics.

The current capabilities of the LEWICE code are summarized in Figure 7 where ice accretion shapes measured on a NACA0012 airfoil in the IRT are compared with LEWICE predictions. Two sets of comparisons are shown for 5 min rime and glaze ice accretions. For each calculation, the flowfield and droplet trajectory analyses were updated every 1 min. The agreement is judged to be good for the rime ice case, but the LEWICE code over predicts the glaze ice accretion, although the general shape appears to be good.

The integral boundary layer code has a simple treatment of the effects of surface roughness on boundary layer transition and heat transfer levels. However, this model is formulated in terms of equivalent sand grain roughness and the relationship to actual ice surface roughness is still a research topic, so currently, "educated guesses" must be input to the model. Other models for wall roughness currently are being considered for incorporation in the LEWICE code.

Recent high-speed photo-micrographic movies of the icing process[18] have suggested that some of the fundamental assumptions made in the ice accretion model may be in error. Efforts will shortly begin to formulate either changes to the existing model or an alternate model in order to see if ice shape predictions can be improved.

Other research begun recently in order to support the ice accretion modeling efforts include the measurement of convective heat transfer coefficients from a smooth and rough surface airfoil both in low and high turbulence environments and application of a Navier-Stokes solver to predicting heat transfer coefficient distributions around bodies with ice accretions.

Aerodynamic Performance Degradation Analysis

Accurate predictions of aerodynamic performance degradation of an aircraft due to icing is one of the desired end products of the icing analysis methodology. Currently, the development and verification of computer codes to predict airfoil performance degradation in icing is the primary research effort, but some more empirically based approaches are being developed for predicting degradations of propellers, helicopter rotors, and complete aircraft. The analysis for the airfoil will provide the basis for developing more exact analyses for components such as wings, tails, propellers, rotors, and eventually for complete aircraft configurations.

Currently, two advanced analysis codes are being evaluated for use in predicting iced airfoil performance - a Navier-Stokes solver and an interactive boundary layer code. Code predictions are being compared to data being gathered in the IRT and in the Ohio State University 0.9 by 1.5 m low-speed wind tunnel. These codes were chosen since they have both demonstrated the ability to treat flows which have regions of separation-reattachment, a phenomenon which often occurs with ice shapes. Previously, more conventional airfoil analysis codes were considered, but the codes all were incapable of handling the iced airfoil problem without major revisions being incorporated. A summary of these investigations is given in Reference 2.

The Navier-Stokes code being evaluated is the ARC2D code developed the at NASA Ames Research Center.[19] The code has been used to analyze the flowfields about a large number of airfoil geometries including airfoils with extended spoilers which create a large separated zone. The code can be run in either of two modes - the full Navier-Stokes mode or the so-called thin layer Navier-Stokes mode which removes the viscous terms in the axial direction. To date, most calculations have been done with the thin layer Navier-Stokes mode, although, limited comparisons of the predictions made with both modes failed to reveal any significant differences. The ARC2D code uses the Baldwin-Lomax turbulence model, and the so-called GRAPE grid generation code developed by Sorenson, also of NASA Ames.[20]

Initial ARC2D calculations were made for a NACA63$_2$-A415 airfoil with a simulated leading edge glaze ice shape.[21] The ARC2D results are compared in figure 8 to measurements made in the IRT with a general aviation wing section with a NACA63$_2$-A415 airfoil section with a wooden leading ice shape affixed. The predicted results (assuming no laminar boundary layer growth) are judged to be in good agreement with the IRT data with the exception of the over prediction of C_l. Similar over predictions of C_l with ARC2D have been found by other researchers for clean airfoil configurations.[22] The agreement in drag polars is thought to be exceptionally good. The velocity vector plot shown in the figure indicates that the ARC2D code predicted sizable zones of separated flow on both upper and lower surfaces, but reattachment was aslo predicted for both surfaces.

While these initial results suggested that the ARC2D code could predict the performance of airfoils with leading edge ice shapes, the data acquired in the IRT was judged to be not detailed enough to serve as a validation/verification data base. It was determined that such a database should include, in addition to the airfoil performance data (C_l, C_d, C_m), much more detailed surface pressure distributions, velocity and turbulence profiles, especially, in the separation-reattachment zones, and flow visualization data. In order to acquire this database, an extensive experimental program was initiated in the Ohio State University low speed wind tunnel. Two summary papers of that effort are given in References 23 to 24.

The airfoil geometry chosen for the program was a 0.53 m (21 in.) chord NACA0012 airfoil. A removable leading edge was fabricated which had an ice shape which approximated an ice accretion measured in the IRT. The ice shape and its relation to the IRT ice shape are shown in Figure 9. The ice shape geometry can be described by a constant radius section, two rounded edges of specified radius, and two straight line sections. Thus, an exact specification could be used to input the geometry into any flowfield analysis code. The wind tunnel model was instrumented with a surface static pressure every 1 percent chord in the leading edge region. This large number of pressures gave excellent definition of the separation-reattachment zones on the surfaces.

Figure 10 presents the ARC2D predictions compared to the OSU data. Again, the agreement is judged to be quite good for the lower angles-of-attack. However, it was observed that the ARC2D code did not converge to a steady state solution for angles of attack greater than about 6°. Currently, flow visualization experiments are being conducted to determine if this is purely a computational result, or if the experimental flowfield is not steady at these higher angles-of-attack.

To date, velocity and axial turbulence intensity profiles have been measured every 2 percent chord for the upper surface separation-reattachment zone. Figure 11 shows two selected profile comparisons - one just downstream of the measured point of separation and the other just upstream of the experimental reattachment point. The ARC2D predictions are in reasonable agreement with the data; however, the predicted reattachment occurred more upstream than was observed in the experiment. Investigations are underway to improve the code predictions. Areas of investigation include the sensitivity to ice shape definition and grid generation as well as to the turbulence model employed.

A similar evaluation of the capabilities of the interactive boundary layer code was begun more recently. This code was developed by Cebeci and associates under grant to the National Science Foundation[25] to predict clean airfoil behavior including the higher angles-of-attack and the onset of stall. The code has two major modules - a potential flow panel routine to calculate the inviscid region and an inverse finite difference boundary layer routine which is capable of treating regions of separation-reattachment. The two routines are coupled together to solve further airfoil flowfield by iterating back and forth until a converged solution is acquired.

Initial studies have been completed for lower angle-of-attack results for the "iced" NACA0012 airfoil already discussed with comparisons made of airfoil performance (i.e., C_l, C_d). The predictions were in very close agreement with the experimental data. Some oscillations in the final solutions obtained suggested some additional improvements are required in the numerics. These improvements are currently being made and the more detailed velocity profile comparisons are also being made. Also, comparisons are being made for the higher angle-of-attack conditions.

Currently, it is judged that both the Navier-Stokes and interactive boundary layer methods show great promise for being able to predict iced airfoil performance. It is felt that the two methods are more complementary than competitive as both can be used for icing analysis. The Navier-Stokes approach, while computationally more expensive (approximately 10 to 20 min per solution on the Cray XMP) is thought to be capable of treating larger, more extreme ice shapes. Navier-Stokes results, possibly, can be used to help in the more approximate modeling in the interactive boundary layer code. The interactive boundary layer code is much faster (approximately 4 to 30 sec per solution on the Cray XMP) and would be very attractive for those problems which require many aero performance calculations to be made (e.g. the helicopter rotor in forward flight).

Besides those areas of improvements currently being investigated for both codes which have been discussed, each will require a model to be developed to handle the extreme levels of surface roughness which exist for any ice shape. At present, neither code can handle anything other than smooth surfaces. Several approaches for treating surface roughness are being evaluated. Regardless of the model employed, some means must be found for quantifying the nature of the ice shape roughness. Currently, the equivalent sand grain approach is employed to treat rough surfaces, but it is not clear that that approach would work for ice accretion roughness.

As already indicated, more approximate methods have been developed for predicting the aero performance degradation of propellers, helicopter rotors (hover and forward flight), and complete aircraft. References 26 to 30 review these efforts. These various efforts all use the same approach - a set of correlation equations is used to predict airfoil performance degradation due to icing and, then an appropriate performance code is used to determine the total component or aircraft performance degradation.

The correlation equations are relations developed from an airfoil icing data base which relate the change in lift, drag, and pitching moment to known aerodynamic and icing variables. The first such correlations were developed by Gray of NACA.[31] More recently, Bragg developed a rime ice correlation.[4] Both of these correlations used data gathered in the NASA IRT. Flemming,[29] acquired a large data base in the Canadian NRC high speed icing wind tunnel for a series of reduced scale rotor airfoil sections which he used to develop a series of correlation equations.

Unfortunately, it is not possible to a priori select one set of correlation equations with assurance that the predictions will yield accurate results. Studies made with the above mentioned sets of correlations have determined that the errors can be as large as 100 to 200 percent for selected conditions. Some of this error is undoubtedly due to the rather limited airfoil icing data base which exists. Also, questions can be asked about how the icing results from one facility can relate to those from another facility which were calibrated using different techniques. Thus, extreme care must be exercized when using these correlations. Miller[28] gives an excellent discussion of typical effects of using the different correlation equations to predict propeller performance.

In spite of the above concerns, some reasonable results have been acquired. Figure 12 shows propeller performance predicted in rime icing conditions when compared to natural icing data gathered by NACA researchers. The propeller efficiency variation as a function of advance ratio measured in flight icing conditions was closely duplicated by the analytical methodology for this particular set of tests. As Reference 26 indicates, the agreement was not as good for some of the other rime icing encounters.

Korkan, et al., used a similar analytical approach to analyze the helicopter rotor, first in hover[26] and then in forward flight.[27] The particular rotor configuration analyzed was the front rotor of the Boeing Chinook CH47. Unfortunately, no experimental data existed for comparison with the predictions. All that could be said was the results were reasonable when compared with previously reported torque rises measured in icing for other heliocpter configurations.

Flemming used the previously discussed airfoil performance in-icing correlations along with appropriate rotor performance codes to predict rotor degradation for the S-76, UH1H, and UH-60A helicopters. The predicted results compared to available experimental data are shown in Figure 13. Generally the agreement was better for the hover comparisons than for the forward flight. As Figure 13 indicates, the forward flight predictions were generally lower than the experimental measurements. At present, it is not known why this is true, although, as Flemming points out,[29] it is not clear how accurate are the experimental measurements. These results point out the need for dedicated icing flight programs for acquiring high quality verification data.

Figure 14 shows selected results from the prediction of overall aircraft performance degradation in icing using the NASA code[30] compared to data gathered as part of the NASA icing research flight program[32] using the Twin Otter. The airfoil correlation developed by Bragg[4] was used to determine airfoil performance degradation. Even though this correlation was developed to handle rime icing conditions, the figure indicates it appeared to provide reasonable inputs for the mixed icing conditions of the icing flight shown. The code, as currently configured, can predict aero performance degradations only for lifting components (e.g. wings, tails, struts). The contributions of other components such as wheels, flap hinges, antennas, etc., must be estimated and input. For the predictions shown in Figure 14, this contribution was estimated by forcing the code to agree with the drag increase measured for the completely iced aircraft for the lowest lift coefficient data point (filled symbol in the figure). This amount of drag increase was not varied but kept constant for all the other code predictions. Note the reasonable agreement between theory and experiment not only for the fully iced, but also for the wing and wing plus tail deiced data. Additional comparisons of the code predictions using the various airfoil correlations available with additional natural icing flight data are planned. Also, simple methods for estimating the drag increase due to nonlifting components are being considered.

Ice Protection Systems

NASA has sponsored the development of a series of computer codes which model the electrothermal deicer, a system currently being used for many helicopter rotor and fixed wing aircraft applications. Table 2 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. Codes 2 through 6 use the weak enthalpy method[34-37] while code 1 uses an approximate method.[33]

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 various levels of modeling complexity.

Figure 15 shows the test model used in a recent IRT test. The model was a section of a Bell Helicopter Textron UH1H rotor (0.53 m (21 in. chord)) with a spanwise electrothermal deicer configuration installed. The deicer, provided by the BF Goodrich Company, is typical of a flight design. The model was instrumented with a large number of thermocouples to measure the transient temperature response at various locations in the model. The test model was run over a wide variety of dry, wet (above freezing), and icing conditions, and a large data base was acquired. Reference 36 gives a description of the test program.

Figure 16, taken from Reference 38, shows one selected result of the comparison of code 2 predictions with experimental measurements. As the figure shows, thermocouples were located at (1) the abrasion shield surface, (2) the heater, and (3) the internal spar of the model. For this comparison, the model predictions were judged to be in close agreement with the experimental data for all three cycles of electrothermal deicer operation. The model predicted a melting of the ice for the second and third heater cycles, and the experimental results showed the same occurrence. While the agreement was not as good for all cases as the one shown here, the one-dimensional code predictions were found to be generally in good agreement with the data. Currently, efforts are underway to make similar comparisons with the other codes to see if the increased complexity in the numerical modeling can give better agreement with the experimental results.

Ice shedding is a key aspect of electrothermal deicer performance. The one-dimensional model of Reference 34 attempts to model this phenomenon by assuming that shedding occurs when the thickness of melted ice reaches a user specified amount. A better treatment of shedding may be required.

Another ice protection system, the fluid freezing point depressant system, has been modeled. A simple engineering procedure for predicting the minimum anti-icing flowrates required has been developed.[39] The code predictions compared with flowrates measured in the IRT for a full-scale general aviation wing section model equipped with this system are shown in Figure 17. In general, the method is judged to give reasonable agreement with the experimental data. As Reference 39 points out, some of the error can be attributed to the experimental values measured for minimum anti-icing flowrates. This determination based on visual observations was found to sometimes vary significantly for repeat test conditions and was also sensitive to the interpretations of different observers as to when the minimum flow rate was achieved. Given these inherent uncertainties in the experimental approach, the predictive method is felt to be acceptably accurate.

The third ice protection system being modeled is the electromagnetic impulse deicer (EIDI). EIDI is a concept which is receiving much attention, both in the United States and Europe. It shows great promise for being a low power consumption, highly efficient deicing system. NASA has sponsored an intensive research effort, the results of which are summarized in Reference 40, to acquire an experimental data base to aid in the design of the system for various aircraft applications.

Work is also underway to develop the required structural and electrodynamic codes to model the key features of the EIDI system. The current status of the structural dynamic modeling capabilities is discussed in Reference 41. The simple configuration which is being modeled is shown in Figure 18. The half cylinder is meant to model a wing leading edge and has a single 2.54 cm radius coil located 18 cm (0.07 in.) beneath the surface. Finite element model predictions for surface acceleration at two locations and the circumferential and longitudinal strains at the coil location are shown in the figure. Agreement in all cases is judged to be at least reasonable and surprisingly good in some instances (e.g. peak circumferential strain).

A key input into the structural dynamic analysis is the force produced by the coil. Both ther temporal and spatial characteristics of this force must be known. Until recently, no analytical solutions had been obtained for this force function, and thus experimental data had to be used. The results shown in Figure 18 were acquired using a simple force model. However, recently, a transmission line model obtained from the governing field theory equations has been achieved which appears to yield good predictions of the force for the case of a coil with its axis perpendicular to a flat plate.(42) Figure 19 shows a comparison of the force versus time predicted by this transmission line model with the force versus time calculated from the measured induction fields for a 3.08 cm (2 in.) diameter 0.478 cm (0.188 in.) thick coil rigidly mounted next to a fixed 0.0813 cm (0.032 in.) thick 2024 T3 Aluminum disc with a 12.7 cm (5 in.) diameter. It is hoped that the use of this force model will improve theoretical predictions such as those shown in Figure 18.

While the modeling of the EIDI system shows great promise, the effort is still in its infancy. A better understanding of the ice adhesion properties and removal mechanisms must be gained before a complete modeling of the system can be attempted. Also, the EIDI system modeling for most applications will probably require three-dimensional structural analysis codes.

As already indicated, NASA has sponsored efforts to measure some of the key physical properties of ice(3) which are required as inputs into any surface deflection type ice protection system model. The results are being used along with a finite element analysis approach to begin a quasi steady modeling of a generic pneumatic boot ice protection system. Companion experiments are being planned to measure the ice fracture process of the generic boot configuration for comparison with modeling predictions.

Concluding Remarks

This paper has presented a current status review of the progress being made toward developing and validating the computer codes required to assemble an aircraft icing analysis methodology. While it is felt that much progress has been made since the initial review presented in Reference 2, much work remains to be done. While many of the codes which are needed to form a core capability have been developed, many validation/verification experiments are still required. This is especially difficult (and expensive) when it comes to determining the performance in icing of complex configurations such as helicopter rotors and complete aircraft configurations. Analysis of the steady state and dynamic behavior of those complex configurations in icing may require significant levels of empiricism to be incorporated in the modeling.

Nevertheless, it is felt that once developed and validated, this icing analysis capability will be of great benefit to the industry in reducing the fixed and rotary wing development and certification costs for future aircraft configurations which are required to safely fly into forecast icing conditions.

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TABLE 1. - DROPLET TRAJECTORY ANALYSIS CODE CHARACTERISTICS

Geometries	Flowfield analysis code used	Comments	Reference
1. Single Element Airfoils	Theodorsen Transformation	Incompressible Flowfield, Direct Solution	4
2. Single Element Airfoils	Navier-Stokes	Compressible Flowfield, Grid Generation	5
3. Multiple Element Airfoils	Panel Method	Incompressible Flowfield, Direct Solution	5
4. 2D, Axisymmetric Inlets	Panel Method	Incompressible Flowfield, Direct Solution, 2D Trajectories	5
5. 3D Inlets	Transonic, Full Potential	Compressible Flowfield Grid Generation	6
6. Complex Configurations (incl. Complete Aircraft)	Panel Method	Incompressible Flowfield, Direct Solution	7,8

TABLE 2. - ELECTROTHERMAL DEICER CODES

Geometry	Ice thickness	Number of heaters	Phase change	Reference
1. One Diménsional	Constant	One	Approximate	33
2. One Dimensional	Constant	One	Weak Enthalpy	34
3. Two Dimensional (Rectilinear)	Constant	One	Weak Enthalpy	35
4. Two Dimensional (Rectilinear)	Constant	Variable	Weak Enthalpy	
5. Two Dimensional (Rectilinear)	Variable	One	Weak Enthalpy	37
6. Two Dimensional (Exact)	Variable	Multiple	Weak Enthalpy	36

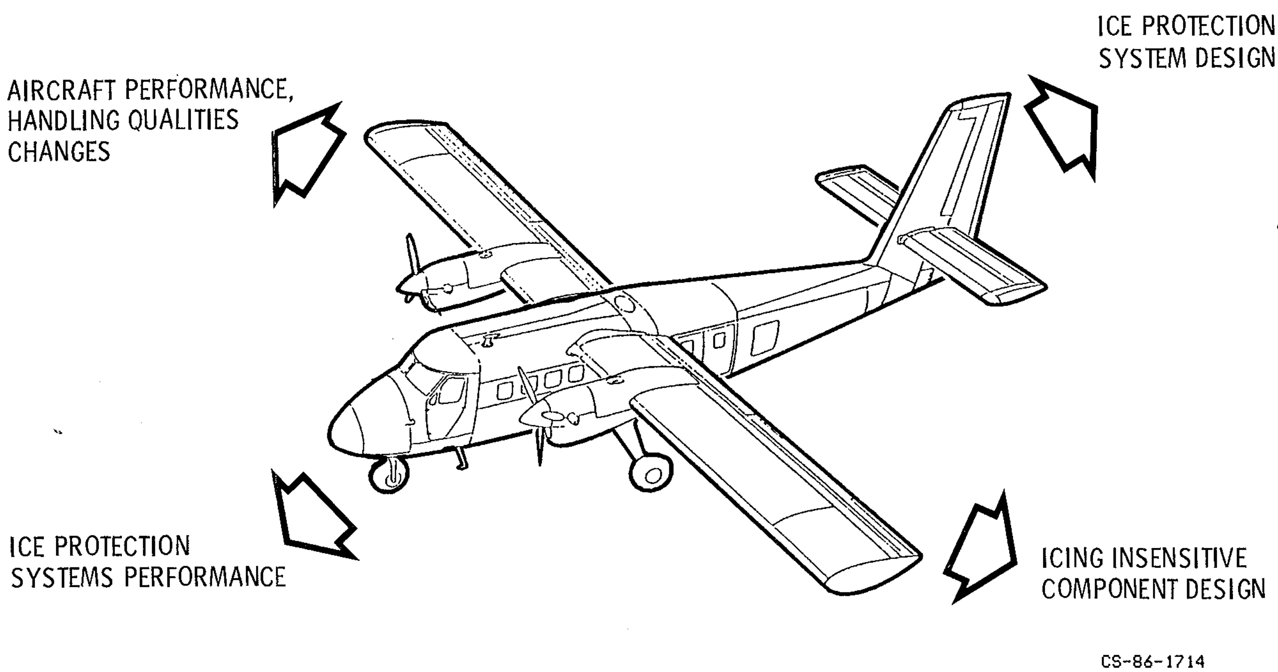

Figure 1. - Uses of aircraft icing analysis.

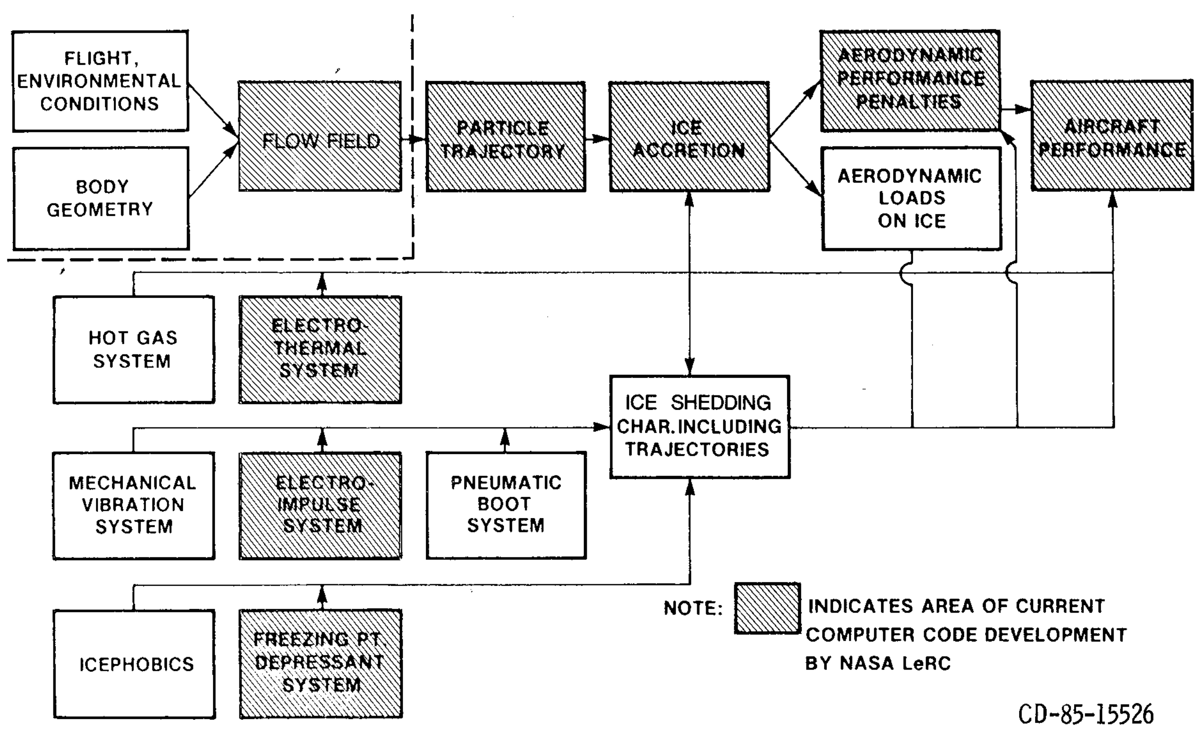

Figure 2. - Aircraft icing analysis methodology.

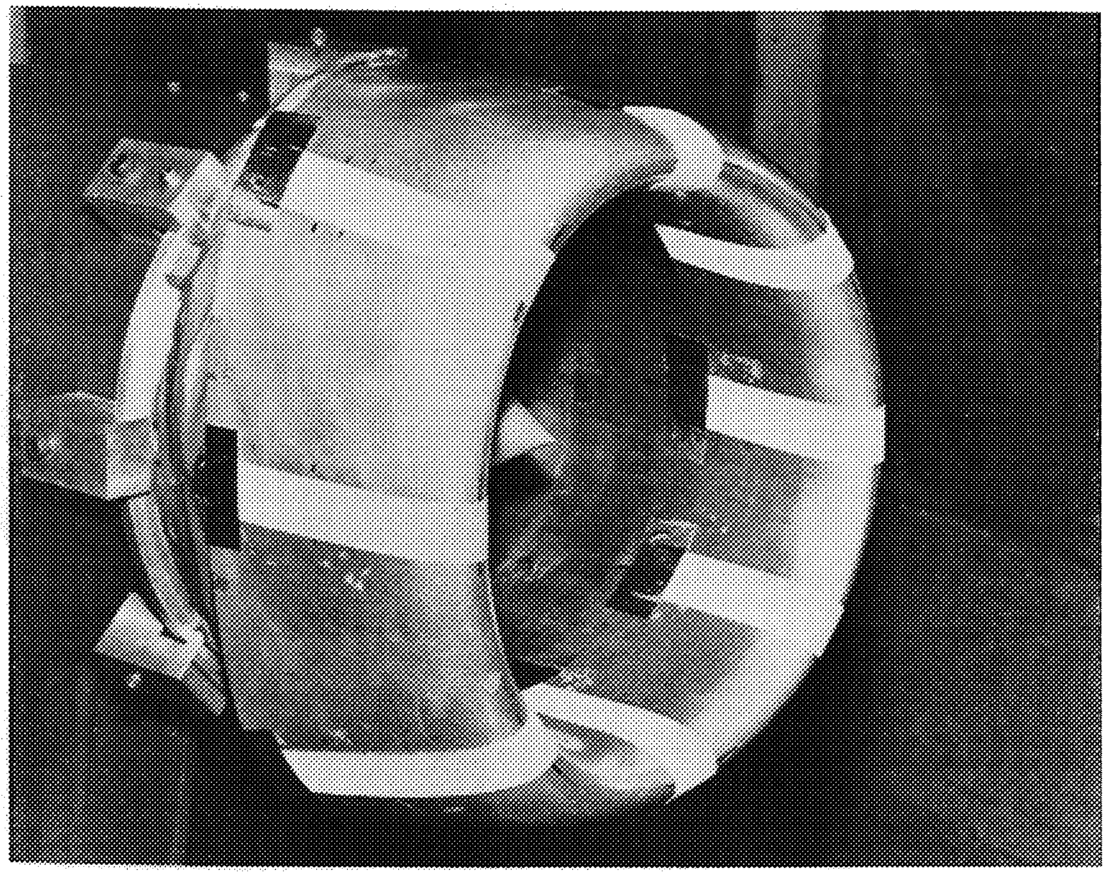

Figure 3. - Boeing 737-300 inlet in Icing Research Tunnel with blotter strips attached.

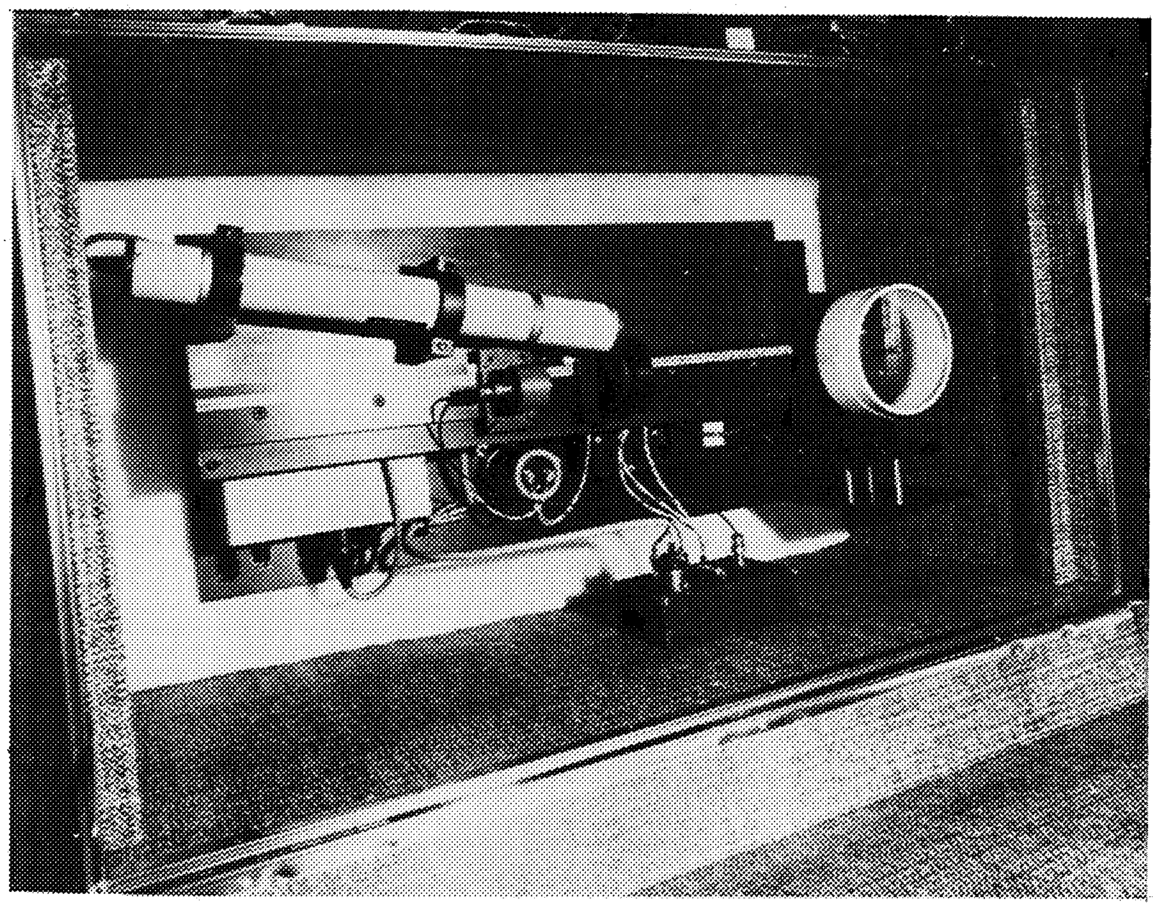

Figure 4. - He-Ne laser system to reduce drop impingement blotter samples.

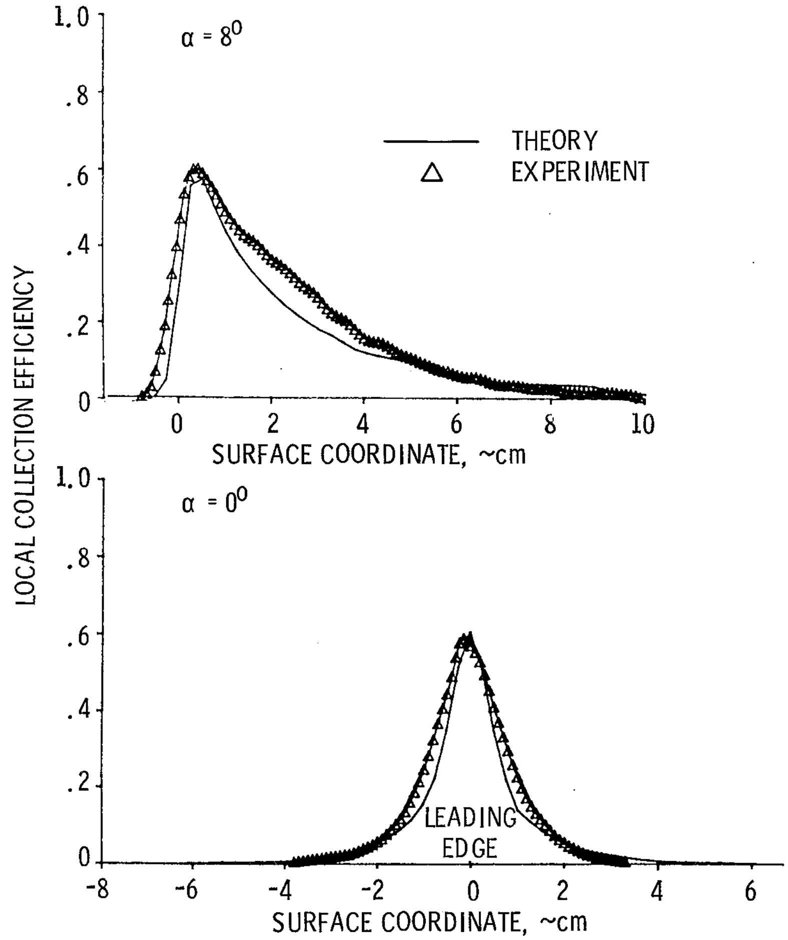

Figure 5. - Preliminary collection efficiency results for NACA 65_2-015 airfoil. V_∞ = 82 m/sec; MVD = 15 μm.

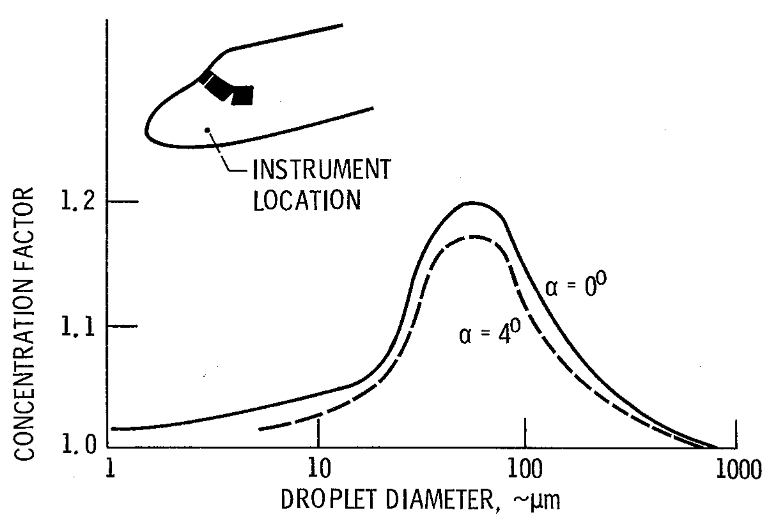

Figure 6. - Concentration factor calculations for NASA icing research aircraft, V_∞ = 67 m/sec.

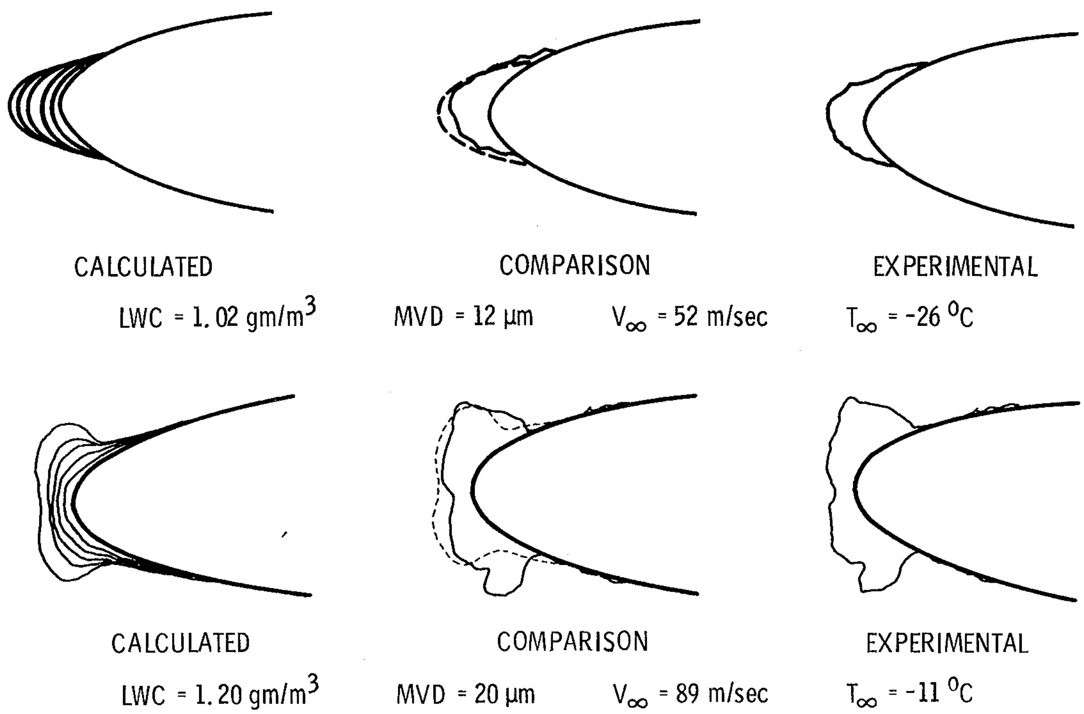

Figure 7. - LEWICE predictions of airfoil ice accretions compared to IRT data. NACA 0012, 0.53 m chord, 5 minute ice accretion, 0^0 angle of attack.

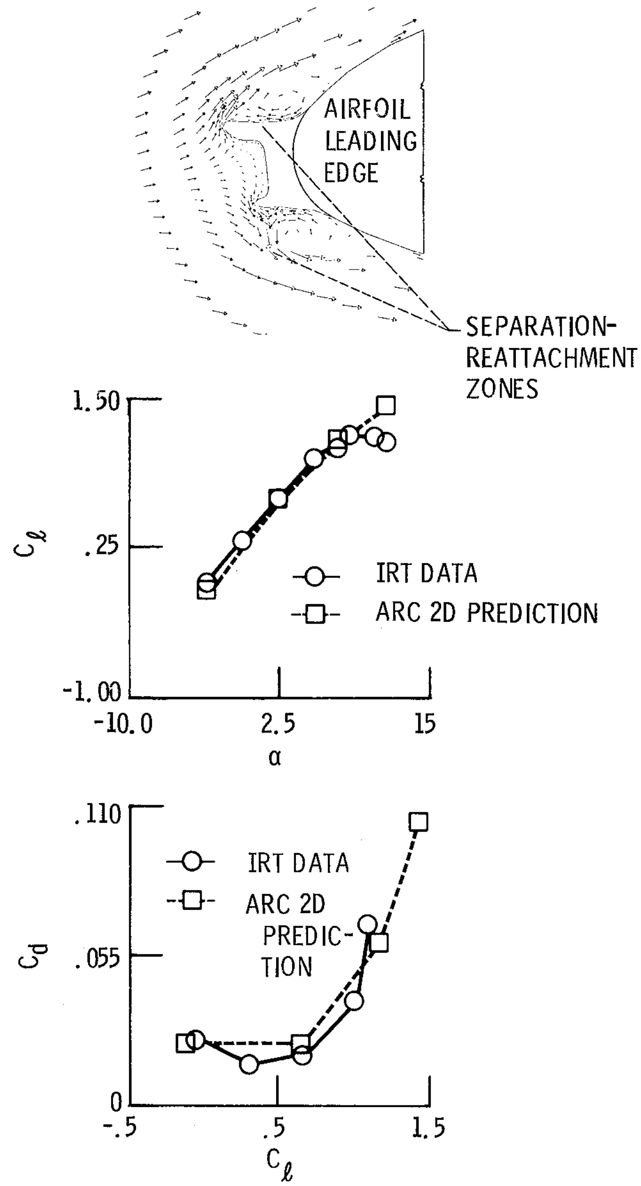

Figure 8. - Navier-Stokes analysis of NACA 63_2-A415 airfoil with glaze ice (ref. 21).

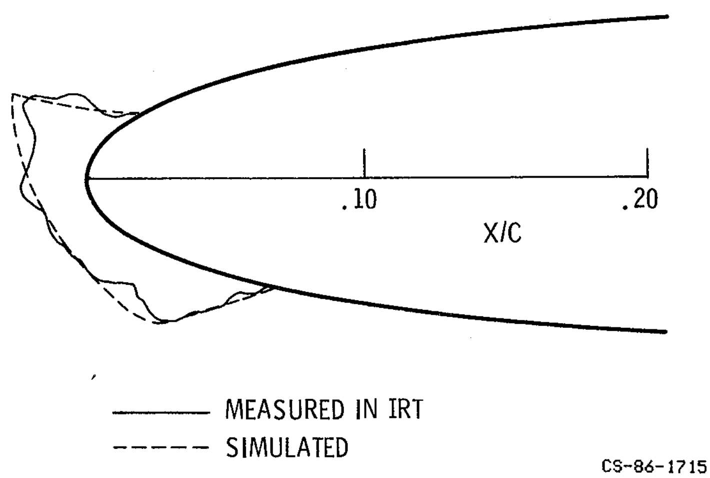

Figure 9. - Comparison of measured and simulated ice shapes NACA 0012 airfoil, 0.53 m (21 in.) chord.

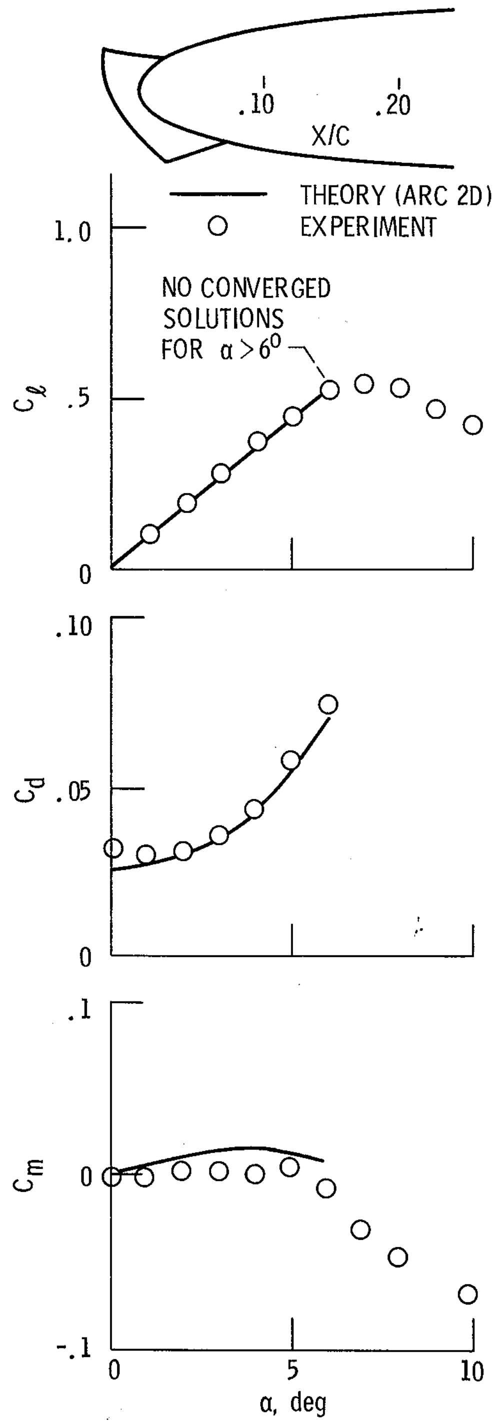

Figure 10. - Comparison of measured and predicted airfoil performance for NACA 0012 airfoil with artificial ice shape.

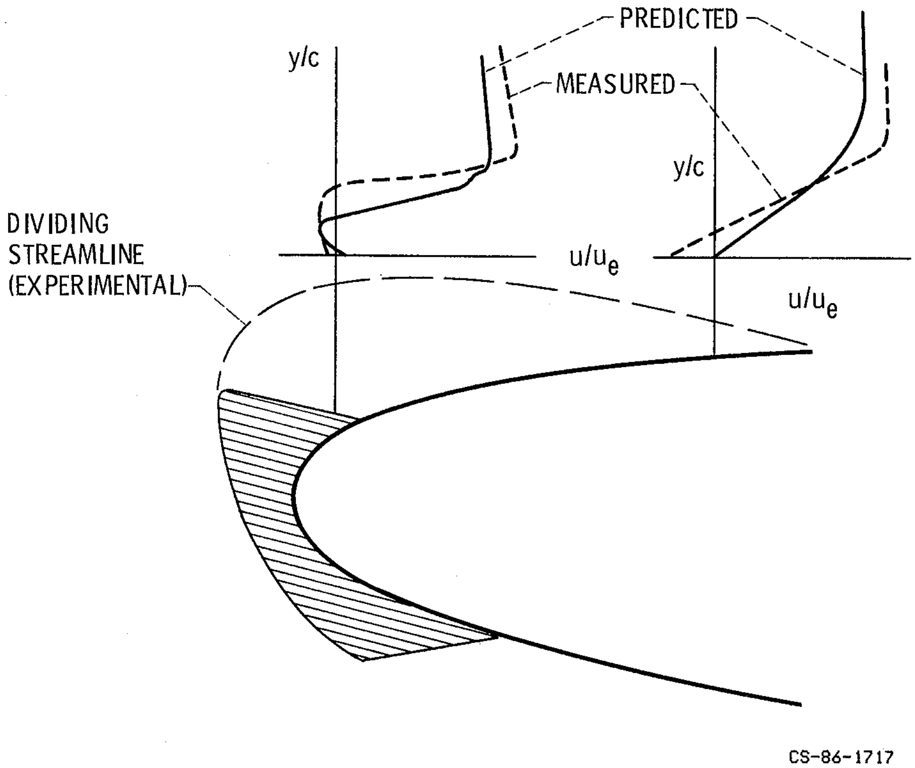

Figure 11. - Comparison of measured and predicted velocity profiles using ARC 2D code.

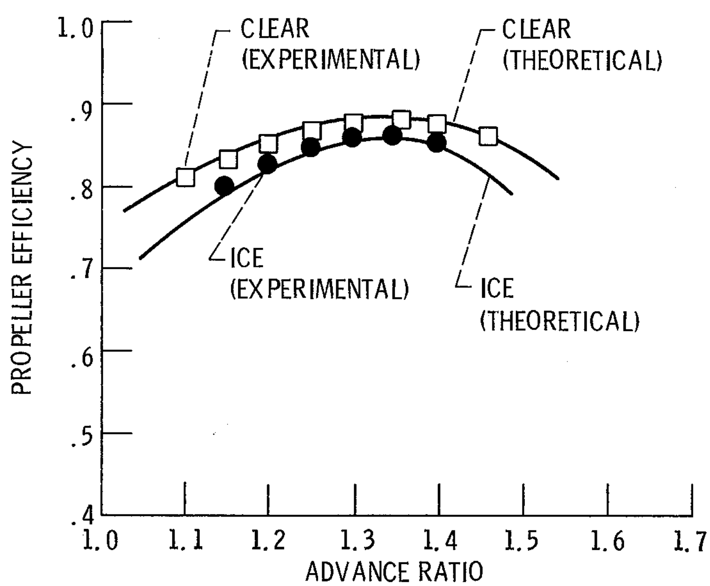

Figure 12. - Comparison of measured and predicted propeller performance in rime icing conditions (ref. 26).

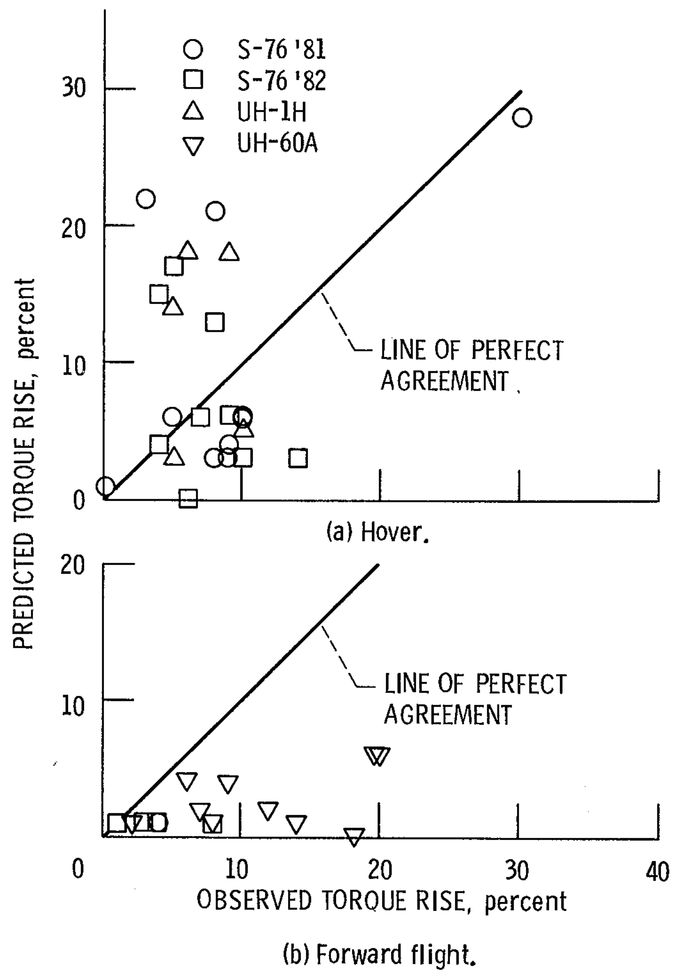

Figure 13. - Comparisons of measured and predicted helicopter performance in natural icing (ref. 29).

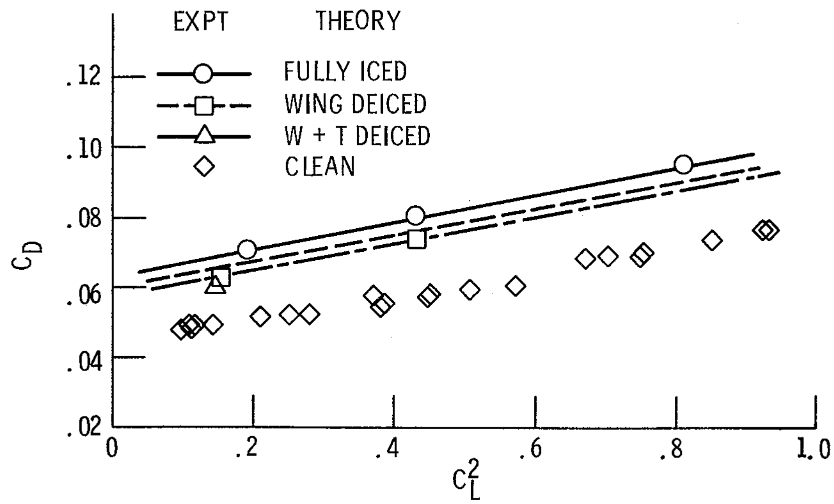

Figure 14. - Comparison of predicted and measured aircraft performance in natural icing conditions (ref. 30).

ELECTROTHERMAL DE-ICER EXPERIMENT IN IRT

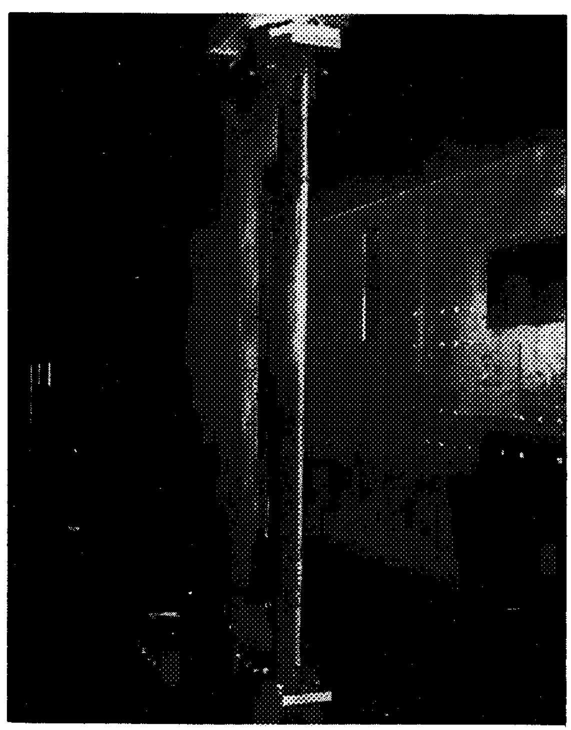

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Figure 15. - Electrothermal de-icer experiment in IRT.

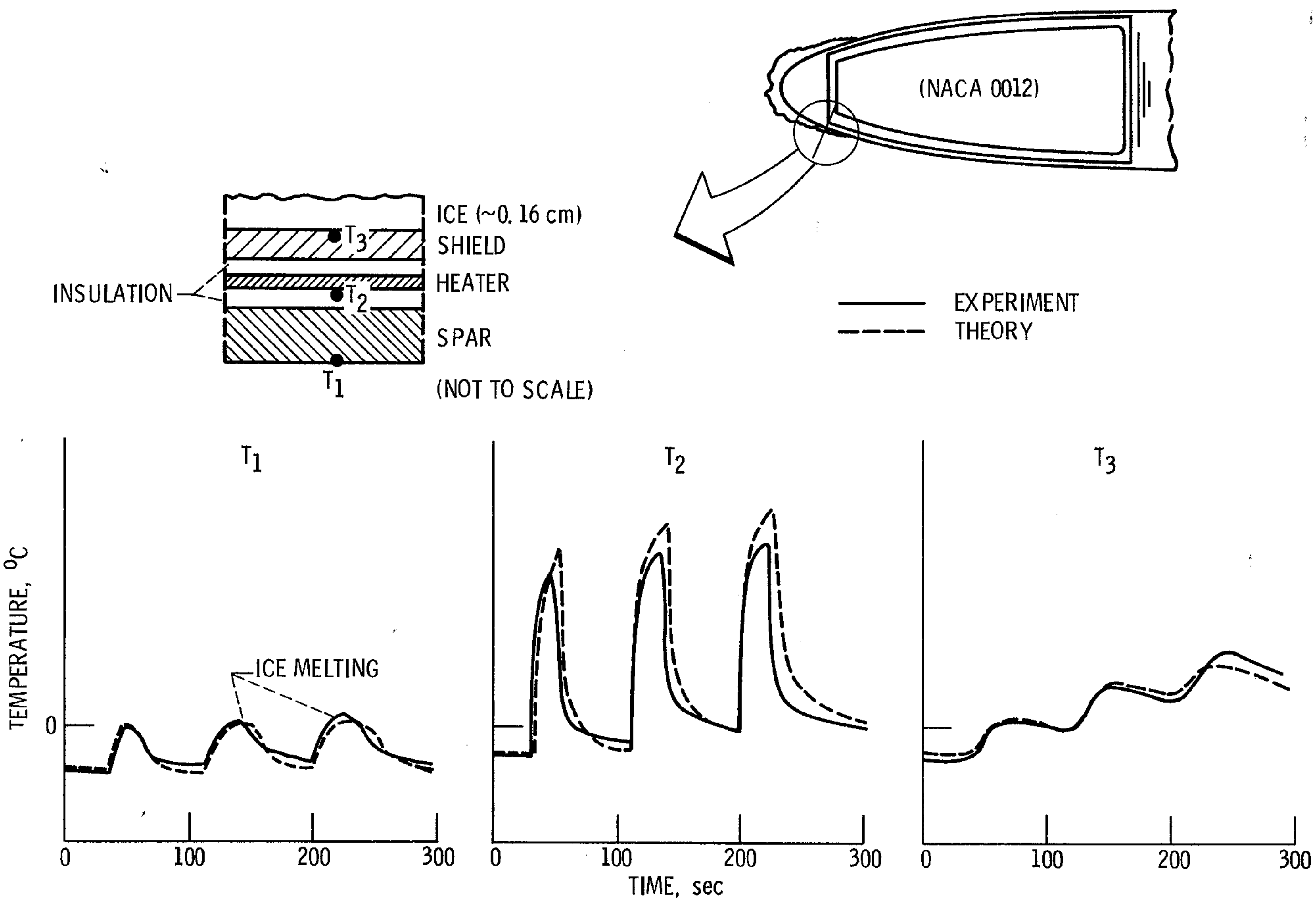

Figure 16. - Comparison of transient temperature profiles measured in IRT with predictions of one dimensional, transient heat conduction code (ref. 38).

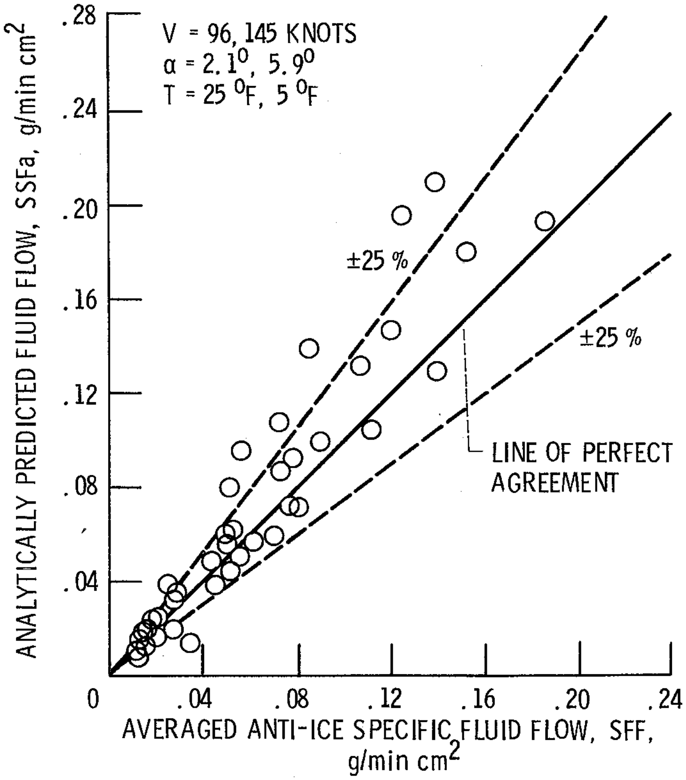

Figure 17. - Comparison of predicted and measured minimum anti-icing flow rates for NACA 2412 (mod) airfoil with fluid freezing point ice protection system (ref. 39).

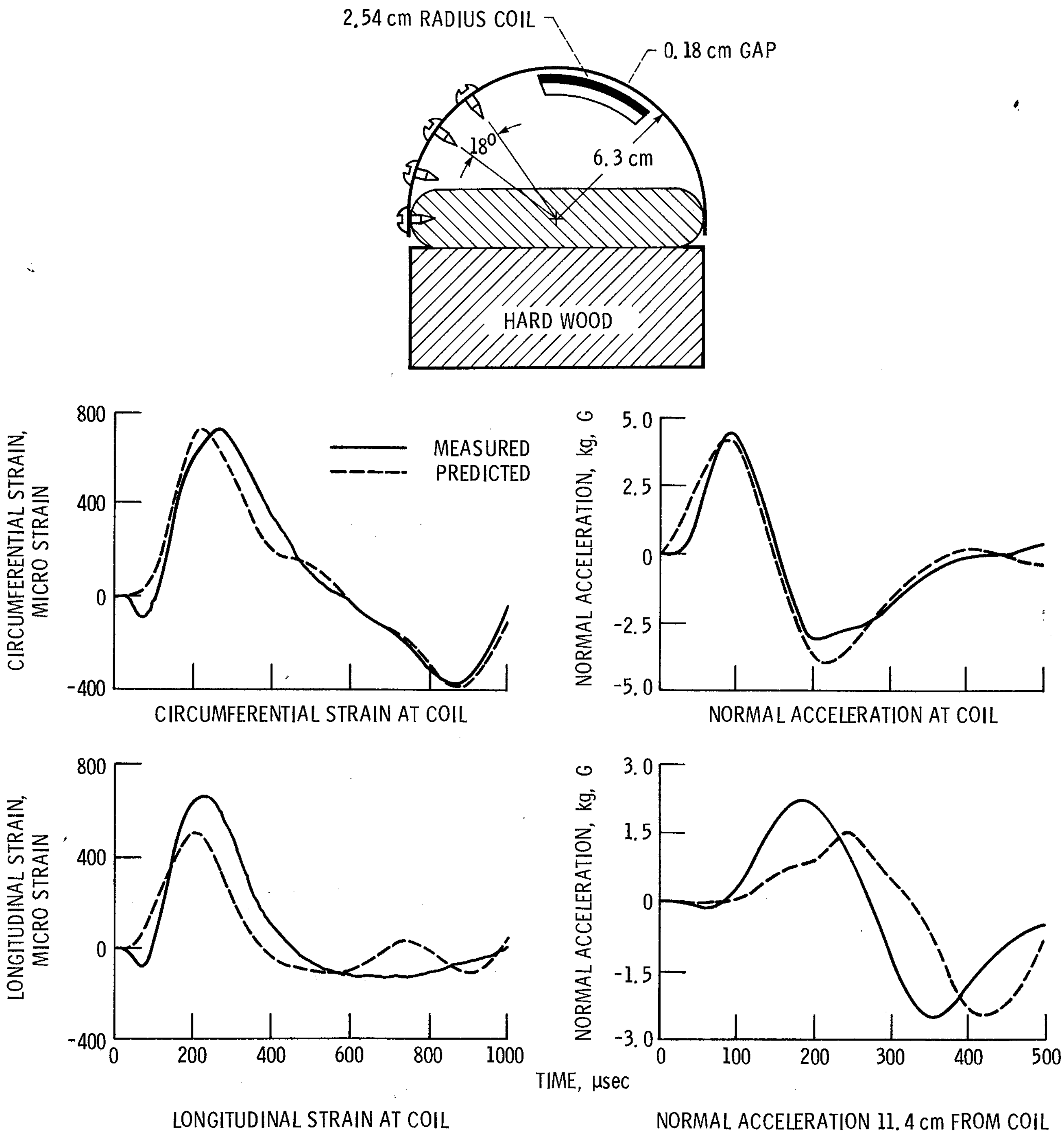

Figure 18. - Comparison of measured and predicted accelerations and strains for idealized deicer model (ref. 41).

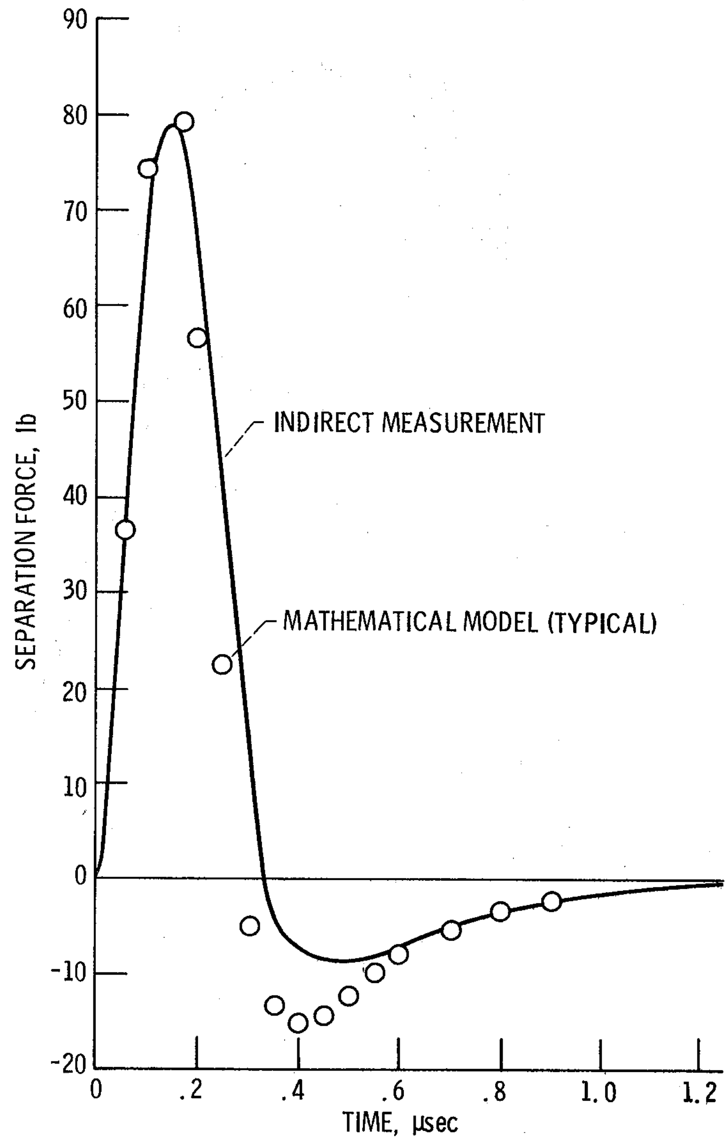

Figure 19. - Coil-metal target separation force.

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15. Supplementary Notes

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16. Abstract

An overview of the NASA ongoing efforts to develop an aircraft icing analysis capability is presented. Discussions are included of the overall and long term objectives of the program as well as current capabilities and limitations of the various computer codes being developed. Descriptions are given of codes being developed to analyze two and three dimensional trajectories of water droplets, airfoil ice accretion, aerodynamic performance degradation of components and complete aircraft configurations, electrothermal deicer, fluid freezing point depressant antideicer and electro-impulse deicer. The need for bench mark and verification data to support the code development is also discussed and selected results of experimental programs are presented.

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