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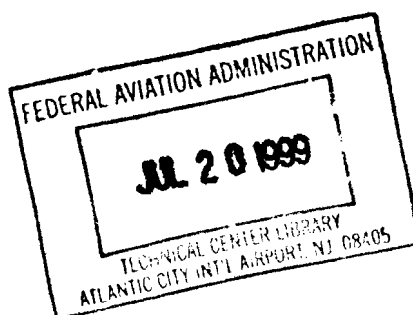
Analytical Ice Shape Predictions for Flight in Natural Icing Conditions

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Brian M. Berkowitz
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Cleveland, Ohio

and

James T. Riley
Federal Aviation Administration
Technical Center
Atlantic City International Airport, New Jersey



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16. Abstract LEWICE is an analytical ice prediction code that has been evaluated extensively against icing tunnel data, but on a more limited basis against flight data. The purpose of this report is to compare ice shapes predicted by LEWICE with experimental ice shapes accreted on the NASA Lewis Icing Research Aircraft. The flight data selected for comparison includes liquid water content recorded using a hot wire device and droplet distribution data from a laser spectrometer; the ice shape is recorded using stereo photography. The main findings are as follows: (1) An equivalent sand grain roughness correlation different from that used for LEWICE tunnel comparisons must be employed to obtain satisfactory results for flight. (2) Using this correlation and making no other changes in the code, the comparisons to ice shapes accreted in flight are in general as good as the comparisons to ice shapes accreted in the tunnel. As in the case of tunnel ice shapes, agreement is least reliable for large glaze ice shpes at high angles of attack. (3) In some cases comparisons can be somewhat improved by utilizing the code so as to take account of the variation of parameters such as liquid water content, which may vary significantly in flight.					
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NOMENCLATURE

h	Local heat transfer coefficient
k	Roughness parameter
k_f	Roughness parameter for natural icing predictions
k_t	Roughness parameter for tunnel predictions
M	Mass of water entering control volume
MVD	Median Volume Droplet Diameter, μm
L	Latent heat of fusion for liquid water
LWC	Liquid water content, d/m^3
n	Freezing fraction
S	Surface Distance
T_{edge}	Local temperature at edge of boundary layer
T_{surf}	Local temperature at ice surface

EXECUTIVE SUMMARY

The NASA-Lewis Research Center in Cleveland, Ohio, with the support of the FAA under an interagency agreement for icing research, has directed the development of a time-dependent, analytical model of the ice accretion process. This model predicts the shape of the ice accretion that would form on an arbitrary two-dimensional geometry, such as an airfoil, when exposed to icing conditions. The model is embodied in a computer code called LEWICE, which has now been operational for several years. Predictions from the code have been extensively compared to ice shapes grown under the same conditions in the NASA-Lewis Icing Research Tunnel (IRT) and the British RAE tunnel with generally encouraging results. In this study, LEWICE ice shape predictions are systematically compared for the first time to ice shapes formed on the wing of the NASA-Lewis Twin Otter Icing Research Aircraft during research flights in natural icing conditions over several icing seasons.

The NASA-Lewis Twin Otter is fitted with an array of instrumentation and an on-board tape and monitoring system to record the flight parameters and icing cloud properties associated with each icing encounter.

During each flight, a digital tape recorder was used to record the flight parameters, which include aircraft speed, altitude, and angle of attack. Icing cloud properties were also recorded, including ambient air temperature, liquid water content (LWC), and the droplet size distribution, from which the volume median droplet diameter (MVD) is computed.

An important difference between natural and tunnel ice shape data is the method used to document the ice shape profile. Profiles obtained from tunnel experiments are created by conventional ice shape tracings. In natural icing, because of the effects due to sublimation and erosion, it is generally not feasible to wait until the aircraft returns to the ground to obtain a tracing. Therefore, natural ice shape profiles are obtained soon after exiting the cloud from a stereo photography system developed jointly by NASA Lewis and the U.S. Air Force Arnold Engineering and Development Center (AEDC). This system utilizes two Hasselblad 70 mm format cameras mounted in the nose of the Dehavilland DHC-6 Twin Otter Icing Research Aircraft. The cameras photograph the ice shape from two different viewpoints simultaneously, producing a stereo image which is later photogrammetrically analyzed to obtain a profile of the ice shape.

The main findings of this study are as follows: (1) An equivalent sand grain roughness correlation different from that used for LEWICE tunnel comparisons must be employed to obtain satisfactory results for flight. (2) Using this correlation and making no other changes in the code, the comparisons to ice shapes accreted in flight are in general as good as the comparisons to ice shapes accreted in the tunnel. As in the case of tunnel ice shapes, agreement is least reliable for large glaze ice shapes at high angles of attack. (3) In some cases comparisons can be somewhat improved by utilizing the code so as to take account of the variation of parameters such as liquid water content (LWC), which may vary significantly in flight.

ANALYTICAL ICE SHAPE PREDICTIONS FOR FLIGHT IN NATURAL ICING CONDITIONS

Brian M. Berkowitz
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Cleveland, Ohio 44135

and

James T. Riley
Federal Aviation Administration
Technical Center
Atlantic City International Airport, New Jersey 08405

INTRODUCTION

The NASA-Lewis Research Center in Cleveland, Ohio has directed the development of a time-dependent, analytical model of the ice accretion process. This model predicts the shape of the ice accretion that would form on an arbitrary two-dimensional geometry, such as an airfoil, when exposed to icing conditions. The model is embodied in a computer code called LEWICE, which has now been operational for several years. The LEWICE code is part of the overall aircraft icing analysis methodology being developed by NASA. Portions of this activity, such as the development and evaluation of LEWICE, are being done jointly with the FAA. Predictions from the code have been extensively compared to ice shapes grown under the same conditions in the NASA-Lewis Icing Research Tunnel (IRT) and the British RAE tunnel with generally encouraging results. In this study, LEWICE ice shape predictions are systematically compared for the first time to ice shapes formed on the wing of the NASA-Lewis Twin Otter Icing Research Aircraft during research flights in natural icing conditions over several icing seasons. Such comparisons are essential to the eventual validation of LEWICE for specific uses in applied icing analysis by industry and the FAA.

DESCRIPTION OF CODE

The NASA-Lewis ice accretion prediction code (LEWICE) is an analytical ice accretion model that evaluates the thermodynamics of the freezing process that occurs when supercooled droplets impinge on a body (reference 1). LEWICE consists of three main modules (figure 1). (1) A flow field calculation employing a Hess and Smith 2D paneling method permits the calculation of the air velocity at any point in the flow field. (2) A droplet trajectory calculation determines the trajectories of the water droplets driven by the air velocities and the resulting impingement pattern of the water droplets on the surface. (3) A quasi-steady state surface heat transfer analysis permits calculation of the local ice thickness over the geometry, which in turn determines the ice accretion.

The icing conditions input to the code consist of temperature, LWC, droplet size, velocity, and pressure. The surface of the geometry is defined by line segments joining a set of discrete body coordinates input by the user.

The code applies a time-stepping procedure to "grow" the ice, layer by layer. The length of each time step is input by the user; they need not all be of the same duration. For the first time step, the flow field and droplet impingement pattern are determined for the clean, or "uniced," geometry. Next, the heat transfer analysis, leading to a local ice thickness, is performed for each segment. The body coordinates are then adjusted to account for the first layer of ice accreted. For the second time step, the flow field and droplet impingement pattern are recomputed for the "new geometry," i.e., the original geometry with the first layer of ice. All the computations of the first time step are now repeated, segment by segment, for the iced surface and the body coordinates are adjusted once more to account for the addition of the second layer of ice. This procedure is continued until the end of the icing growth process has been reached.

The heat transfer analysis which is applied to each segment is essentially that given by Messinger (reference 2), which was a modification of earlier work by Tribus (reference 3). A control volume (figure 2) is associated with each segment. The outer boundary of the control volume lies just beyond the boundary layer. The lower boundary is the line segment itself, which for the first time step forms part of the clean geometry and for later time steps forms part of the ice surface accreted up to that time. (Note, therefore, that a control volume is always situated on either the clean surface or the ice surface.) A heat balance equation is formulated for this control volume which includes terms for all significant processes providing heat to or removing heat from the volume. A discussion of all of these terms can be found in reference 1 as well as in the paper of MacArthur (reference 4). The dominant "heat removal" term, to be discussed shortly, is that for convective cooling; the dominant "heat source" term is that for the heat released by the freezing of water entering the control volume. The water entering a control volume has two sources: (1) water droplets impinging on the surface segment; (2) water "running back" from an adjacent control volume closer to the stagnation point. (As will be seen, this "run back" water consists of all water which entered the adjacent control volume but did not freeze.)

Let M denote the mass of all water entering the control volume from either source and let L denote the latent heat of fusion for water; then the heat released by freezing of the incoming water is

$$nML,$$

where n , the freezing fraction, denotes the fraction of the incoming water which freezes for that segment. If $n=1$, then all incoming water freezes. If $n<1$, then a fraction $1-n$ does not freeze. This water will in turn run back into the adjacent control volume further away from the stagnation point.

The discussion thus far shows that, for a given set of icing conditions, each new layer of ice is mainly determined by two factors: (1) the impingement pattern calculated for the current time step; (2) the segment-by-segment distribution of freezing fractions calculated for the current time step, since they determine the runback and the local ice thickness over the surface.

For each segment, the freezing fraction is calculated as follows: Assume that the equilibrium temperature, T_{surf} , is 273.15 K. With this assumption, all quantities in the heat balance except n can be evaluated. Now solve for n . If the calculation yields a value of n between 0 and 1 inclusive, the calculation is complete. If n is calculated to be larger than 1, assume that $n = 1$ and that the excess over 1 was because T_{surf} is actually smaller than 273.15 K. So set n equal to 1 in the heat balance equation, which is now solved iteratively (since several quantities depend on T_{surf}) for T_{surf} . If n is calculated to be smaller than 0, similar reasoning leads to setting n equal to 0 and solving iteratively for T_{surf} , which will now be larger than 273.15 K.

Clearly, a dominant term or terms in the heat balance equation will heavily influence n and, through n , the ice shape. As noted earlier, the two dominant terms for nearly all comparison cases (which have Mach numbers less than .3) are the term for heat released by freezing of incoming water and the term for convective cooling. Since the first includes n but the second does not, the second plays a very important role in determining n . The convective cooling term has the form

$$h(T_{\text{edge}} - T_{\text{surf}}),$$

where h is the local heat transfer coefficient, T_{edge} is the local temperature at the edge of the boundary layer, and T_{surf} is the local temperature at the surface. The icing cases most challenging to an ice prediction code are the so-called glaze ice cases such that n is substantially less than 1 over a significant part of the surface. For any segment such that $0 < n < 1$, $T_{\text{surf}} = 273.15$ by definition. T_{edge} is calculated from the local edge velocity V_{edge} , which is provided by the flow field module. Thus calculation of the convective cooling term is essentially a matter of calculating h . The method used by LEWICE to calculate h is described in the next section.

HEAT TRANSFER COEFFICIENT AND SURFACE ROUGHNESS PARAMETER

If the flow field calculation in LEWICE were done using a Navier-Stokes solver, the flow field module could provide the heat transfer coefficients h for each surface segment in addition to the on- and off-body velocities. Since LEWICE uses a panel method to compute an incompressible, potential flow (which requires a much less powerful computer), the values for h have to be obtained in another way. LEWICE employs an integral boundary layer method for this purpose; the method was described in a 1983 AIAA paper by MacArthur (reference 4). Makkonen (reference 5) published an interesting study of a similar method in 1985, discussing the derivation in detail and comparing calculated heat transfer coefficient distributions to some of the rather limited experimental data available. Makkonen's method differs from that used in LEWICE in that his method uses a most probable roughness element height to compute transition from laminar to turbulent flow in the boundary layer, and an equivalent sand grain roughness to compute the heat transfer coefficient in the turbulent region. LEWICE uses a single roughness parameter for both calculations.

In LEWICE, the local value of h depends chiefly on the local velocity at the boundary layer edge and the local roughness parameter k . In the icing process, one would expect k to vary with both position and time, and ideally LEWICE ought to attempt to account for this. For example, for the clean airfoil of the first time step, k might be taken to be constant over the entire surface. After each layer of ice is accreted, k might then vary as a function of surface position with the nature of the accreted ice (e.g., glaze in the stagnation region, rime further aft). It would be desirable if LEWICE could realistically adjust the surface k -distribution as the ice accretion develops. Unfortunately, the present state of knowledge is far from making this possible. In fact, there seems to be no generally accepted way for quantifying the roughness of ice accretions, although some recent work may be promising (reference 6); thus no equivalent sand grain roughness values are yet available for iced surfaces. Therefore, at this time there is no possibility of treating k in the way described above.

How, then, is k handled by LEWICE? It uses an empirical correlation for k that was developed by Ruff as follows (reference 1). First, a set of icing tunnel ice accretion shapes was chosen; for each shape, reliable and complete information on the icing conditions was available. The set of ice shapes used were grown in the RAE icing tunnel and are reported on by Gent (reference 7). Second, for each experimental shape, a sequence of LEWICE runs was done varying the value of k (using a single value for k over the entire surface and for all time steps for each run). The value of k which yielded the best agreement between the

LEWICE prediction and the experimental shape was identified. At the end of this process, a data set had been generated which contained the icing conditions and a "best" value of k for each experimental shape. Third, this data set was used to develop a correlation expressing k as a function of freestream velocity, LWC, and ambient temperature.

Since the local h values strongly influence the ice shape, and the local k values in turn strongly influence the local h values, it is unfortunate that k cannot be treated in a more fundamental way. Unfortunately, as noted above, not enough is known about ice roughness to make this possible. However, the following points should be noted. First, many comparisons of LEWICE predictions made using this correlation to shapes grown in the IRT have been made, with generally encouraging results. The fact that this correlation was developed using data from another facility (the RAE tunnel) speaks well for the practical utility and applicability of the correlation. Second, once qualitative data on ice roughness does become available, it will be useful to relate Ruff's correlation to this data. This could be one way of developing a kind of "equivalent ice roughness index." Third, if the same correlation gives reasonably good agreement for one facility and generally unsatisfactory agreement for another facility or for natural icing in flight, it may point to a fundamental physical difference between facilities or between a facility and natural icing in flight. This point will also be discussed in more detail later.

COMMENTS ON THE ICING MODEL

The icing model described previously relies on a simplified description of the icing process. Recent high-speed photo-micrographic films by Olsen (reference 8) have been interpreted as showing that fundamental assumptions are in error; of particular importance, it has been said that in these films runback is no more than an initial transient phenomenon. Bilanin (reference 9) has pointed out that liquid film dynamics, momentum transfer from the air to water flow, and other possibly important aspects of the icing process are neglected. Hansman and Turnock (reference 10) have proposed a zonal approach to ice roughness based on their experimental studies. NASA-Lewis (reference 11) has initiated efforts to "formulate either changes to the existing model or an alternate model in order to see if ice shape predictions can be improved."

Certainly the model can be modified so as to achieve greater physical realism; however, for the foreseeable future there will be severe constraints on the accuracy of the predictions that any model can achieve. Foremost among these constraints is the accuracy of current icing instrumentation. For example, to assume less than a twenty per cent error in LWC or MVD, two very important icing parameters, is rather optimistic even in controlled icing facilities (reference 12). The performance of LEWICE when compared both to tunnel shapes and natural flight shapes must be assessed in light of these constraints, as well as the apparently inherently stochastic nature of the aircraft icing process itself.

RESULTS OF PAST TUNNEL COMPARISONS

Comparisons of LEWICE predictions to ice shapes grown in the IRT and the British RAE tunnel have been encouraging. Although a systematic study has not yet been published for tunnel comparisons, NASA studies have shown that LEWICE often provides reasonable engineering approximations.

Examples of comparisons of LEWICE predictions to ice shapes grown in the IRT are shown in figure 3. Figure 3a presents a fairly challenging case because of the quantity of ice, the type of ice (glaze), and the angle of attack (4 degrees). The ice shape in figure 3b was grown at 0 degrees angle of attack; the LEWICE prediction achieves good agreement with the

impingement limits and the cross-sectional area, the main discrepancy in shape being in the region of the lower horn. These examples are "typical" of tunnel comparisons with LEWICE predictions. More "extreme" cases (large amounts of glaze ice, perhaps at high angles of attack) can result in poorer comparisons.

STEREO PHOTOGRAPHY IN NATURAL ICING

An important difference between natural and tunnel ice shape data is the method used to document the ice shape profile. Profiles obtained from tunnel experiments are created by conventional ice shape tracings. In natural icing, because of the effects due to sublimation and erosion, it is generally not feasible to wait until the aircraft returns to the ground to obtain a tracing. Therefore, an alternative method is needed to obtain natural ice shape profiles soon after exiting the cloud.

A stereo photography system developed jointly by NASA Lewis and the U.S. Air Force Arnold Engineering and Development Center (AEDC) utilizes two Hasselblad 70 mm format cameras mounted in the nose of the Dehavilland DHC-6 Twin Otter Icing Research Aircraft. The cameras photograph the ice shape from two different viewpoints simultaneously, producing a stereo image which is later photogrammetrically analyzed to obtain a profile of the ice shape. Figure 4a shows the layout of the stereo photography system on the Twin Otter; detailed descriptions of the stereo photography system and analysis methodology can be found in references 13 and 14. One limitation of the system is that the stereo photography pairs must be taken in clear air, so that it is not possible to obtain any ice shape data while the aircraft is in the clouds. Typically, the ice shape surface can be resolved to within ± 0.08 cm, which is thought to be adequate resolution for comparisons between experimental and predicted ice shapes. Examples of resultant ice shape profiles produced by this system will follow in the results section.

The interpretation of the stereo photographic ice profiles requires some discussion. The profiles for Flights 84-29, 84-34, 85-14, 86-17, and 86-21 are "composite profiles" (reference 14). That is, rather than representing a cross-section of the ice accretion at a fixed station on the wing, the profile includes points within a 4 inch span of the wing (approximately ± 2 inches about a nominal station). Figure 4b illustrates the area on the leading edge that is used for stereo photography analysis. A distance of approximately 45 inches is available within which a 4 inch section of the wing is used to determine a "composite profile" of the ice. Thus an ice profile can be thought of as an overlay or intermingling of several cross-sectional ice shapes; a sort of band results and this might be interpreted as a "variability band" within which it is hoped that the LEWICE prediction will fall. However, a significant caveat must be entered: Some of the points shown may only represent bubbles or cracks below the surface of the ice. This would have the effect of moving the inner boundary of the "band" closer to the clean airfoil surface. In some cases, there may not be a reasonably well defined ice shape; Figure 5 is an example where this is true in the lower region, probably because of cracks and bubbles below the ice surface. Such cases were excluded from this study since meaningful comparison with prediction would be difficult.

To better define the ice shape profile, an alternative method of analysis was developed in the last year. The profiles produced by this method are cross-sections at a given station on the wing. It was possible to obtain profiles of this type for Flights 85-17, 85-24, 86-20, 86-21, 86-31, 86-33, 87-08, and 87-10. In figure 6, profiles are shown at three different stations (at two-inch intervals) for Flight 87-08. These plots are overlaid in figure 7, again yielding a kind of "variability band." It would appear that for most attributes the variability is on the order of ten per cent. This method generally yields a more well defined ice shape profile.

ICING CLOUD PROPERTIES

The NASA-Lewis Twin Otter Icing Research Aircraft was used for the collection of all natural icing data. The aircraft is fitted with an array of instrumentation and an on-board tape and monitoring system to record the flight parameters and icing cloud properties associated with each icing encounter.

During each flight, a digital tape recorder was used to record the flight parameters, which include aircraft speed, altitude, and angle of attack. Icing cloud properties were also recorded, including ambient air temperature, liquid water content (LWC), and the droplet size distribution, from which the volume median droplet diameter (MVD) is computed. Three liquid water content instruments were operational for most of the flights that were selected for this study: 1) Johnson-Williams (J-W), 2) Rosemount, and 3) Leigh. The J-W is a hot wire probe while the other two are ice-accretion type instruments (more will be said on this shortly). The droplet size distributions were obtained from a Forward Scattering Spectrometer Probe (FSSP), a laser instrument that sizes particles and assigns them to one of fifteen bins, which ordinarily cover a size range of droplet diameters from 2.0 to 47.0 microns. For a fuller description of the instrumentation, see reference 15.

Previous comparisons between instruments in natural icing have shown that the liquid water content measurements from the J-W have agreed quite well with the measurements made with a rotating multicylinder (RMC) (reference 15). The Rosemount and the Leigh did not agree as well, showing much higher data scatter. For this and other reasons, the LWC from the J-W was used whenever possible in this study. For several flights the J-W was not available, and then either the Rosemount or the Leigh was used.

A software package developed at NASA-Lewis was used to reduce the data from the digital tapes (reference 15). Flight data and cloud properties were averaged at the rate of 1/sec. Time-averaged values (averaged over the total icing encounter) of velocity, altitude, angle of attack, temperature, LWC and MVD were calculated and are given in Table 1 for each of the flights selected for this study. Also given in Table 1 is the total time for the icing encounter and the type of ice accreted. For several of the flights, additional processing of the flight data was needed and this will be discussed in the results section as warranted.

Figure 8 presents the complete set of parameter traces for the icing encounter of Flight 86-17. Note that although it was a twenty minute encounter, the MVD trace terminates after thirteen minutes because of problems with the FSSP. Instrumentation problems of this and other kinds were not so rare that such cases could be routinely excluded from the study. In this instance, the flight had produced a reasonably "interesting" ice shape for comparison with prediction, and was otherwise well-documented. Since the MVD had been very steady for the first thirteen minutes, it did not seem unreasonable to assume that it continued around the same level for the rest of the flight. Thus the flight was included in the study, using for the entire encounter the average MVD computed for the first thirteen minutes. Decisions of this kind had to be made for several of the flights included in the study; in a number of cases, it was decided that the flight had to be excluded since there was simply too much uncertainty concerning the behavior of one or more of the parameters during a large part of the encounter.

Unlike the LWC trace in Figure 8, the trace in Figure 9 is characterized by the presence of a significant number of "spikes." Several of the flights had LWC traces of this type. Are LEWICE predictions less accurate for flights with "spiky" traces? This question is briefly addressed in the results section.

MODIFICATION OF THE ROUGHNESS PARAMETER FOR FLIGHT COMPARISONS

The importance of the roughness parameter k has been stressed. During the first phase of this study, Ruff's tunnel correlation for k (denoted k_t) was used for all predictions. The agreement of the predictions with the actual ice shapes was generally not as good as had been found earlier for tunnel comparisons. At this point, calculations were made for Flight 86-17 using a value of k equal to 25% of k_t . There was a marked improvement, as shown in figure 10. We then decided to do new runs using a roughness parameter $k_f = .25k_t$. In most cases, there was improvement, sometimes striking. In no case was there, in our judgement, any significant degradation.

Why the improvement? Consider figure 11, which shows the two predictions for Flight 86-21, as well as the accompanying plots of h and n for the first time step. Using k_t , the downward shift in h results in a wider and deeper trough in the plot of n . This causes the water to run further back on the first time step before freezing. The situation is similar on subsequent time steps; this results in better agreement with experiment for this flight.

Figure 12 is for Flight 85-14; in this case, there is no significant difference in the predictions. The reason is indicated in the plots of h and n for the first time step. Although h again shifts downward, the heat balance is such that n remains unity over the entire surface (the change in h is reflected in a higher predicted surface temperature in the affected region). Thus the predictions for the first time step (not shown) are identical. The freezing fraction remains at unity for all four time steps; the slight differences in the final predictions are due to secondary effects.

It must be stressed that the rule $k_f = .25k_t$ is rather arbitrary. Using a different percentage might give somewhat better results. Furthermore, a more sophisticated modification in Ruff's correlation than simply taking a fixed percentage might give improved results. Further investigation of this matter is warranted. Nonetheless, this simple rule did result in a definite overall improvement in the LEWICE predictions.

What is the physical explanation for the difference in k for flight predictions versus icing tunnel predictions? It could be at least partly due to an actual difference in the nature of the ice roughness in the two environments; unfortunately, there is no quantitative data that bears on this question. Another hypothesis, for which some independent supporting evidence does exist, is that it reflects lower turbulence levels in flight. Hansman and Kirby (reference 16) have addressed this matter, and their work indicated that lower turbulence levels in flight resulted in reduced heat transfer, as would be expected. Thus the 25% adjustment might be regarded as a kind of "turbulence correction."

RESULTS

Since the addition of the stereo photography system to the Twin Otter in 1983, stereo photography data has been collected over four icing seasons. This data formed the basis for this study. An effort was made to establish a set of ice shapes for comparison which, while not excluding rime ice accretions, favored glaze and mixed accretions, since these present the greatest challenge to an ice prediction code and also entail the worst performance penalties. It was also the intent to include flights with a wide range of LWC's and MVD's. These objectives had to be pursued in the presence of a variety of "practical" considerations. Many flights were excluded for one or more of the following reasons. First, in the early years of development of the stereo photography system, there were problems of poor image quality of the photographs, resulting in difficulties with the analysis of the data; such flights had to be excluded from this study. Second, as has been discussed above, in some cases the presence of bubbles and cracks below the surface resulted in profiles that could not be used for

meaningful comparison with a LEWICE prediction, and such flights were excluded. Third, a few of the flights were excluded simply because flight or icing cloud data was not available on tape. Fourth, as briefly discussed above, several flights could not be used because of instrument failure during the icing encounter. Fifth, some flights were excluded because the size of the ice accretion was so small as to render it of little interest for comparison to a LEWICE prediction.

Twelve research flights were finally included in the study. Included in the documentation for nearly all the flights was information permitting a classification of the kind of ice; there were three rime accretions, five glaze accretions, and four mixed accretions. LEWICE was used to predict the ice shapes for each of the twelve flights. The time-averaged values shown in Table 1 were used as inputs to the code along with an airfoil chord of 1.98 m. An equivalent sand grain roughness (k) was calculated as described earlier based on the time-averaged values of velocity, LWC, temperature, MVD, pressure, and angle of attack. In each case, four or fewer time steps were used to predict the ice shape.

Figures 13-24 show the ice shape profiles and the LEWICE ice shape predictions for each of the twelve flights. The LEWICE predictions show fairly good agreement with the experimental ice shapes except for flights 86-20 and 86-31 (figures 19 and 21, respectively). LEWICE tends to predict the impingement limits and cross-sectional area of the ice reasonably accurately. The prediction of ice shape is, in general, somewhat less satisfactory.

The shape of an ice accretion is directly related to the type of ice being accreted. Rime ice, which was accreted in Flight 85-14 (figure 15), has a shape which tends to conform to the leading edge of the airfoil. For most of the rime ice accretions, LEWICE provides reasonably good predictions (as is also true for tunnel comparisons). Glaze ice is often characterized by the formation of horns like those shown for Flight 86-20 (figure 19). As noted earlier in the discussion of tunnel comparisons, LEWICE sometimes does a relatively poor job of shape prediction for "extreme" glaze shapes such as this one; although the shape is poorly predicted, the impingement limits and cross-sectional area of the ice are reasonably well predicted.

All predictions shown in figures 13-24 used as input parameters values that were averaged over the entire icing encounter. These parameters all vary to some extent during flight, and LWC often varies strikingly. The pattern of variation could theoretically have a dramatic effect on the ice shape, as the following purely hypothetical example illustrates. Consider a ten-minute icing encounter during which the LWC was relatively steady at 0.5 grams/cubic meter and the temperature was always just low enough so that the entire accretion was rime. Now consider a second ten-minute encounter during which all parameters were identical to the first except that LWC was relatively steady around 0.9 grams/cubic meter during the first five minutes and around 0.1 grams/cubic meter during the second five minutes, giving an average of 0.5 grams/cubic meter for the encounter. A glaze layer would accrete during the first five minutes followed by a rime layer during the second five minutes; the resulting shape would be quite different than that for the first encounter, although the average parameter values would be the same for both.

The hypothetical example described in the previous paragraph suggests another potential advantage of a time-stepping ice prediction code such as LEWICE. The time steps can simply be chosen to coincide with the two five-minute subintervals, and the LWC used for each step can be the subinterval average for that step, rather than the overall average for the entire encounter. If the heat balance equation is sufficiently accurate, the first predicted layer should be glaze and the second rime, so that the final prediction should agree better with the actual ice shape than the prediction of a single-time-step code that is forced to use LWC averaged over the entire encounter.

This potential advantage can be an actual advantage only for flights such that the LWC trace can be divided into subintervals over which LWC is relatively steady; moreover, the LWC

levels associated with the subintervals should differ significantly among themselves. Such flights were rare among those we examined. There were only three such that subinterval averaging appeared to offer any significant advantage. The prediction using overall average LWC is shown in figure 25a, and that using the indicated subinterval averages in figure 25b. There appears to be some improvement, but it is not marked; this is a secondary effect when compared to the impact of the adjustment in the roughness correlation.

As noted, several of the flights possessed "spiky" LWC traces. Basing subintervals on the spikes is not practical, since far too many time steps would be required; furthermore, there is no reason to think it would improve the predictions. Does the use of overall averages for these spiky traces tend to result in worse predictions than for the steadier traces? No such tendency is revealed when predictions using overall averages for the two classes are compared.

CONCLUSIONS

The main findings of this study are as follows: (1) An equivalent sand grain roughness correlation different from that used for the tunnel comparisons must be employed to obtain satisfactory results for flight. (2) Using this correlation and making no other changes in the code, the comparisons to ice shapes accreted in flight are in general as good as the comparisons to ice shapes accreted in the tunnel. As in the case of tunnel ice shapes, agreement is least reliable for large glaze ice shapes at high angles of attack. (3) In some cases comparisons can be somewhat improved by utilizing the code so as to take account of the variation of parameters such as liquid water content (LWC), which may vary significantly in flight.

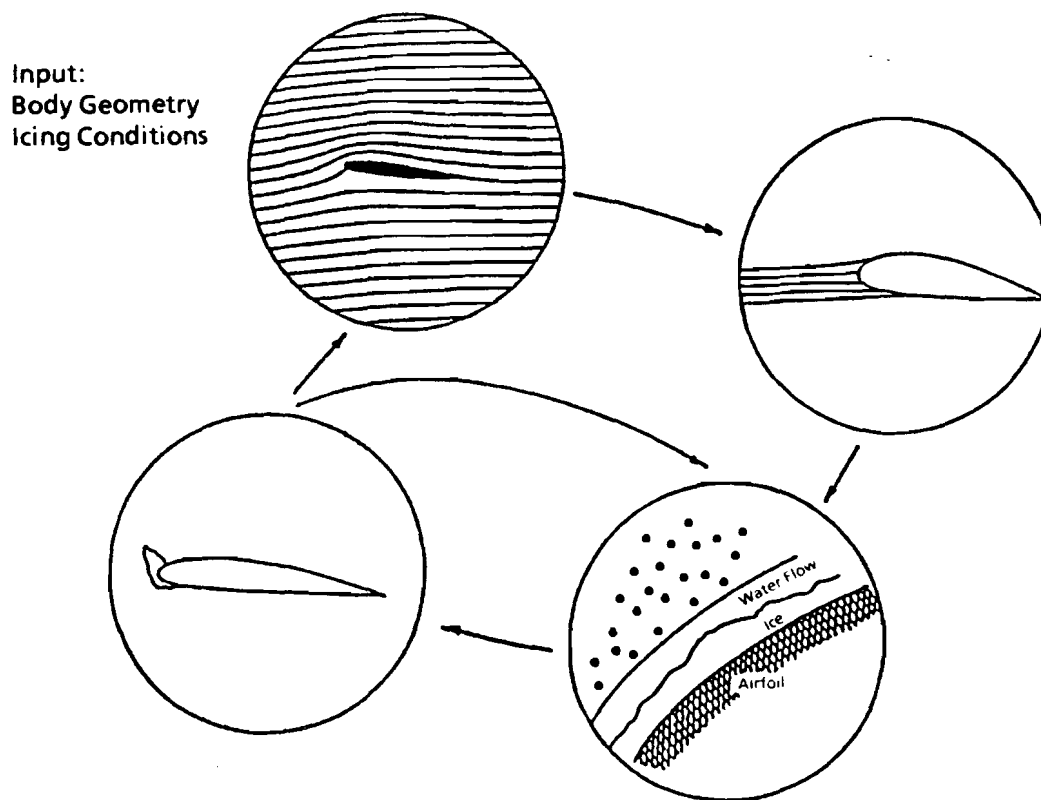
FUTURE EFFORTS

The NASA icing analysis program can be depicted by the triangle in figure 26, where each leg indicates comparison between data obtained by the methods at the adjacent nodes. The ultimate goal of the program is the development and validation of computer programs to predict ice accretion and attendant performance degradation for flight in natural icing conditions. Although this paper is confined to ice accretion shapes, the figure also represents concurrent efforts underway for aerodynamic performance codes. The research flights of the NASA icing research aircraft are an essential part of the program, and systematic comparison of LEWICE predictions (as well as performance code predictions) to flight data will continue in the future. Controlled experiments can be carried out in the IRT which are not possible in flight, and the comparison of such experiments to code predictions will also continue; this activity has played an essential role in LEWICE model development and validation. Finally, it is desirable that the IRT simulate icing conditions in flight as realistically as possible, and also that researchers understand the unavoidable differences. To this end, a full scale wing section for the Twin Otter will be tested in the IRT under conditions as nearly as possible duplicating several selected icing flights.

Efforts already underway to better formulate the fundamental physics underlying the LEWICE model (references 8, 9, 10) will continue. To determine if any modifications resulting from this research are effective, more accurate measurement of icing conditions, particularly droplet size and LWC, is necessary. NASA and the FAA will continue to support research in this area as well (Reference 17).

ACKNOWLEDGMENT

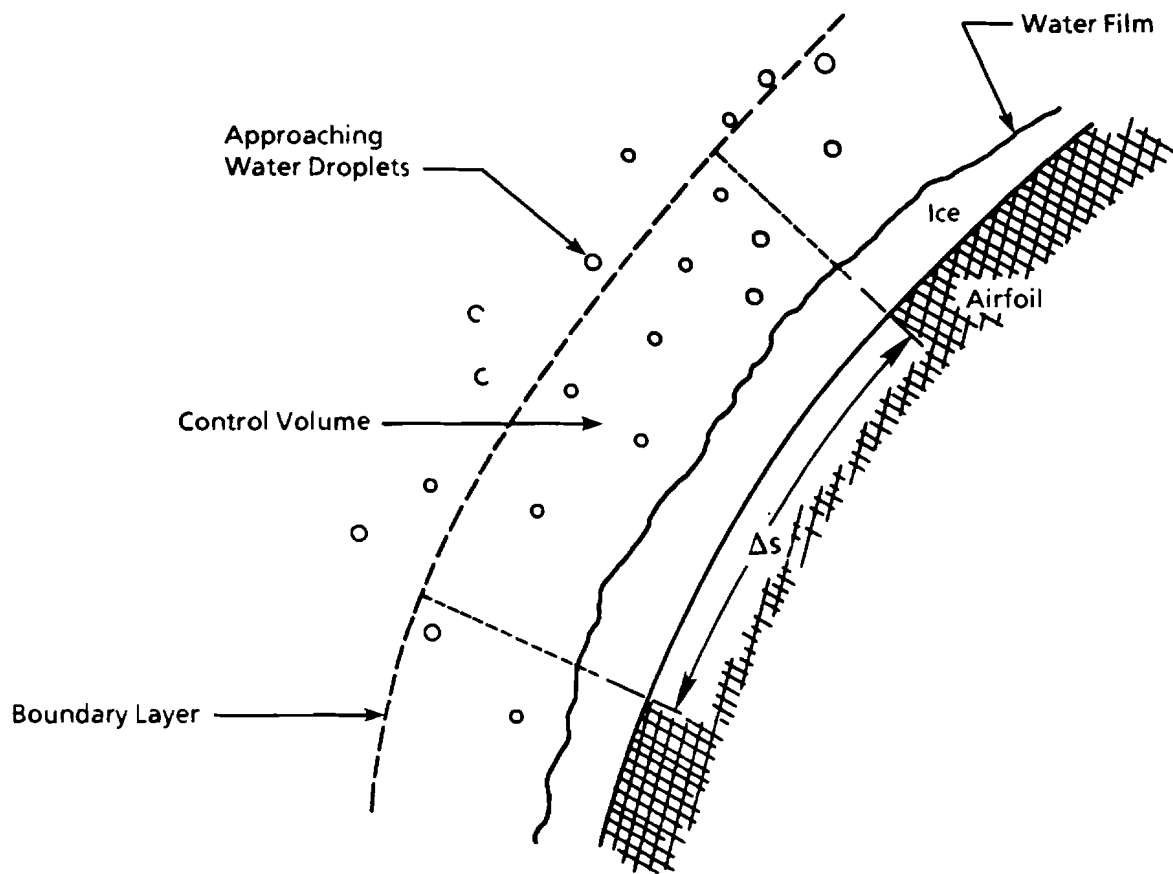
The authors wish to gratefully acknowledge the contribution of Mr. Chris Daughters of Northrop Corp. He first investigated the modification of the roughness parameter for flight in natural icing conditions and suggested the flight correlation rule employed in the study. In addition, he suggested the general approach to assessing the accuracy of the LEWICE predictions which is described in Appendix A.



Method of Solution

- Flow Field Calculation
 - Hess and Smith 2-D Paneling Method For Potential Flow
- Droplet Trajectory/Impingement Calculation
 - FWG 2-D Particle Trajectory Code
- Thermodynamic Analysis/Ice Accretion Calculation
 - Integral Boundary Layer Equations

FIGURE 1
LEWICE Ice Accretion Prediction Code



Single Control Volume of the Ice Surface

FIGURE 2
Illustration of Control Volume Used to Formulate Heat Balance Equation

VELOCITY (M/S)	58.11
TEMPERATURE (C)	-7.78
PRESSURE (KPA)	95.76
HUMIDITY (%)	100.00
LWC (G/M**3)	2.10
DROP DIAM (MICRONS)	20.00
TIME (SEC)	300.00

VELOCITY (M/S)	58.00
TEMPERATURE (C)	-7.78
PRESSURE (KPA)	99.12
HUMIDITY (%)	100.00
LWC (G/M**3)	2.10
DROP DIAM (MICRONS)	20.00
TIME (SEC)	150.00

— Experimental
 - - - LEWICE

— Experimental
 - - - LEWICE

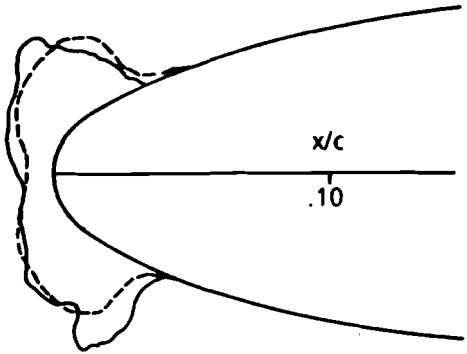
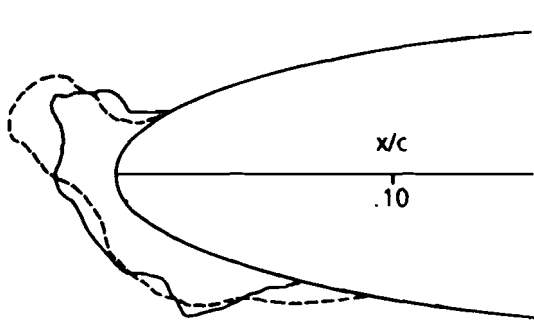
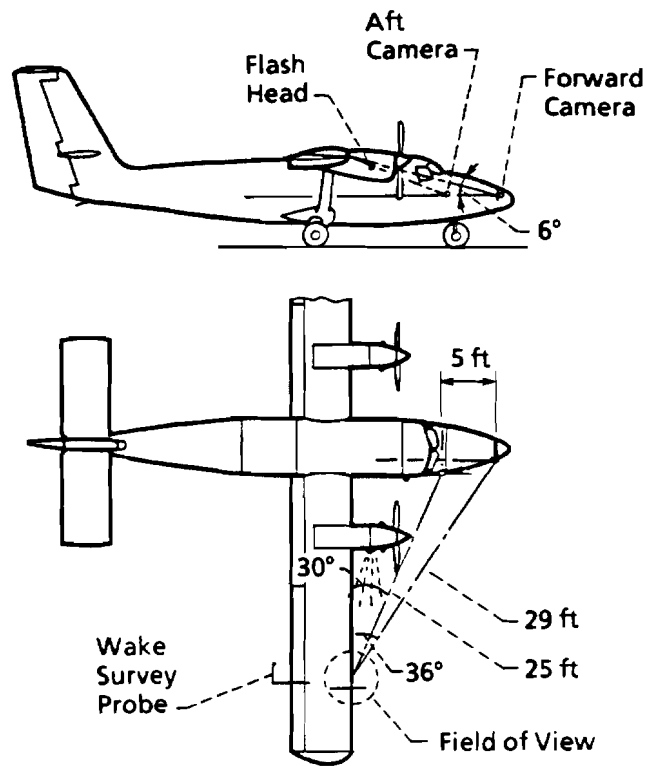
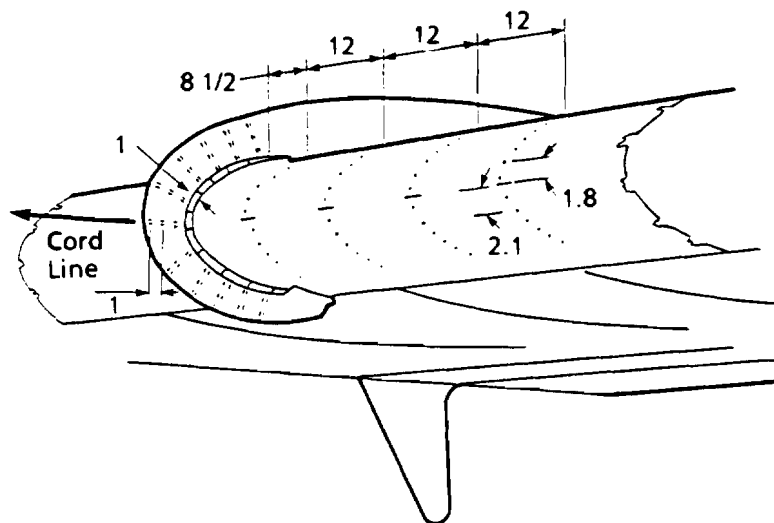


FIGURE 3
Examples Comparing LEWICE Predictions to Ice Shapes
Grown in the NASA LEWIS Icing Research Tunnel



(a) Stereo camera system layout



(b) Reference control points on wing surface and wing fence used in analyzing stereo pair photographs. Dimensions are in inches. Control points on wing fence positioned on lines that intersect the wing surface at 2% chord spacing.

FIGURE 4
Stereo Camera System used to Document Ice Shape
on Wing Ahead of Wake Survey Probe

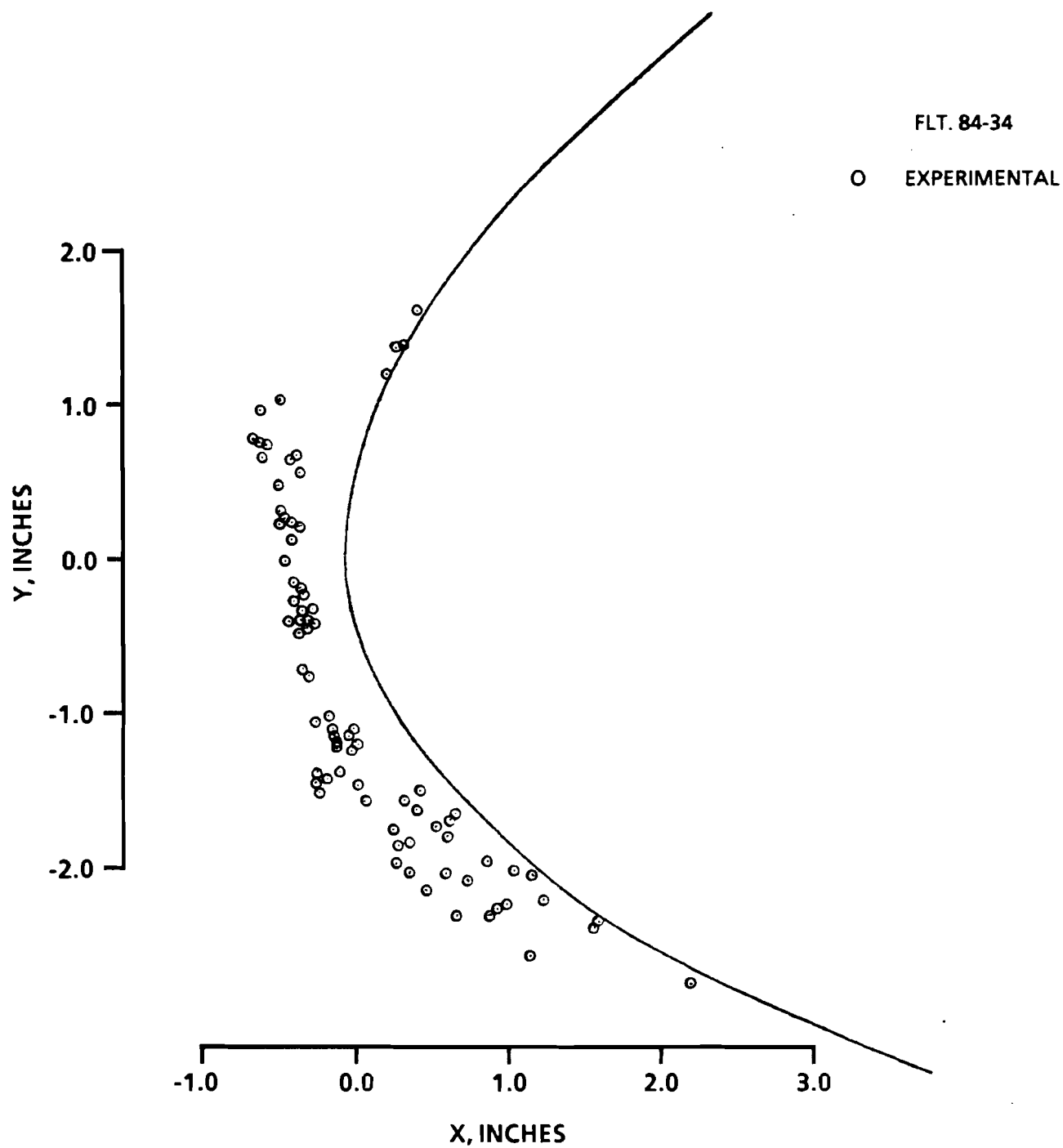


Figure 5
Example of Ice Shape Profile Lacking Sharp Definition in Lower Region

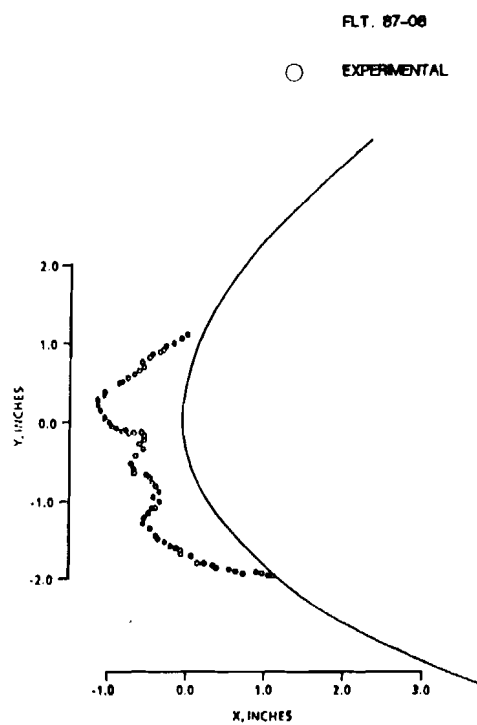


Figure 6a

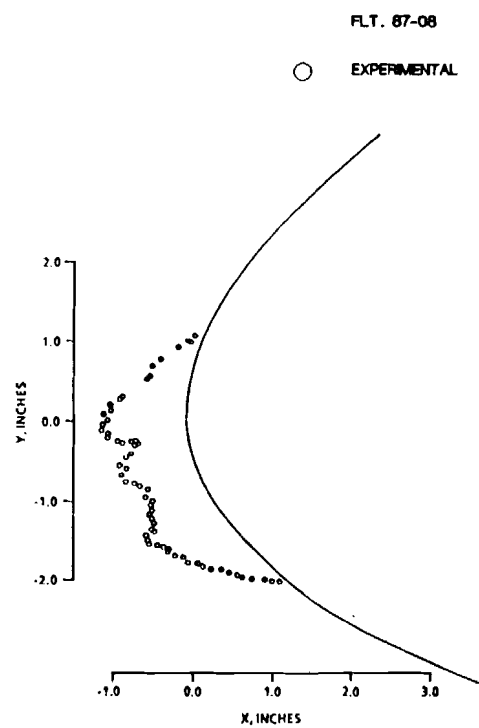


Figure 6b

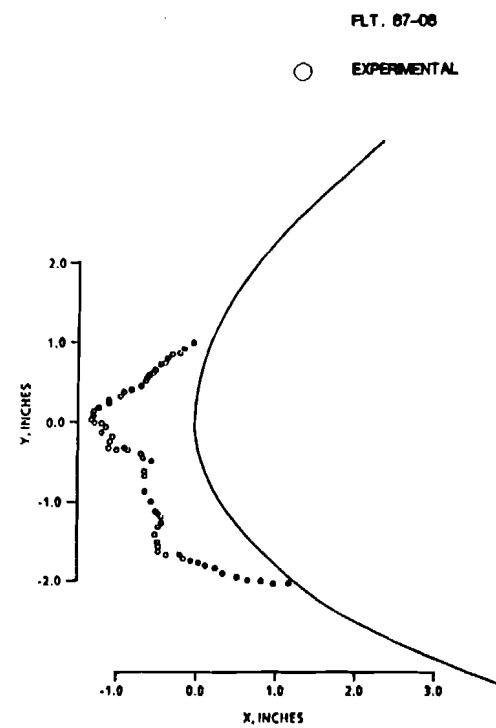


Figure 6c

Figure 6
Ice Shape Profiles at Three Different Stations
along Wing Span for Flight 87-08

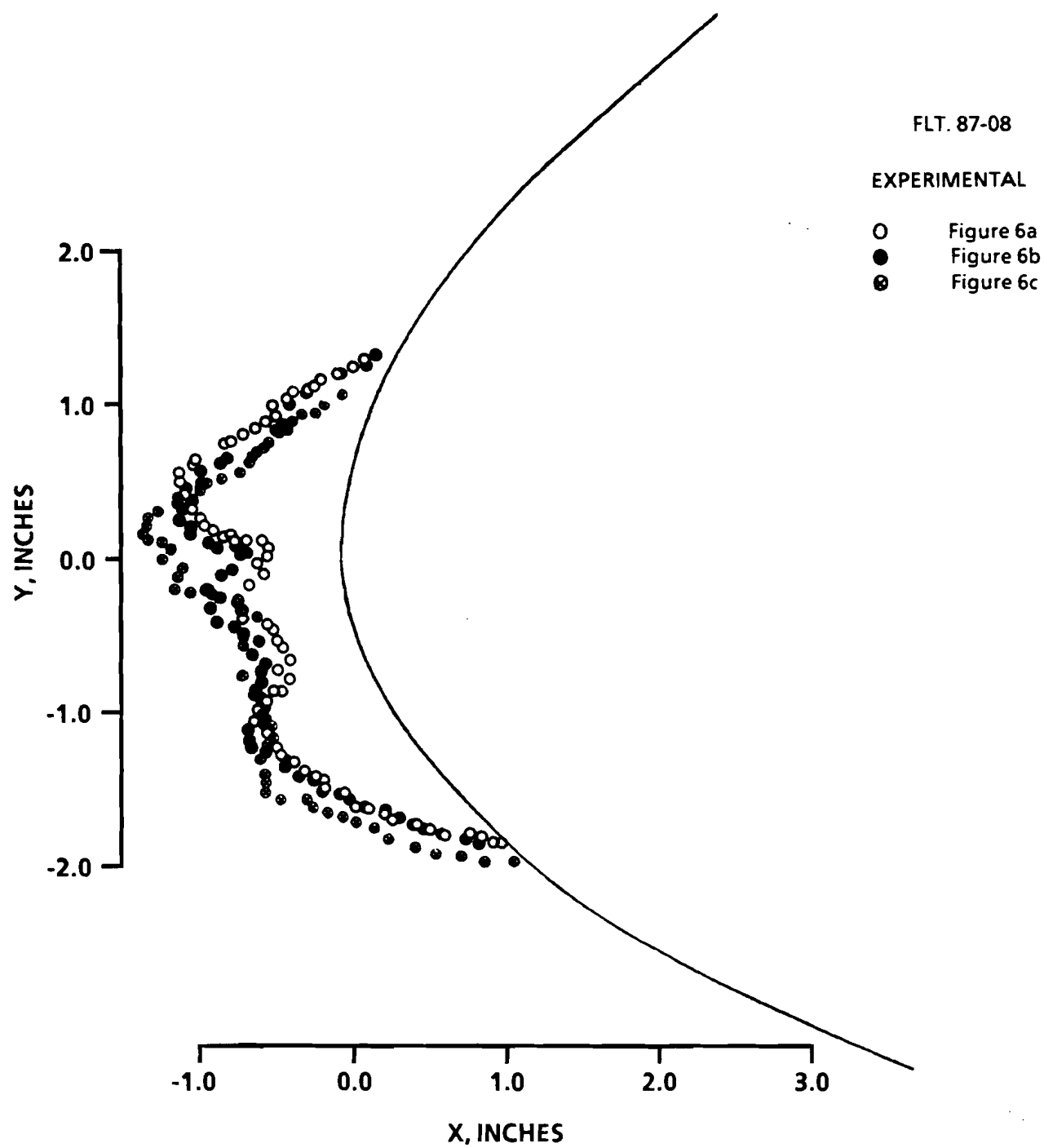


Figure 7
Overlay of Ice Shape Profiles from Figure 6 For Flight 87-08

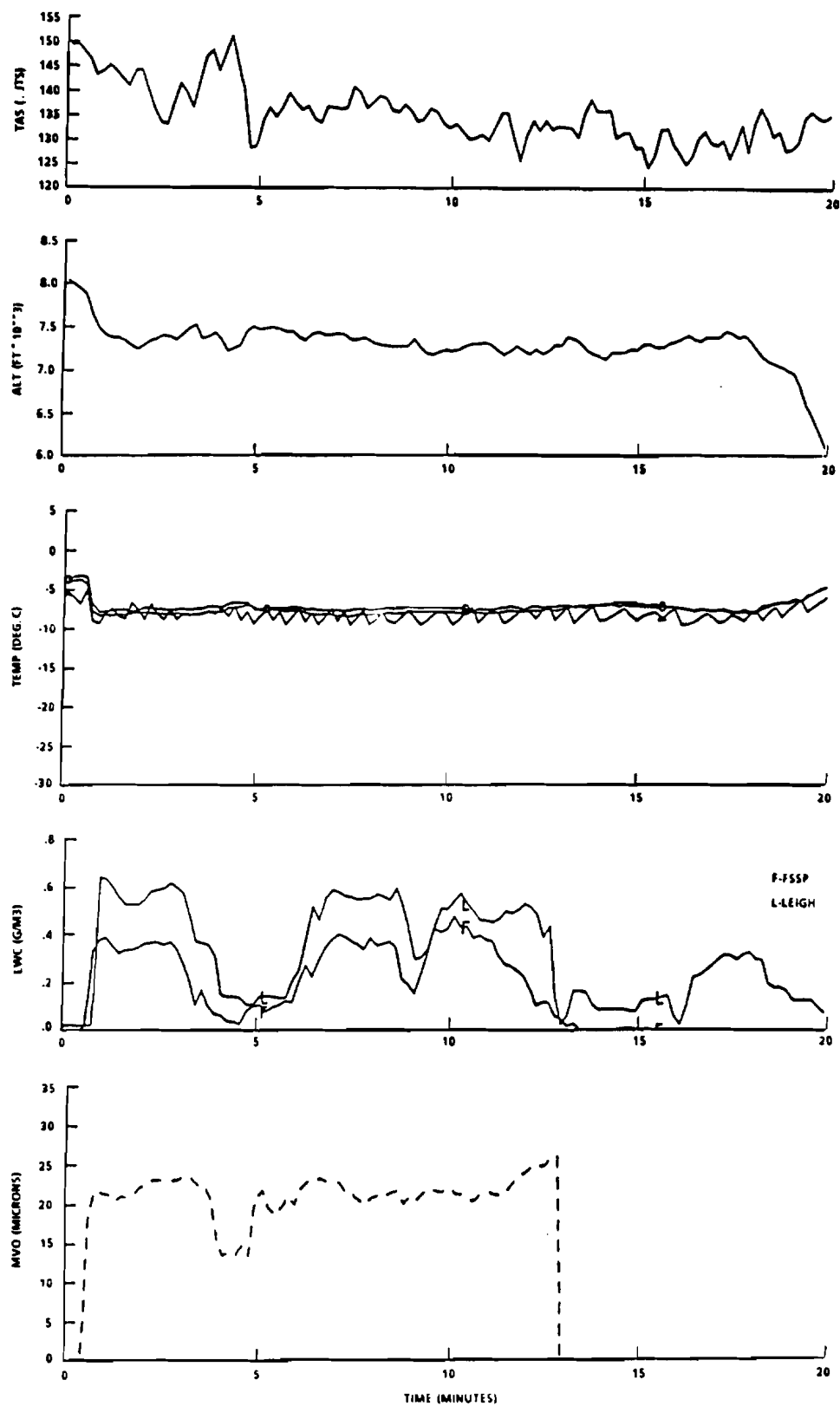


Figure 8
Parameter Traces for Flight 86-17

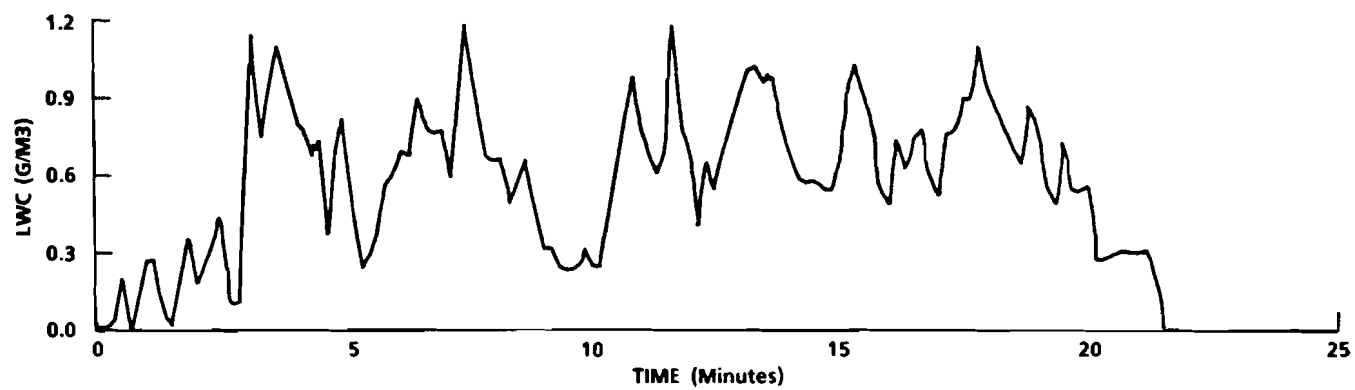


Figure 9
LWC Trace with a Large Number of "Spikes"

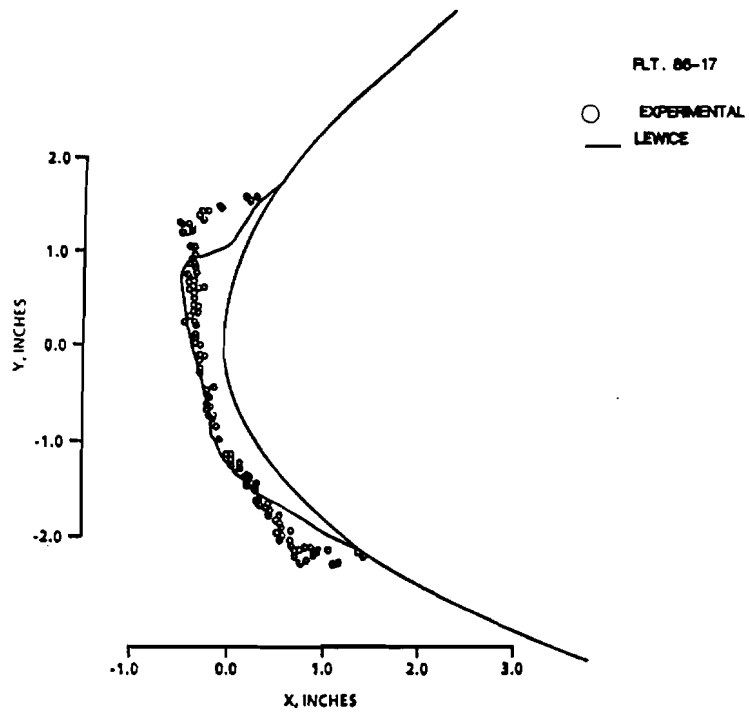


Figure 10a
LEWICE Prediction Using Roughness Parameter K_t

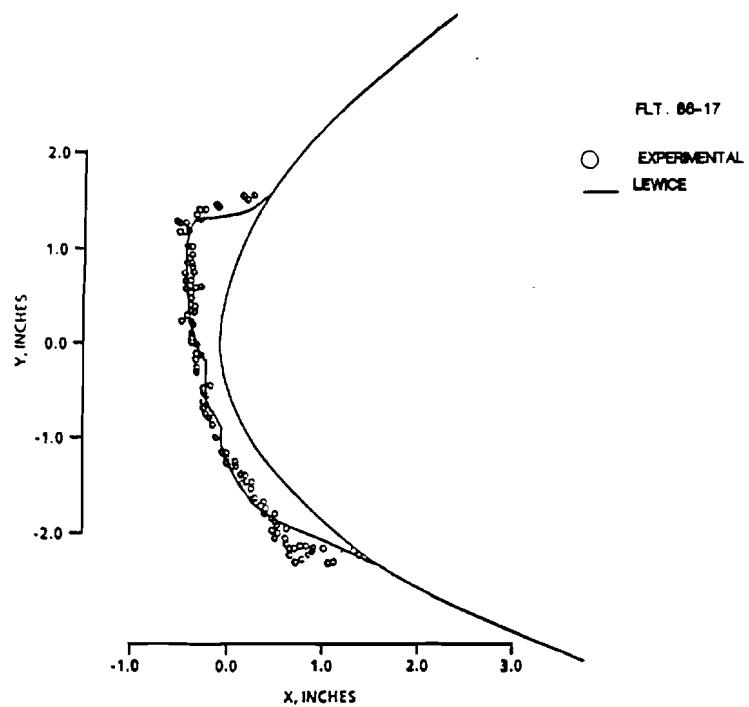


Figure 10b
LEWICE Prediction Using Roughness Parameter K_f

Figure 10
Comparison of LEWICE Predictions for Flight 86-17
Using Roughness Parameters k_t and k_f

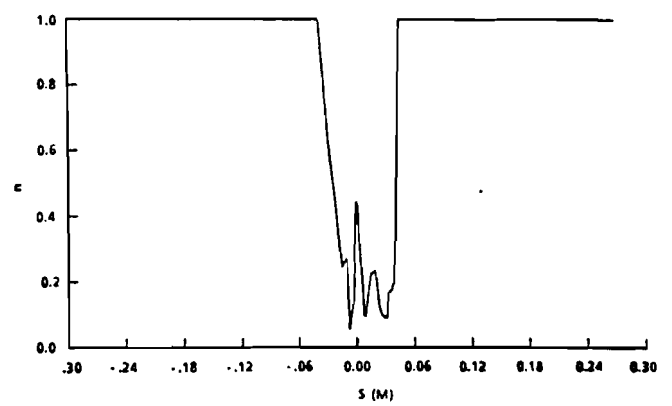
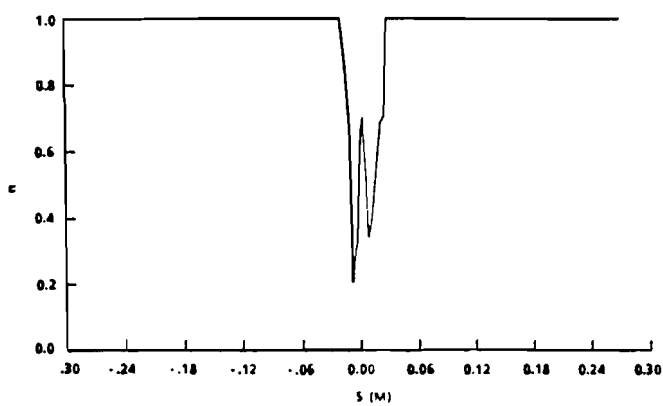
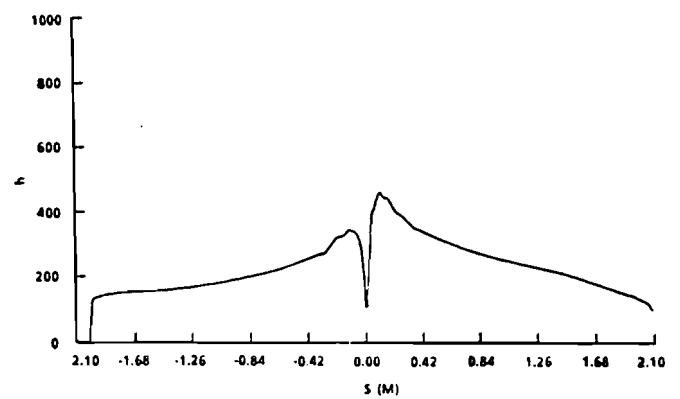
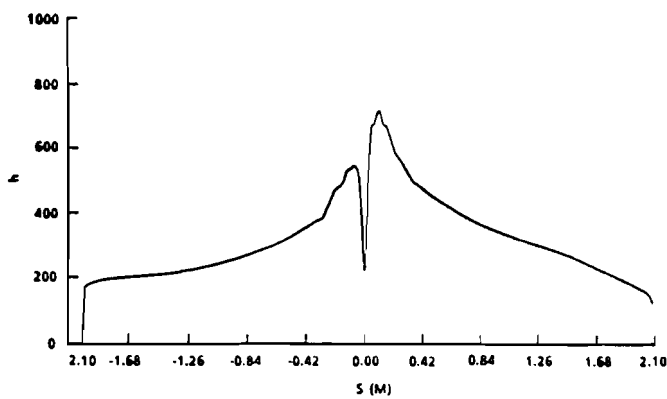
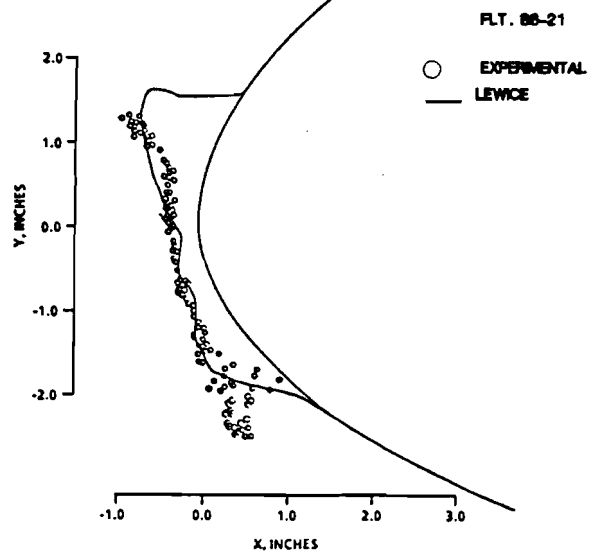
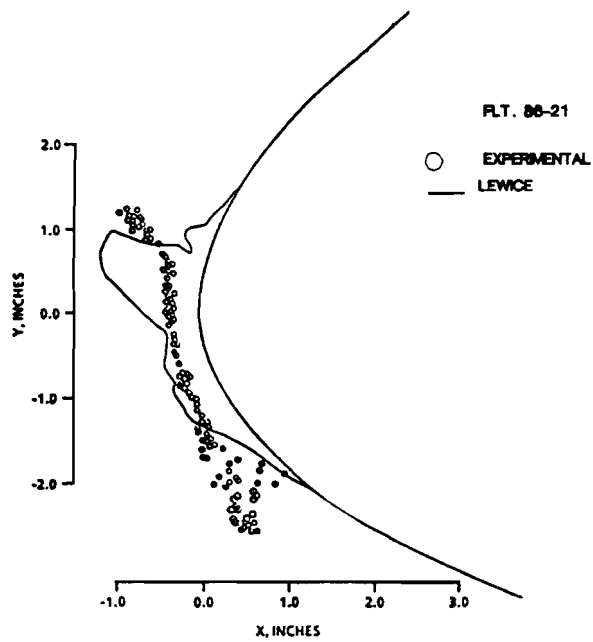


Figure 11a
Predicted Ice Shape, HTC, and FF Using Roughness Parameter k_t

Figure 11b
Predicted Ice Shape, HTC, and FF Using Roughness Parameter k_f

Figure 11
Comparison of LEWICE Predictions for Flight 86-21
Using Roughness Parameters k_t and k_f

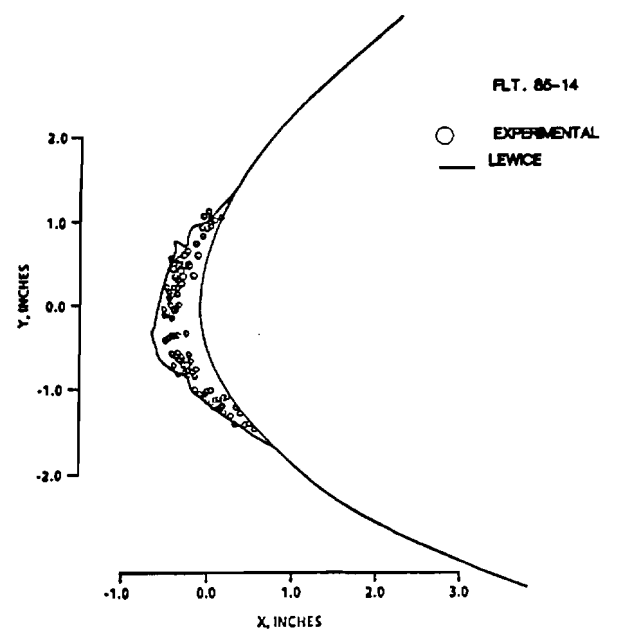
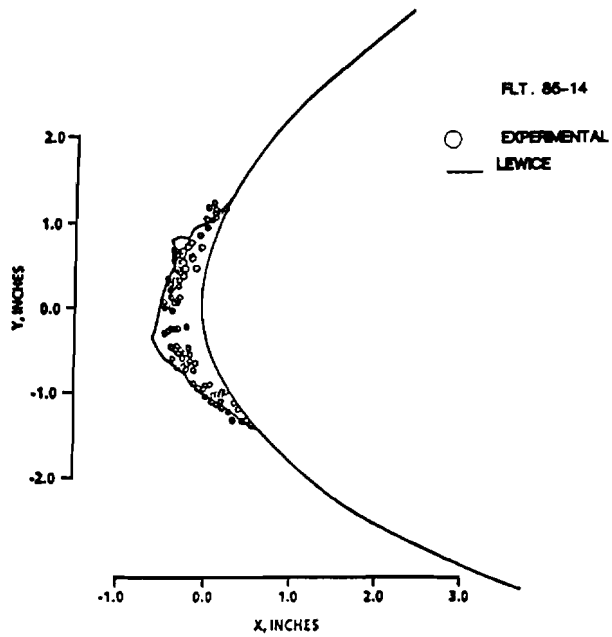


Figure 12a

Predicted Ice Shape, HTC, and FF Using Roughness Parameter K_t

Figure 12b

Predicted Ice Shape, HTC, and FF Using Roughness Parameter K_f

Figure 12
Comparison of LEWICE Predictions for Flight 85-14
Using Roughness Parameters k_t and k_f

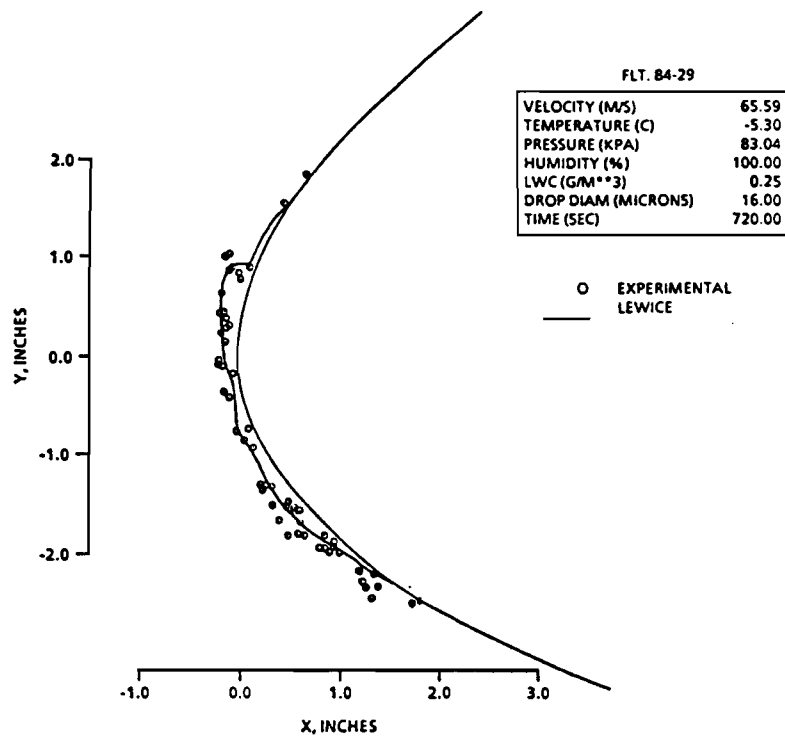


Figure 13
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 84-29

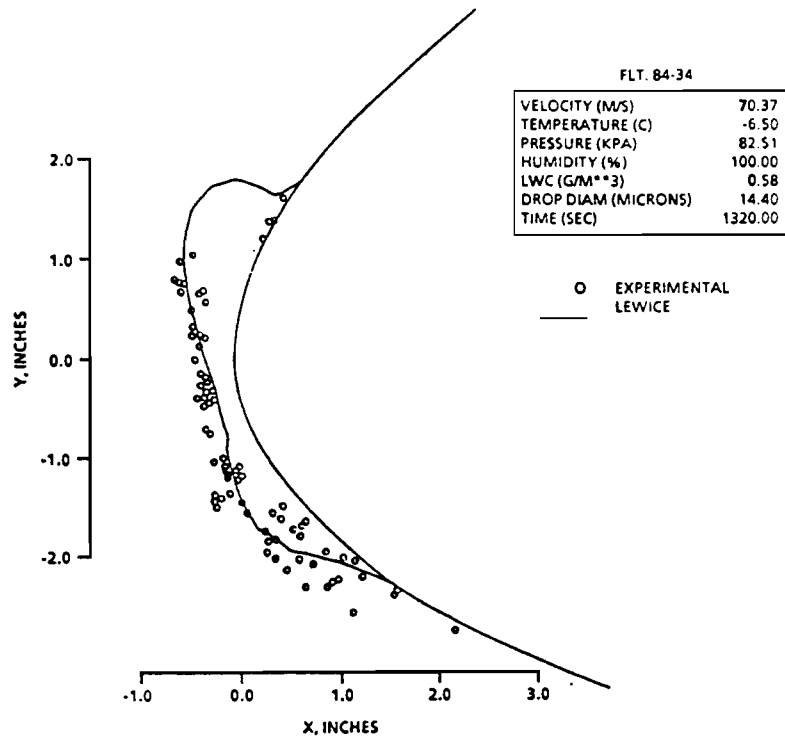


Figure 14
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 84-34

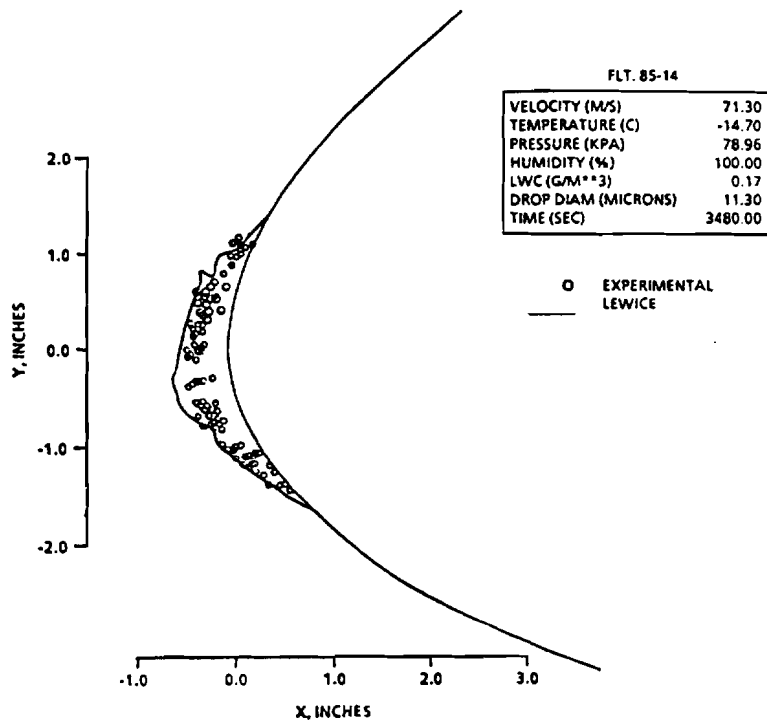


Figure 15
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 85-14

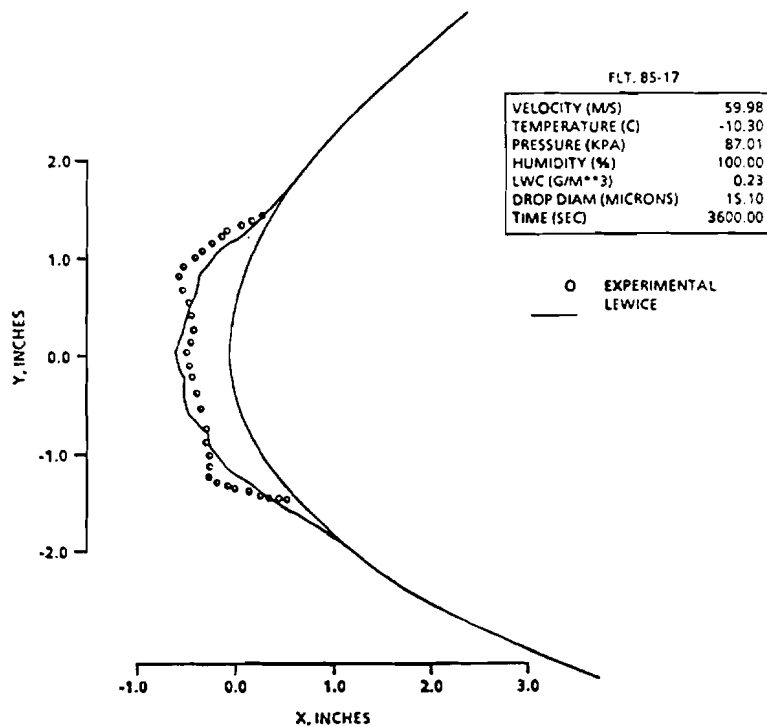


Figure 16
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 85-17

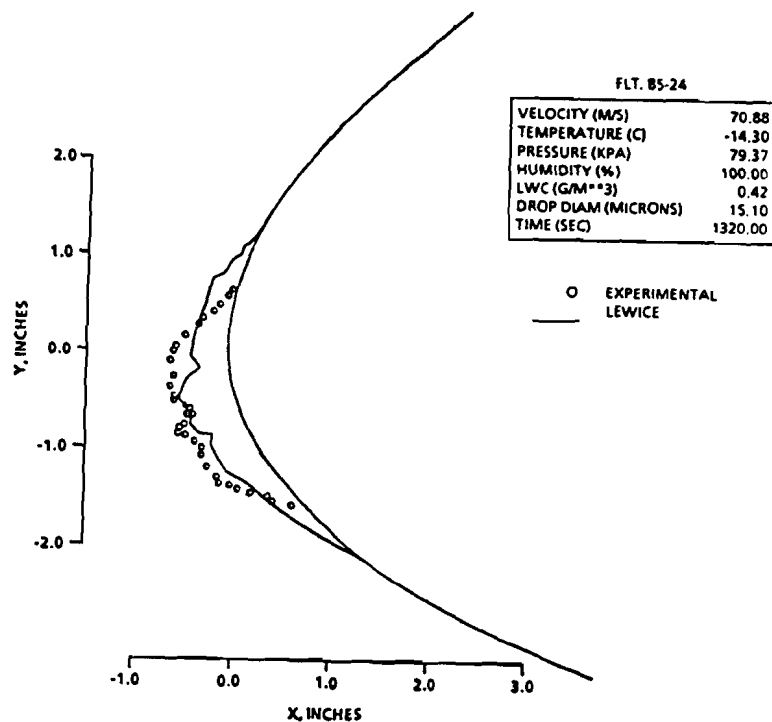


Figure 17
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 85-24

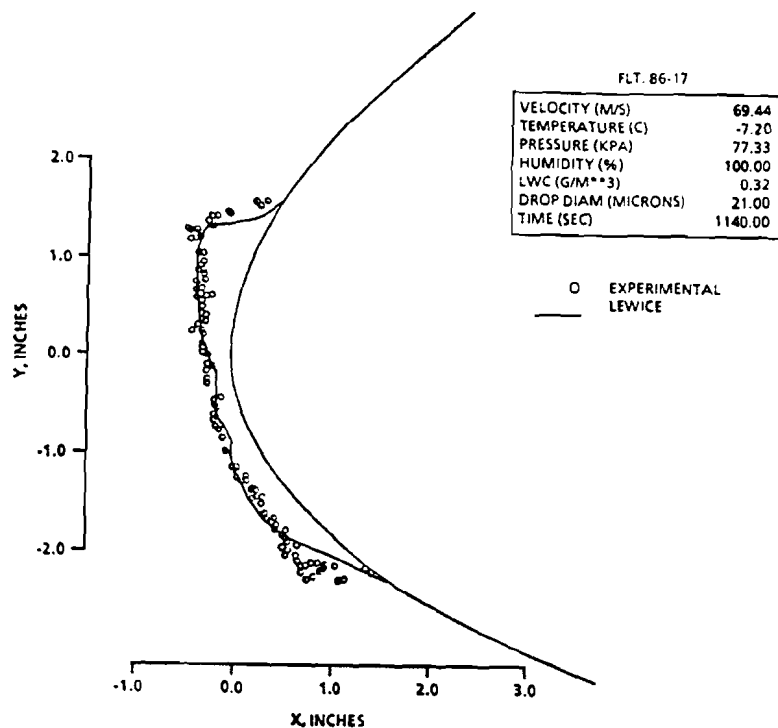


Figure 18
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 86-17

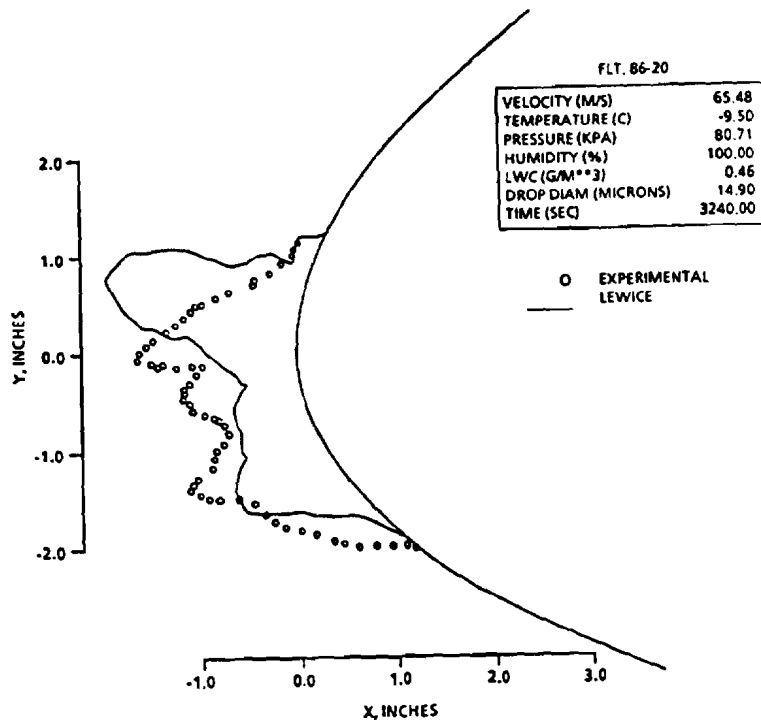


Figure 19
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 86-20

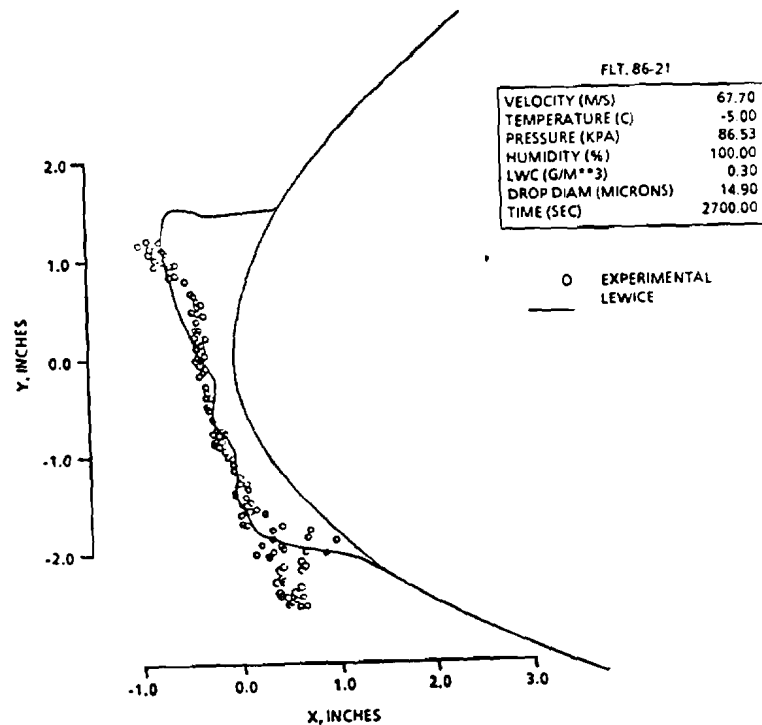


Figure 20
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 86-21

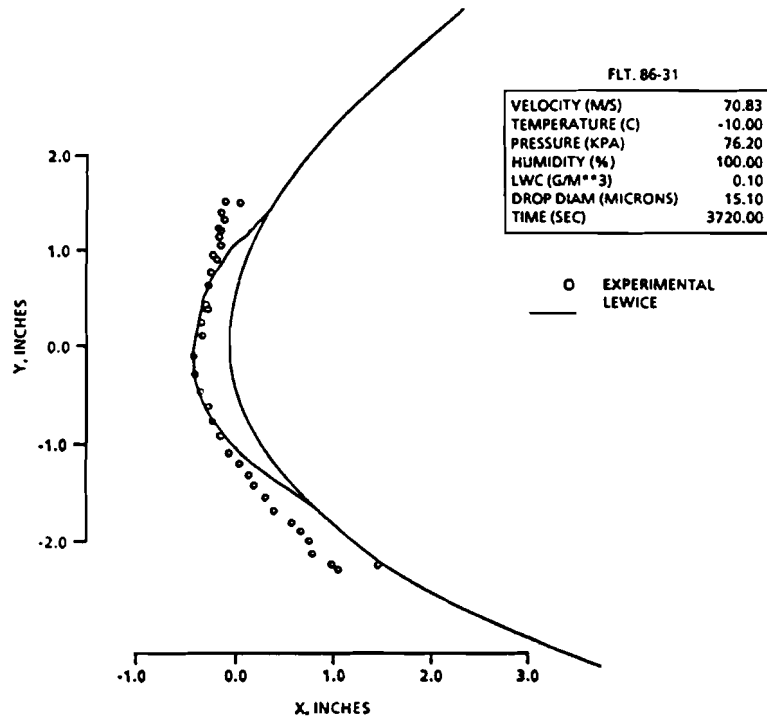


Figure 21
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 86-31

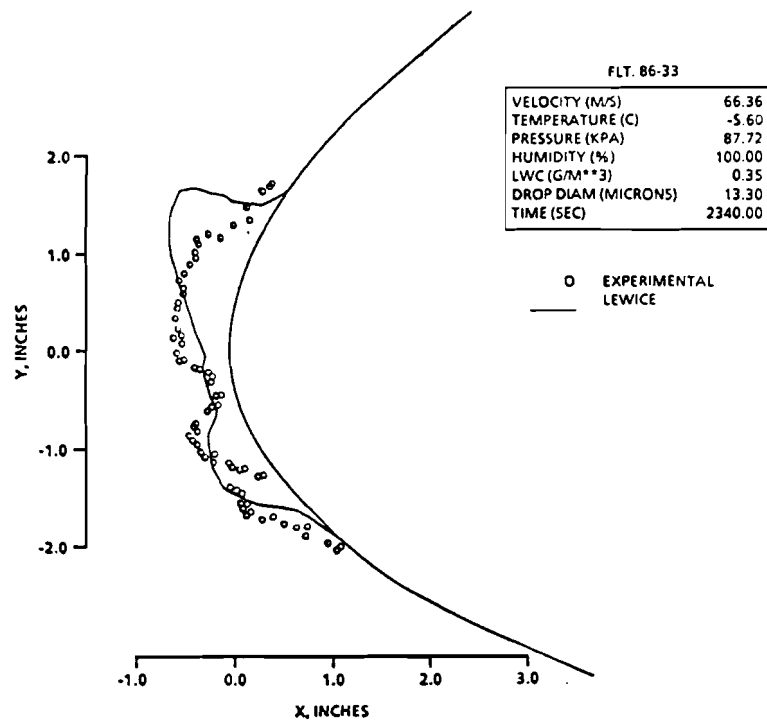


Figure 22
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 86-33

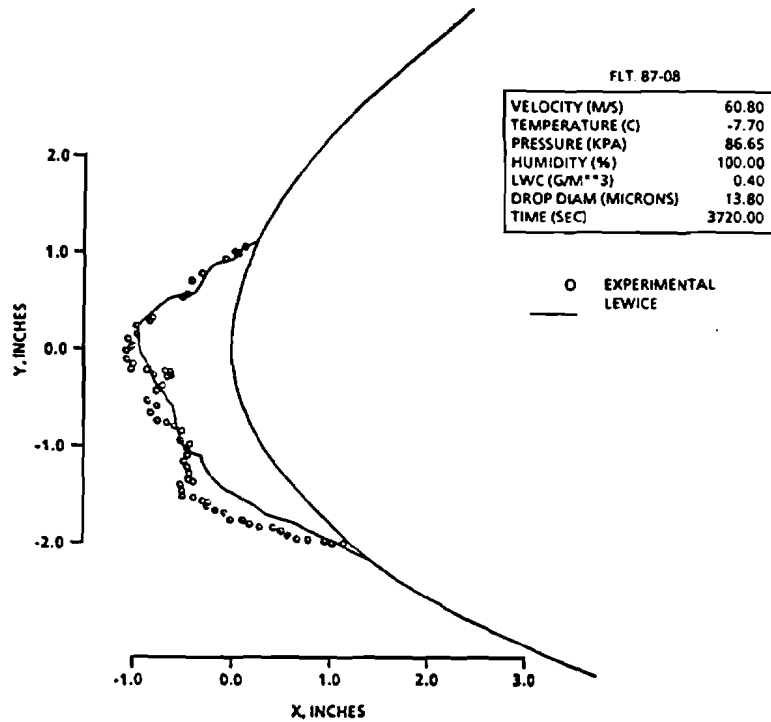


Figure 23
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 87-08

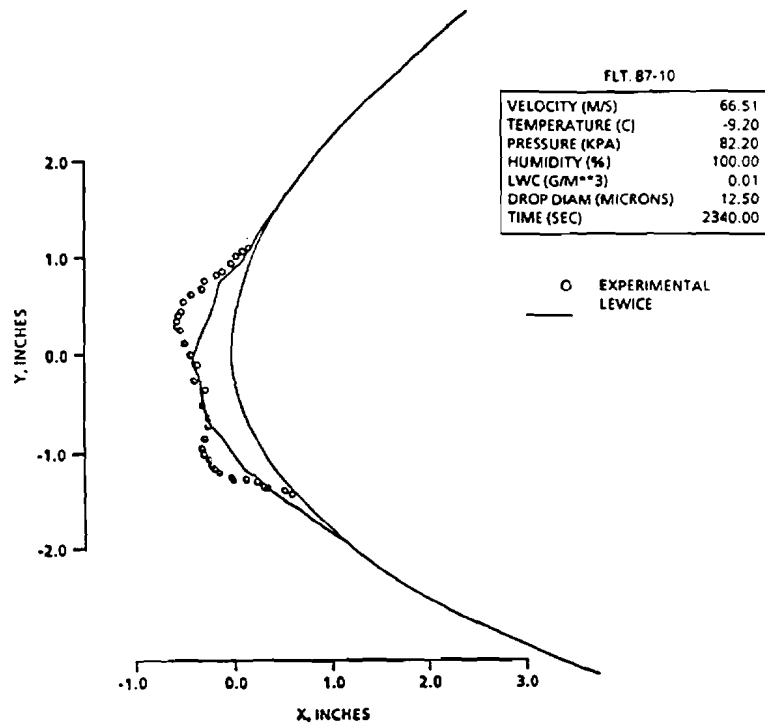


Figure 24
Comparison of LEWICE Prediction to Natural Ice
Shape for Flight 87-10

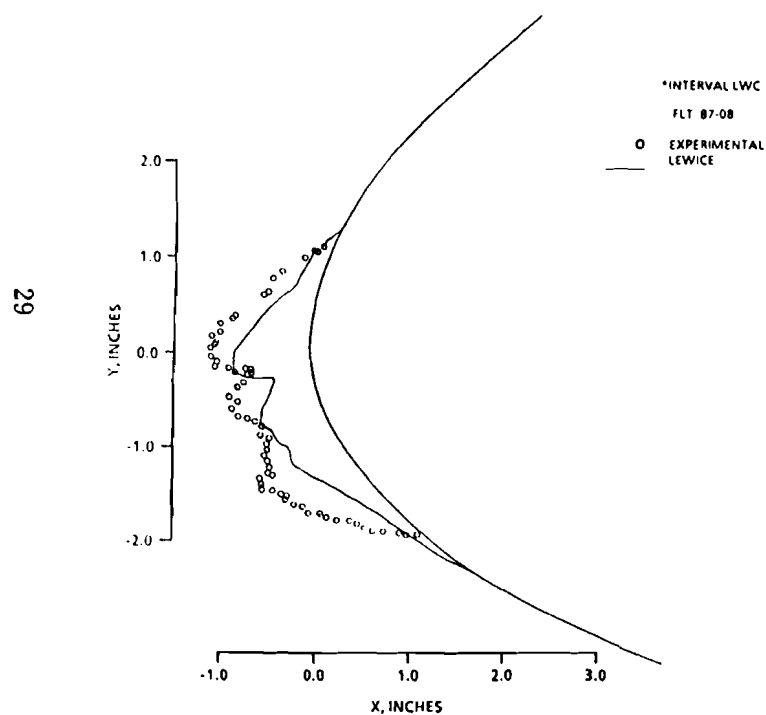
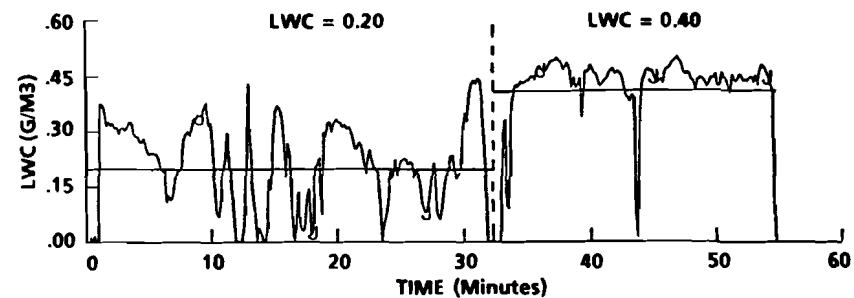
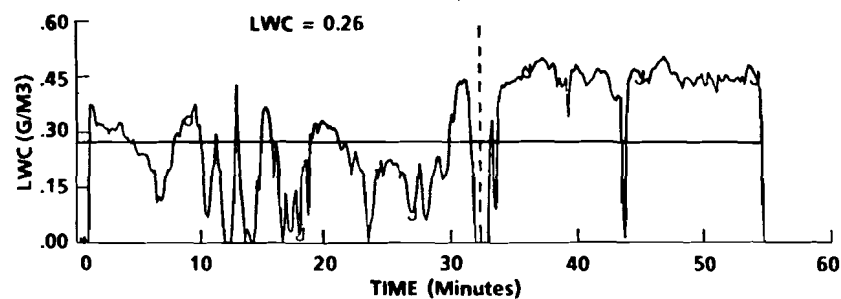


Figure 25a
LEWICE Comparison Without Subinterval Averaging

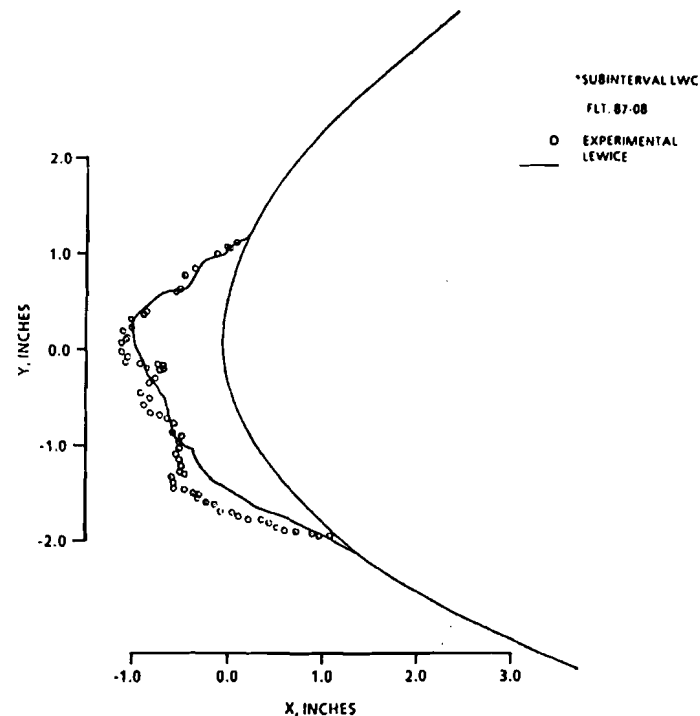


Figure 25b
LEWICE Comparison With Subinterval Averaging

Figure 25
Comparison of LEWICE Predictions for Flight 87-08
With and Without Subinterval LWC Averaging

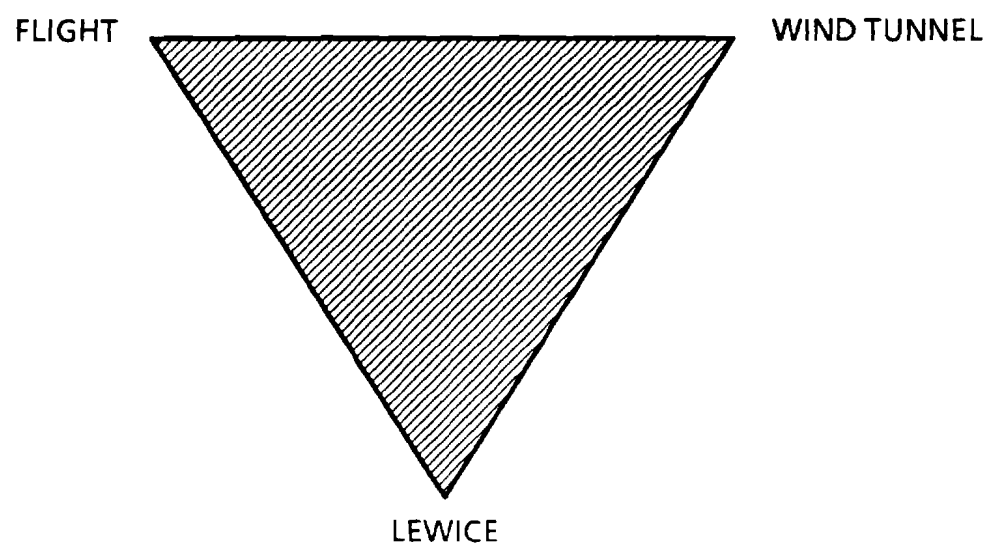


Figure 26
NASA Aircraft Icing Analysis Program

TABLE 1 - TWIN OTTER TIME-AVERAGED FLIGHT DATA

FLIGHT	84-29	84-34	85-14	85-17	85-24	86-17	86-20	86-21	86-31	86-33	87-08	87-10
Duration of Icing Encounter, min.	12	22	58	60	22	19	54	45	62	39	62	39
Type of Ice	Glaze	Mixed	Rime	Rime	Mixed	Glaze	Glaze	Glaze	Rime	Glaze	Mixed	Mixed
Airspeed, m/s	65.59	70.37	71.30	59.98	70.88	69.44	65.48	67.70	70.83	66.36	60.80	66.51
Static Temperature, °C	-5.3	-6.5	-14.7	-10.3	-14.3	-7.2	-9.5	-5.0	-10.0	-5.6	-7.7	-9.2
Altitude, m	1648	1700	2055	1267	2013	2228	1878	1312	2341	1206	1300	1730
Liquid Water Content, g/m ³ (J.W. unless noted)	0.25	0.58	0.17	0.23	0.42	0.32	+	++	+	++	0.35	0.26
Median Volume Diameter, Microns	16.0	14.4	11.3	12.4	15.2	21.0	14.9	14.9	15.1	13.3	13.8	12.5
Angle of Attack, Degrees	2.1	1.6	1.0	2.4	1.5	1.6	1.8	1.6	1.2	1.1	2.3	1.7

+ Leigh
 + + Rosemount

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APPENDIX A

RATING THE AGREEMENT OF LEWICE PREDICTED ICE SHAPES WITH NATURAL ICE SHAPES

In assessing the results of this study, it is desirable to have criteria of agreement between prediction and experiment. The approach suggested here is to consider separately three attributes: (1) limits of impingement; (2) cross-sectional area; (3) shape. The first two can be treated quantitatively by measuring the percentage difference between prediction and experiment, although only a rough visual assessment has been made here. A rating of 1 roughly corresponds to a difference of 10% or less, 2 to 20%, 3 to 30%, 4 to more than 30%. (Note that the 10% difference can be regarded as corresponding to a kind of "variability band" reflecting the variability in cross-section along the wing span.) In cases where it was especially difficult to distinguish between a rating of 1 and 2, say, a 1.5 was awarded. The third attribute, shape, does not easily lend itself to a qualitative approach. One must ask if the prediction captures the important features of the actual ice shape (without predicting any additional important features not present). This requires a judgement as to what features are important (which may depend on the intended application for the predictions), as well as to whether a feature has been "captured" and, if so, how well. We will simply offer our admittedly subjective judgement, this time with a rating of 1 corresponding to excellent, 2 to good, 3 to fair, and 4 to poor, and with halves again allowed in cases of indecision. The ratings for all three attributes are given for each flight in table A1. This admittedly crude rating system should serve as a stimulus to discussion and perhaps to the formulation of a better system; if LEWICE is to be modified to achieve greater physical realism, there should be a systematic way to determine if greater predictive accuracy has been achieved as well.

A summary of the ratings is presented in table A2. Note that the predictions were rated at least 2.5 on impingement limits in ten cases out of twelve, on cross-sectional area in ten cases out of twelve, and on shape in seven cases out of twelve.

TABLE A1. RATINGS OF THE LEWICE PREDICTIONS FOR THE TWELVE FLIGHTS

	Impingement Limits	Cross-sectional Area	Shape
Flight 84-29	2	2	2
Flight 84-34	2.5	1	2
Flight 85-14	1	1.5	1.5
Flight 85-17	3	1.5	3
Flight 85-24	1.5	1.5	2.5
Flight 86-17	1	1.5	1
Flight 86-20	1.5	1.5	4
Flight 86-21	1.5	1.5	2.5
Flight 86-31	3.5	4	3
Flight 86-33	2	2	3.5
Flight 87-08	1.5	2	2.5
Flight 87-10	2.5	3	3

TABLE A2. SUMMARY OF RATINGS

Rating	Impingement Limits	Cross-sectional Area	Shape
1	2	1	1
1.5	4	6	1
2	2	3	2
2.5	2	0	3
3	1	1	3
3.5	1	0	1
4	0	1	1