



AEROSPACE RECOMMENDED PRACTICE

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Droplet Impingement and Ice Accretion Computer Codes

RATIONALE

ARP5903 has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE:

This document provides information, guidelines, and practices for the application, use, and administration of two-dimensional and three-dimensional droplet impingement and ice accretion computer codes. The codes provide computational simulations of inflight icing that predict droplet trajectory, water loading, and ice accretion on aircraft components. These ice accretion characteristics are used during the aircraft design and certification process.

1.1 Background:

The U.S. Federal Aviation Administration established an icing plan in 1997 to respond to a need for a comprehensive program to create an awareness of inflight icing issues and to establish documents to provide training and guidance for regulatory authorities, aircraft operators, research organizations, and aircraft manufacturers. The FAA published a 14-task plan, entitled the "FAA Inflight Aircraft Icing Plan," and identified groups of people within the U.S. Government and throughout the aircraft industry to address the action items contained in this plan. Task 11 of this plan called for the development of "validation criteria and data for simulation methods used to determine ice shapes on aircraft." It also indicated that this task was to include data on "wind tunnel[s], ice accretion computer codes, and icing tankers." The FAA suggested "a coordinated effort among research organizations, industry, and regulatory authorities" and individuals were asked to participate in this work. Task 11 was divided into three subtasks and the people that participated in Subtask A were tasked with addressing criteria for the use of tankers, tunnels, and codes. Three documents were developed by the members of the Task 11A Working Group and these three documents are being published as SAE ARPs. While each document follows a format that is appropriate to the topic, the three documents provide guidance for the application of codes (ARP5903), tankers (ARP5904), and tunnels (ARP5905) to the icing certification or qualification process.

1.2 Purpose:

The purpose of this document is to provide a resource for industry and certification authorities relative to the capabilities and uses of droplet impingement and ice accretion computer codes. As with any tool, the use of droplet impingement and ice accretion codes requires some judgment on the part of the user as to whether the code is appropriate for the intended use. This document provides information, guidelines, and practices with respect to the use of these tools. These codes, when used properly, can provide the designer and airworthiness authorities with useful information about water loading and ice growth on aircraft components, and on other phenomena associated with the ice growth process.

This document describes practices used by code developers for the creation and documentation of droplet impingement and ice accretion codes and practices used by aircraft and component manufacturers when employing these codes for the design and certification or qualification of their products. Applications of these codes are described.

1.2 (Continued):

Since other practices exist or may be developed in the future, these guidelines and practices are not considered all inclusive nor are certification authorities compelled to accept implementation of these guidelines and practices as part of an aircraft certification program.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the referencing document. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AIR5504	Aircraft Inflight Icing Terminology
AIR5906	Ice Shape Measurement and Comparison Techniques Workshop
ARP5904	Airborne Icing Tankers
ARP5905	Calibration and Acceptance of Icing Wind Tunnels

2.1.2 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

FAA Reports (Documents with numbers such as DOT/FAA/AR-00/37 or DOT/FAA/CT-88/8-3) are available through the National Technical Information Service (NTIS), Springfield, VA.

FAA Regulations: Superintendent of Documents, U.S. Government Printing Office, Internet: bookstore.gpo.gov, Phone: (202)512-1800, Fax: (202)512-2250, Mail: Stop SSOP, Washington DC 20402-0001.

Advisory Circulars: U.S. Department of Transportation, Subsequent Distribution Office, SVC-121.23, Ardmore East Business Center, 3341 Q 75th Avenue, Landover, MD 20785.

2.1.2 (Continued):

-----	"FAA Inflight Aircraft Icing Plan," United States Department of Transportation, Federal Aviation Administration, April 1997.
-----	U.S. Standard Atmosphere, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration and United States Air Force.
AC 20-73	U.S. Department of Transportation, Federal Aviation Administration Advisory Circular, Aircraft Ice Protection, April 21, 1971.
ADS-4	Engineering Summary of Airframe Icing Technical Data, FAA Technical Report ADS-4, March 1964.
CFR 14 Part 23	Title 14 of the US Code of Federal Regulations, Part 23, Airworthiness Standards, Normal, Utility, Acrobatic, and Commuter Category Airplanes.
CFR 14 Part 25	Title 14 of the US Code of Federal Regulations, Part 25, Airworthiness Standards, Transport Category Airplanes.
CFR 14 Part 29	Title 14 of the US Code of Federal Regulations, Part 29, Airworthiness Standards, Transport Category Rotorcraft.
CR-1999-208690	Validation Results for LEWICE 2.0, NASA CR-1999-208690, January 1999.
DOT/FAA/CT-88/8	Aircraft Icing Handbook, Volumes 1, 2 and 3, DOT/FAA/CT-88/8, March 1991 and subsequent revisions.

2.2 Applicable References:

Anderson, D. N., Hentschel, D. B. and Ruff, G. A., "Measurement and Correlation of Ice Accretion Roughness," AIAA-98-0486, 36th Aerospace Sciences Meeting, Reno, NV, January 1998.

Ruff, G. A., "Automated Comparison of Ice Accretion Shapes," Paper No. AIAA-99-0625, 37th Aerospace Sciences Meeting, Reno, NV, January 1999.

AVT RTO-TR-038, "Ice Accretion Simulation Evaluation Test," NATO RTO, November 2001.

Wright, W.B., and Rutkowski, A., "Validation Results for LEWICE 2.0," NASA CR-1999-208690, January 1999.

2.3 Definition of Selected Terms:

The following terms are used in this document. Additional clarification on the meaning of some terms is given in 5.3. The SAE Aircraft Inflight Icing Terminology AIR is a resource for the definition of additional icing terms.

2.5 DIMENSIONAL: Any method that combines 2D and 3D calculation procedures.

ANTI-ICING: The prevention of ice formation or accumulation on a protected surface, either by evaporating the impinging water or by allowing it to run back and off the surface or freeze on non-critical areas.

APPENDIX C ICING ENVELOPES: The 14 CFR Parts 25 and 29, Appendix C icing envelopes for continuous maximum and intermittent maximum icing conditions.

COLLECTION EFFICIENCY: See water catch efficiency.

EULERIAN DROPLET TRAJECTORY COMPUTATION: A method for calculating the dynamics of the forces exerted on water droplets in the surrounding airflow using a frame of reference that is fixed in space. Thus, the mass flux into and out of a region in space is the outcome of this approach. This approach typically results in equations describing the mass flux through a control volume. These equations are also in a form that is compatible with solution methods normally employed for grid based flowfield codes.

FREEZING FRACTION: The fraction of liquid water that freezes in a given control volume.

ICE CROSS-SECTIONAL AREA: The integral of y with respect to x for the iced coordinates minus the same integral for the clean airfoil (see Equation 1).

$$A = \left(\int y dx \right)_{\text{iced}} - \left(\int y dx \right)_{\text{clea}} \quad (\text{Eq. 1})$$

ICE SHAPE DETERMINATION: Determination of resultant ice shape by computational analysis.

ICING LIMIT: The location farthest aft on a body at which ice accretes. This distance can be measured either as the x distance from the leading edge or as the surface distance from the stagnation point. In this document the icing limit is defined as the x distance from the leading edge.

IMPINGEMENT LIMIT: The location farthest aft on a body at which water droplets impinge on either the upper or lower surface. This distance can be measured either as the x distance from the leading edge or as the surface distance from the stagnation point. In this document the impingement limit is defined as the x distance from the leading edge.

2.3 (Continued):

INVISCID CODE: A code that assumes a zero coefficient of viscosity and, therefore, does not include the effects of fluid shear stresses so that the flow velocity at the surface boundary is the same as the flow velocity of the freestream.

LAGRANGIAN DROPLET TRAJECTORY COMPUTATION: A method for calculating the dynamics of the forces exerted on water droplets in the surrounding airflow using a frame of reference that is fixed on the droplet. These trajectories are typically calculated by determining the forces exerted on individual droplets and then determining the resulting motion of the droplet. The calculation proceeds by sequentially calculating forces and resulting motion as the droplet moves through the flowfield surrounding the body of interest (i.e., the wing, fuselage, engine inlet, etc.) until it either impacts on the body or passes it.

LIQUID WATER CONTENT: The mass of water contained in liquid cloud droplets within a unit volume of cloud, usually given in units of grams of water per cubic meter of air (g/m^3).

LOWER HORN ANGLE: The angle of the lower horn of a glaze ice shape, calculated with the polar direction of 0° being a right-facing horizontal line (see Figure 1). Several approaches have been proposed for the origin of the first line segment, which is the line from some point on or inside the airfoil to the tip of the horn. The first line segment can be measured from the tip of the horn to a fixed reference point at the leading edge (as shown in Figure 1) or near the leading edge, or the first line segment can be measured from the tip of the horn to a fixed reference point at the center of the inscribed circle at the leading edge (defined by the leading edge radius for the airfoil). The second line segment is the horizontal line intersecting the reference point.

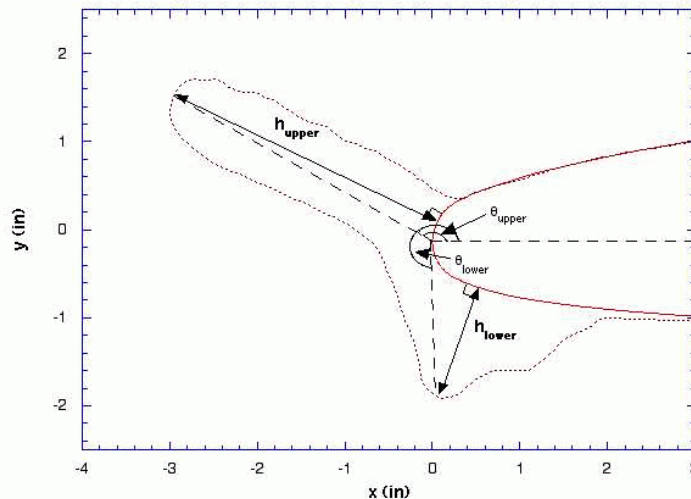


FIGURE 1 – Definition of Lower and Upper Horn Angle

2.3 (Continued):

MEDIAN VOLUME DIAMETER: The droplet diameter, usually given in microns (10^{-6} m), such that one-half the liquid water is contained in droplets smaller than the median volume diameter and one-half the liquid water is contained in droplets larger than the median volume diameter.

MULTI-STEP ICE ACCRETION PROCEDURE: A time-stepping procedure to "grow" the ice accretion; a procedure that calculates the amount of ice accumulated on the surface during a specified time increment and that repeats that calculation over a sufficient number of time increments that add up to the desired exposure time. The flowfield, impingement pattern, energy and mass balances, and ice thickness distribution are recomputed on every time step for the ice shape geometry from the previous step.

NAVIER-STOKES EQUATIONS: The general equations that describe a viscous, compressible flow in a region of space.

PANEL METHODS: A numerical method for calculating the incompressible, inviscid flow about a two- or three-dimensional body or configuration of arbitrary shape. The body is represented by panels (which may be line segments in two dimensions and planar regions bounded by polygons in three dimensions).

PEAK THICKNESS: The length of the line segment from the tip of the larger horn (if there are more than one) to the nearest point on the clean airfoil. This length approximates the length of the line segment along a unit normal to the surface intersecting the point found to have a maximum length from the surface. The closeness of the approximation depends on the number of points employed in representing the airfoil surface.

POTENTIAL FLOW: Given a flow field specified by a vector function V , if V can be written as: $V = \nabla\phi$ for some scalar function ϕ , then the flow is referred to as a potential flow (and ϕ is called the potential function). Inviscid, irrotational flows are potential flows.

UPPER HORN ANGLE: The angle of the upper horn of a glaze ice shape, calculated with the polar direction of 0° being a right-facing horizontal line (see Figure 1). Several approaches have been proposed for the origin of the first line segment, which is the line from some point on or inside of the airfoil to the tip of the horn. The first line segment can be measured from the tip of the horn to a fixed reference point at the leading edge (as shown in Figure 1) or near the leading edge, or the first line segment can be measured from the tip of the horn to a fixed reference point at the center of the inscribed circle at the leading edge (defined by the leading edge radius for the airfoil). The second line segment is the horizontal line intersecting the reference point.

VALIDATION: The process that confirms the code is functioning as intended, that documentation and code version control meet the standards of the validating organization, and that predicted ice shapes match accepted experimental data in accordance with accepted validation standards within established tolerances.

2.3 (Continued):

VERIFICATION: The process of determining that a model implementation (i.e., the computer code) accurately represents the developer's conceptual description of the model and the code solves the equations used to describe that model.

VISCOUS CODE: A code that includes the effects of the coefficient of viscosity and, therefore, includes the effects of fluid shear stresses near the surface boundary.

WATER CATCH EFFICIENCY: The ratio of water droplet flux at the surface to the water droplet flux in the freestream. Also known as the collection efficiency.

2.4 Abbreviations:

2D	two-dimensional
2.5D	two-and-a-half dimensional
3D	three-dimensional
ACO	Aircraft Certification Office
AIAA	American Institute of Aeronautics and Astronautics
AIR	Aerospace Information Report
ARP	Aerospace Recommended Practices
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
DERA	Defence Evaluation and Research Agency, United Kingdom
FAA	Federal Aviation Administration, United States
IPS	ice protection system
LWC	liquid water content
MVD	median volume diameter
NASA	National Aeronautics and Space Administration, United States

2.4 (Continued):

ONERA Office National d'Etudes et de Recherches Aeronautiques, France

SAE Society of Automotive Engineers

SLD supercooled large droplets

2.5 Symbols:

β local water catch efficiency

E total water catch efficiency

3. INTRODUCTION TO DROPLET IMPINGEMENT AND ICE ACCRETION CODES:

Droplet trajectory and impingement codes and ice accretion codes have been developed by a number of universities, companies, and research organizations around the world. Some of these codes are now in use for the design and certification of aircraft ice protection. Several codes have been developed to determine droplet trajectories around a 2D body in a low speed flight condition, and some of these codes extend this technology to allow the calculation of ice accretion. More recently some codes have been able to calculate droplet trajectories and ice accretions on completely arbitrary 3D configurations. Thus, it remains difficult to generalize limitations of the codes and the type of code that is necessary and/or sufficient to do a particular calculation, since this is highly application dependent and can vary from the points of view of geometric fidelity and physical modeling completeness.

3.1 Elements of Droplet Impingement and Ice Accretion Codes:

A droplet impingement code typically includes the first two of the following calculations, and an ice accretion code typically includes all four of the following calculations:

1. Flow field computation (may be 2D or 3D, inviscid or viscous, incompressible or compressible)
2. Droplet trajectory and impingement computation (droplets may be monodispersed or may be for a droplet size distribution)
3. Heat and mass balance computation (heat transfer coefficient calculation can be a part of the flow field computation)
4. Ice accretion shape computation

- 3.1.1 Flow Field Computation: The first calculation to be performed in an icing simulation is normally that of the airflow around the body of interest. The field of computational fluid dynamics (CFD) has provided many different types of tools to perform such calculations. These software tools range from simple two-dimensional potential flow codes to full 3D Navier-Stokes codes including compressibility, transition, and turbulence. The flow field computations are used to provide input to the droplet trajectory calculation, information for determination of the convective heat transfer in the energy balance, and in some cases to evaluate the aerodynamic performance degradation resulting from the ice shape.
- 3.1.2 Droplet Trajectory and Impingement Computation: Droplet trajectory and impingement codes take the flow field results along with information about the water droplets and body geometry to determine the location on the body that the water droplets will impact. These codes are used to calculate the impingement area and/or impingement limits, the water mass flux at the body surface, the local water catch efficiency (β), and the total water catch efficiency (E). This information can be used to determine the mass and associated energy flux values input into the ice growth calculation, the extent of ice protection system coverage and/or the energy that is required to obtain efficient anti-icing (e.g., for windscreen anti-icing power density). Computational studies have shown that for conditions within the Appendix C icing envelopes, the MVD can generally be used for ice shape simulation and the largest droplets of the spectrum can be used to calculate impingement area. The trajectories can be calculated either by a Lagrangian approach or an Eulerian approach.
- 3.1.3 Heat and Mass Balance Computation: The objective of this computation is to obtain the ice mass that accumulates on the body of interest for a given icing exposure. This information can be used to evaluate the effect of the impact of shed ice on another part of an aircraft or the effect of ice ingestion into an engine. Knowing the ice mass (and not the shape) can be important when the ice will have a limited impact on aircraft aerodynamics and the differences between calculated shapes and actual ice shapes is not as important as the mass of ice. A conservative estimate of the mass can be obtained directly from the catch efficiency value on the clean body. The shape of the ice mass may become important when evaluating the fragmentation and trajectory of the shed ice.

The goal of a computational model is to determine the ice growth rate at every location on a body. Heat and mass balances govern this rate.

3.1.3 (Continued):

The main heat fluxes (transfers of heat) are:

- a. convection
- b. evaporation/sublimation
- c. heating of the impacting water and cooling or heating of the running water from a neighboring element or surface, and cooling of ice
- d. latent heat obtained during the freezing of the water
- e. droplet kinetic energy

The 2D codes use a one-dimensional “control volume” approach to calculate this heat and mass balance and the surface is meshed and divided into small elements over which the control volume is defined. Within these control volumes the temperature and the other physical variables are assumed to be constant in 2D codes so that heat transfer balance can be applied.

In the control volume approach positive heat fluxes are considered to be sources and negative ones to be sinks. The heat balance is achieved by varying the freezing fraction and the equilibrium temperature. When the freezing fraction in a control volume has a value between 0 and 1, the water does not freeze completely in that control volume and the remaining water flows into the following (downstream) control volume, where a new heat and mass balance is solved. When the freezing fraction is equal to 1, there is no flow into the next control volume. The inputs of the heat and mass balance calculations include the local water catch efficiency value and the heat transfer coefficient value. The heat transfer coefficient computation for swept wings can be calculated using a 2.5D code that accounts for the velocity component parallel to the leading edge.

The 3D codes represent the surface of the body as a body conforming mesh or series of finite elements. Within and across these regions, the temperature and other physical variables are assumed to vary and a general heat transfer balance is applied. In these calculations, full 3D Navier-Stokes calculations, 3D boundary layer codes coupled to potential flow methods, or 3D corrections to 2D codes have been used by various developers to represent the velocity field. The implementations of the mass and energy transfer processes for these codes are varied. The reader is referred to the individual write-ups in Appendix A for details or for contact information regarding each code.

- 3.1.4 Ice Accretion Shape Computation: Once the mass of ice accumulated during an exposure is known, the shape of the resulting ice can also be calculated. There are several strategies for performing this calculation and these strategies form the basis for the logic of the computational tools. In general, the mass of ice that freezes at a given location is converted into a volume through the application of the mass-volume-density relationship. This volume is then added to the geometry of the body to form an ice-airfoil geometric entity. The methods used to add this geometry vary from code to code and can be one of the features that distinguish one code from another. The shape of the computed ice can be used in several ways. For example, the computed ice shape can be used to build a simulated ice shape that is attached to the aircraft, aircraft model, wing model, or airfoil model for aerodynamic testing in a wind tunnel or in flight. Likewise, the computed ice shape can be used in a subsequent CFD calculation to determine the aerodynamics of the iced body.

3.2 Survey of Current Droplet Impingement and Ice Accretion Simulation Software:

Developers of icing codes were surveyed to determine the intended applications of their icing codes. Included in Appendix A is a compilation of the data collected. Each code is described, points of contact and references are listed, and a matrix is provided of the developer's intended applications of the code in the calculation of impingement limits and water catch efficiency, and in the determination of ice shapes for a range of aircraft components. For example, in the matrix for LEWICE 2.0 (2D) there is no check in the box across from "Spinner" in the column labeled "Ice Shape Determination." This indicates that, in the judgment of the code developer, LEWICE 2.0 (2D) was not developed for this type of calculation. However, there is a check in this box in the LEWICE3D matrix, indicating that LEWICE3D was developed for this type of calculation. As another example, the matrix for LEWICE 2.0 (2D) includes a check in the box across from "Wing – Swept less than 25 degrees" in the column labeled "Ice Shape Determination." This indicates that, in the judgment of the code developer, although the flow is 3D, the 2D icing analysis of LEWICE 2.0 is sufficient to predict the ice shape.

There may be valid applications of the icing codes that are beyond the developer's intended application of the code. This is discussed in Section 4. For example, in the matrix for LEWICE 2.0 (2D) there is no check in the box across from "Fuselage Components" in any of the columns. This indicates that, while in the judgment of the code developer, LEWICE 2.0 (2D) was not necessarily developed for this calculation, a user may prefer to use LEWICE 2.0 (2D) to predict the droplet impingement and ice accretion that will form on a radome under specific flight and meteorological conditions. It may not always be necessary to fully model the component or flow conditions to be able to calculate a representative ice shape. Although the flow about a radome is certainly 3D, it may be sufficient to conduct a 2D calculation and then use engineering judgment in order to obtain a 3D ice shape. It is incumbent on the code user or certification applicant to substantiate acceptably that the results of a 2D code can be used for a specific 3D application or aircraft configuration. This may require correlation of code results with experimental data.

3.2 (Continued):

It is not the intent of this document to evaluate experimental data to assess the performance of any of the codes listed, nor is this document intended to provide guidance as to whether a particular code is acceptable or has been validated. Thus, the document does not indicate whether the developers' assessments of their codes are based on comparison to experimental data for use in certification. It remains the responsibility of the code user or the certification applicant to provide sufficient data to support or validate the application of a particular code for use in certification.

4. DROPLET IMPINGEMENT AND ICE ACCRETION CODE APPLICATIONS:

Many different codes have been developed to simulate droplet trajectories, impingement, and the ice accretion process. This section describes code limitations in general terms and explains how a given code might be used for components of an aircraft that might appear to be beyond the intended use of the code.

For some codes and applications, the ice accretion process is well understood and computed results compare favorably with a large database of acceptable icing data. An example is the use of a 2D code for rime ice accretion on an unswept, single element airfoil section. However, since codes depend upon the modeling of the flow of water from one control volume to another as the mechanism for the development of ice shapes in glaze conditions, glaze ice accretions are more difficult to predict than rime ice accretions.

In some analyses, the ice accretion process is well understood, but the code is used beyond the developer's expected application of the code. This kind of analysis requires more comparison tests, and/or a comprehensive explanation of the way the code was used, and a description of any corrections that were implemented for the application. An example of this type of analysis is the use of a 2D code for glaze ice prediction on a moderately swept wing.

Regardless of the understanding of the ice accretion process, if the code approach is new or under development for a particular application, comparisons with test data are required for the code to be used for the particular application.

When simulation codes are not currently available but the ice accretion process is adequately understood, such as when a configuration is extremely complex, the analysis can proceed if it is possible to restate the icing problem in a manner that falls within the capabilities of an existing code. For example, it may be possible to reduce a complex configuration to several components without affecting the quality of the icing analysis.

When the ice accretion process is not adequately understood, code development for the application is inhibited. Further experiments and research are necessary to support the development of codes for the application. An example of this is lobster tail or scallop ice shapes on a highly swept wing.

4. (Continued):

The goal of both developers and users is to advance code development to where the intended application and the code are well matched so that the calculation for a given configuration can be performed with confidence. Until that goal is met, it is permissible to use codes outside the developer's expected applications, as described above.

4.1 Uses of Droplet Impingement and Ice Accretion Codes:

Codes may be used in the design or certification processes for different objectives and the minimum requirement is not the same in each objective. The use of a code depends heavily on the objective and the application. The main uses for icing codes are given in the sections below. Appendix B presents an example of methodology for the application of an ice accretion computer code for trajectory calculations.

4.1.1 Droplet Trajectory Calculation on Components:

- 4.1.1.1 Unswept (Straight) Wing: 2D codes may be used to calculate the droplet trajectories and local or total water catch efficiency for ice accretion characteristics of an airfoil at a station along the span of an unswept wing, except where the local airflow is significantly three-dimensional, such as near the wing tip, near the intersection of nacelles, the fuselage and other components, and at wing planform breaks. See the example in Appendix B. It is not necessary to make a distinction between wing and tailplane for droplet and water loading, as long as the local flow angle and velocity are used in the calculation. It is especially necessary to determine the local flow field direction to properly calculate the droplet impingement, such as accounting for induced flow angularity, wing geometric and aeroelastic twists, and tailplane downwash caused by the wing (see Figure 2). A 2D viscous code may be necessary if boundary layer separation is present. This may occur at higher angles of attack or higher Mach numbers due to compressibility effects. The viscous code selected should model the expected separated boundary layer wake.

- 4.1.1.2 Swept Wing: 2D codes may be used to calculate droplet trajectories, droplet impingement, and water loading on swept wings at specific locations when the aspect ratio is sufficiently large to allow the use of a 2D aerodynamic code for the clean wing. See the example in Appendix B. If the sweep angle (γ) at the leading edge and the trailing edge are the same, inviscid 2D codes can be used on a cross-section perpendicular to the leading edge (Dorsch correction) for the trajectories computation (see Figure 3). Induced flow angularity of the finite wing should be considered. It may be demonstrated by a code user that 2D codes can be used with the following corrections if the velocity component parallel to the leading edge remains constant as it would for an infinite wing:

$X \rightarrow X \cos \gamma$	X coordinate
$Y \rightarrow Y$	Y coordinate
$U_{\infty} \rightarrow U_{\infty} \cos \gamma$	Freestream velocity
$C \rightarrow C \cos \gamma$	Chord
$\alpha \rightarrow \alpha / \sin \gamma$	Angle of attack

In this case the 3D catch efficiency value is $\beta_{3D} = \beta_{2D} \cos \gamma$.

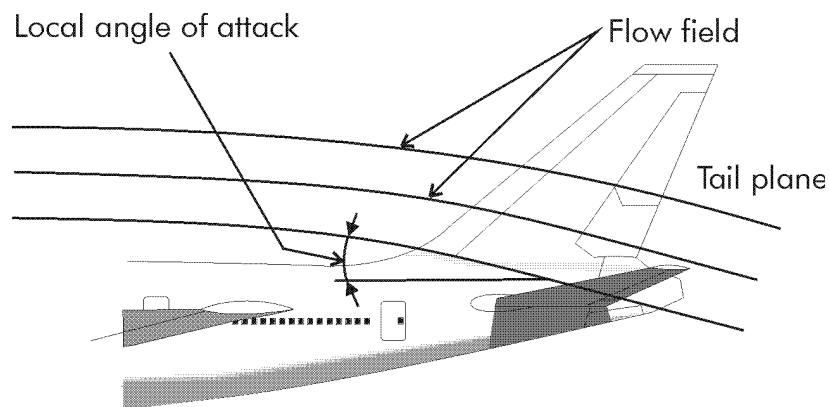


FIGURE 2 - Streamline Deflection from the Wing to the Tailplane

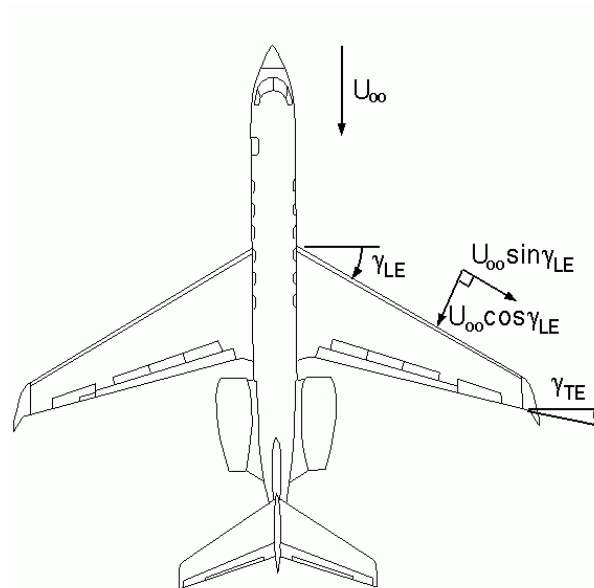


FIGURE 3 - Trajectories Computation on a Swept Wing

4.1.1.2 (Continued):

The use of 2D codes is acceptable in areas where it is not important to account for nacelle, engine, or propeller effects. However, close to the wing tips or for low aspect planforms, there will be 3D effects and use of a 2D code may no longer be acceptable. (See 4.1.1.5 for additional information on twisted wings.) If the leading edge and trailing edge sweep angle are different, the sweep angle (γ) and angle of attack (α) used in the 2D icing code may be determined first using a 3D inviscid code. The sweep angle (γ) is calculated from the spanwise component of velocity at the stagnation line ($U_s = U_{\infty} \sin(\gamma)$), and the angle of attack in the 2D code should give the same stagnation location as the stagnation line in the 3D code. If the wing has twist, 3D effects can be important and a 3D code is recommended.

- 4.1.1.3 Fuselage Components - Radomes and Air Intakes: The flow field and droplet trajectories can be calculated with 3D or 2D axisymmetric flow codes. The 2D codes can be used in the symmetrical plane. The water catch efficiency should be corrected by the ratio of the droplet distance from the symmetrical axis away from the profile to the distance from the symmetrical axis at the impact location, such that the 3D catch efficiency β is

$$\beta_{3D} = \beta_{2D} * r_i / r_{\infty} \quad (\text{see Figure 4}) \quad (\text{Eq. 2})$$

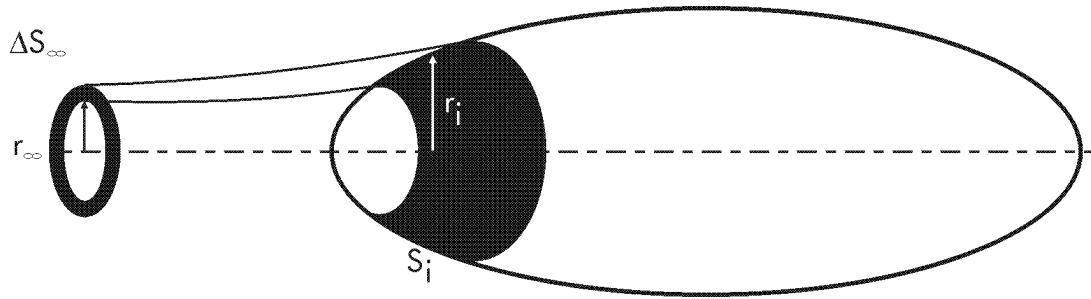


FIGURE 4 - Catch Efficiency Calculation on Axisymmetric Body

- 4.1.1.4 Fuselage Components - Probes and Antennae: For those components mounted adjacent to another body, such as a probe mounted on a fuselage, a 3D trajectory code or 2D axisymmetric trajectory code (depending on the configuration and component location) may be used to determine the droplet trajectories and local LWC at the component. This LWC can be modified (increased or decreased) due to droplet deflection around upstream aircraft components as shown in Figure 5. This effect is droplet size dependent, thus potentially altering the droplet distribution at the impingement site. The local ice accretion for the component can then be calculated with a 2D, 3D, or 2D axisymmetric code.

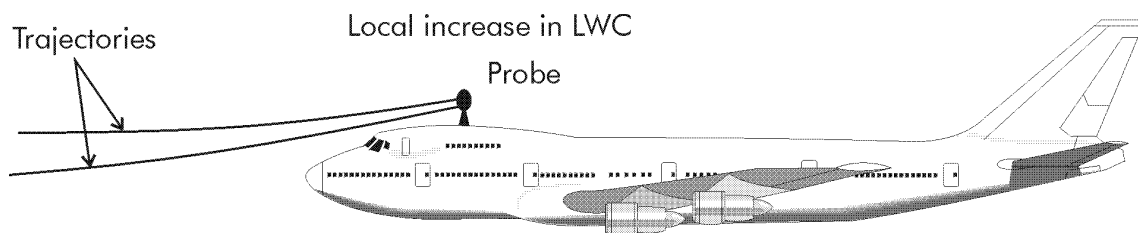


FIGURE 5 - Deflection of Non-Impinging Trajectories, Causing a Local Increase in LWC (Droplet Enhancement)

- 4.1.1.5 Winglets and Other Wing Components: The use of 2D codes may be acceptable for winglets and other components if the flow is substantially 2D. However, care should be taken when using MVD for the droplet trajectories, since MVD may not always be appropriate because of shielding effects of upstream surfaces. In some cases, because of the component location downstream of another component, only the larger droplets impinge on the downstream component and the use of a modified droplet distribution may be necessary (see Figure 6). 2D codes can be used for multi-element effects if the profile is modified to take into account the aerodynamics with flap deflection. Since winglets tend to operate at low angles of attack, 2D codes may be used if the local angle of attack and velocity are used; however, a large experience base does not exist to justify confident use of the 2D codes in areas where local flow conditions can be highly three-dimensional and viscous, such as at the wing intersection, at the winglet tip, and with high winglet leading edge sweep.

4.1.1.5 (Continued):

In the case of multi-element high-lift systems, the flow between elements is highly complex and the use of potential flow codes, as is the normal procedure for most current 2D codes, may be questionable. In such cases, a Navier-Stokes based flow calculation may be needed to provide the flow field for the droplet trajectory calculation. Additionally, the use of Lagrangian versus Eulerian droplet trajectory calculations should be examined to determine which is more appropriate for these conditions.

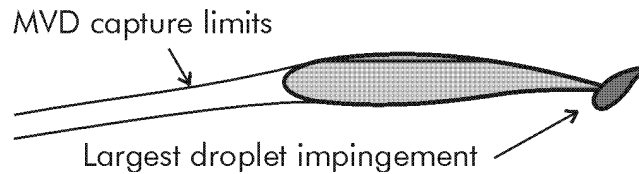


FIGURE 6 - Impingement on a Winglet Horn

- 4.1.2 Ice Accretion Calculation: The vast majority of ice shape measurements made for validation of icing simulation codes has been for 2D airfoils and circular cylinders. Calculations of ice shapes for these geometries, therefore, have the largest amount of validation. Typical comparisons indicate that icing simulation codes do a good job of simulating rime ice shapes and an inconsistent job of simulating glaze or mixed ice shapes. This generalization should be verified for each individual code and can be accomplished through use of the publicly available ice shape data published by NASA and the NATO/RTO Working Group (see 2.1.2).

Codes with a 3D flow calculation and 3D droplet trajectory calculation coupled to a 2D ice growth calculation have been used for ice accretion calculations. In such cases, the ice growths are typically calculated at several stations around the body of interest. Such calculations have been compared to a small number of experimental results and have shown reasonable agreement.

Currently there are no significant experimental ice shape data available for comparison to 3D computational simulations. As a result, the capabilities and validity of the simulation tools are not as well known as the existing 2D codes.

- 4.1.2.1 Unswept (Straight) Wing: 2D codes may be used to calculate the amount and shape of ice growth on an airfoil at a station along the span of an unswept wing. However, this may not be done where the local airflow is significantly three-dimensional, such as near the wing tip, near the intersection of nacelles, the fuselage and other components, and at wing planform breaks. It is not necessary to make a distinction between wing and tailplane for ice accretion, as long as the local flow angle and velocity are used in the calculation. Ice accretions vary somewhat from station to station along the span of even a straight 2D wing model mounted in an icing tunnel. 2D codes do not capture this spanwise variability and thus can be considered to represent some nominal value for the ice shape at any given location. 2.5D and 3D codes can be used on unswept wings in an effort to capture some of these effects. However, the research and validation on unswept wings to date has focused on 2D calculations.
- 4.1.2.2 Swept Wing: For swept wing configurations, tunnel experiments have indicated that at certain combinations of sweep angle and airspeed, the ice deposit varies more radically along the span of a wing. Feather growth can result in the development of a periodic ice shape structure known as a lobster tail or scallop ice shape (see Figure 7). The lobster tail growth increases the volume of deposited ice when the "filling ratio" (the ratio of actual ice shape density to a 2D ice density) is less than 1. Codes are under development to calculate swept wing ice shapes. Constant span shapes can be calculated with 2D, 2.5D, and 3D codes. Engineering judgment suggests that aerodynamic effects resulting from these uniform ice thickness models could be more adverse than the effects resulting from scalloped ice shapes that would result from the same icing conditions. The ice shapes obtained with a uniform ice shape calculation that are of equivalent or greater size than those obtained with a non-uniform calculation can be expected to impose similar or more severe aerodynamic performance penalties.

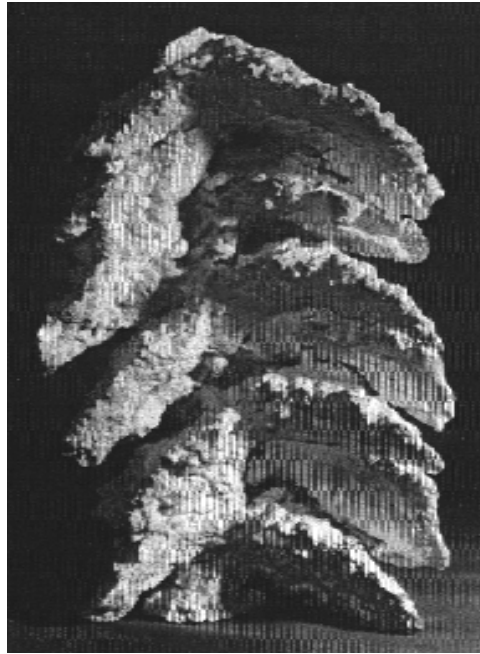


FIGURE 7 - Front View of a Lobster Tail or Scallop Ice Formation

- 4.1.2.3 Fuselage Components - Radomes and Air Intakes: The ice growth on radomes and air intakes can be predicted with 3D, 2.5D, or 2D codes. With any type of code, care should be taken to assure that enough of the surrounding geometry and flow field is modeled to assure that water droplets will indeed impinge on the body of interest and that the potential for either shadowing (upstream deflection or interception of approaching droplets) or concentration (narrowing of the local trajectory paths relative to their original separation distance) is accounted for in the simulation. With 2D codes additional caution should be taken to assure that 3D effects are not important. For example, a 2D calculation might be considered for an axisymmetric engine inlet whereas a 3D code may be more appropriate for a non-axisymmetric inlet.
- 4.1.2.4 Fuselage Components - Probes and Antennae: See the comments regarding droplet trajectory calculations for such geometries in 4.1.1.4. The use of 2D, 2.5D, or 3D codes will be highly dependent on the geometry of the body being simulated. The ice accretion on a probe or antenna having a cross-section of a circular cylinder might be calculated with a 2D code. Recent evaluations of 2D codes attempting such calculations indicate that the correct determination of the convective heat transfer coefficient is critical to simulating the ice growth. For other, non-cylindrical probe geometries a 3D calculation may be warranted. Most of the available experimental data for comparison to codes has been for circular cylinders.

- 4.1.2.5 Winglets and Other Wing Components: See the comments regarding droplet trajectory calculations for such geometries in 4.1.1.5. The use of 2D codes for such calculations has not been validated by comparison to experimental data. 2.5D and 3D codes may be the more appropriate tools, however, they have not been validated for these purposes either. As in most of the nominally 3D geometries, there is not a large amount of data available at this date for validation of codes.

There is one component under this category that has had some validation. Multi-element airfoils have been tested in the NASA Glenn Icing Research Tunnel. Two series of tests have provided ice shape data for comparison to icing simulation codes. The data has been used for comparison to 2D codes and results suggest that such codes can be used for these geometries. However, there has not been sufficient data at this date to warrant the same degree of confidence in such simulations as is placed in simulations of single element geometries. Current research is investigating the use of higher order codes to evaluate these geometries.

- 4.1.2.6 Rotating wing: The use of a 2D inviscid code may be acceptable for rotor blade ice accretion calculations.

5. COMPARISON PARAMETERS:

The validity of ice shapes calculated by a code may be judged by the geometric fidelity of the computed ice shape with acceptable empirical ice shapes. Validity of drop impingement codes may be judged by the fidelity of the calculated impingement limits and water catch characteristics relative to that of acceptable empirical data. Also, the appropriateness of a code for a particular application can be determined by comparing certain parameters that are selected depending on the purpose of the analysis and the intended use of the code results.

The parameters listed below have been selected by the FAA 11.A Working Group for possible use in comparing ice accretion and impingement codes with test data. These parameters are primarily related to airfoils, but some also apply to other aircraft components. The first eight parameters were targeted for use in ice shape (ice accretion) code comparisons, and the subsequent five parameters were selected for use in impingement code comparisons. The parameters are listed in order of importance for determining the accuracy of code comparisons. Comparison parameters which were identified as being used by various organizations, but considered to be less important for this study, are included following the main parameter list. Note the following large ice shape parameters do not address hazardous thin ice, for which surface roughness may be a significant parameter.

5.1 Parameter List:

5.1.1 Ice Shape Evaluation Parameters: (see 2.3 for the definition of terms).

TABLE 1

Rank	Parameter	Units	Code Conservatism (Versus Dataset)
1	Upper (suction surface) horn peak thickness (height)	---	Equal or greater height
2	Upper Horn Angle (at upper peak thickness)	Degrees	Criticality of location
3	Lower (pressure surface) horn peak thickness (height)	---	Equal or greater height
4	Lower Horn Angle (at lower maximum thickness)	Degrees	Criticality of location
(Note that the first four parameters presuppose that icing horns exist, which is not always the case)			
5	Total ice cross-sectional area	---	Equal or greater area
6	Leading edge minimum thickness	---	Equal or lesser thickness
7	Upper icing limit	% x/c*	Equal or greater x/c
8	Lower icing limit	% x/c*	Equal or greater x/c
* ~ Percent of local component chord			

TABLE 2

Rank	Parameter	Units	Code Conservatism (Versus Dataset)
1	Upper impingement limit (suction surface)	% x/c*	Equal or greater x/c
2	Lower impingement limit (pressure surface)	% x/c*	Equal or greater x/c
3	Total water catch efficiency, E	---	Equal or greater magnitude
4	Maximum local water catch efficiency, $\beta_{\max}$	---	Equal or greater magnitude
5	Water catch efficiency (Beta) curve	---	Equal or more adverse β distribution
* ~ Percent of local component chord			

- 5.1.2 Other Icing Parameters Considered: Several other parameters were considered for this report. The following list, included here for completeness, shows those parameters that were determined to be of less significance for code evaluations.

TABLE 3

Parameter	Units
Cavity width between horns	---
Width (thickness) of upper horn	---
Summation of thickness error	---
Upper ice cross-sectional area	---
Lower ice cross-sectional area	---
Ice roughness measurement	---
Parameters developed for ice shape evaluation by Dr. Gary Ruff	
Normalized difference in maximum coefficient, E1	---
Frequency weighted difference, E2	---
Maximum ice width geometric parameter	---
Y=0 ice thickness geometric parameter	---
Maximum ice thickness geometric parameter	---
Impingement width geometric parameter	---

5.2 Definition Sources:

There are several sources that describe the 25 parameters listed above. The Dynacs, Boeing, and Drexel University presentations from the Ice Shape Measurement and Comparison Techniques Workshop (see AIR5906) are excellent sources, especially to obtain the descriptions and definitions of the Drexel parameters.

5.3 Clarification of Parameter Definitions:

- 5.3.1 Horn Angle: Many ice shapes have nearly horizontal horns and this angle is defined as 180°. The use of an aft facing line as the origin of the angle is recommended, because otherwise, a forward facing horizontal horn would have a zero angle. Use of a fixed reference point at the center of the leading edge radius of curvature, or the leading edge point itself, makes it easier to obtain the ice thickness than trying to define the surface normal.
- 5.3.2 Leading Edge Minimum Thickness: The leading edge minimum thickness is the minimum ice thickness in the region between the upper and lower ice horns of a glaze ice shape. This term has no meaning for a rime ice shape. This term is non-dimensionalized by dividing by the maximum ice thickness, which is defined as $LWC \times V \times \text{time} / \text{ice density}$. This thickness is a geometric means of finding an approximate freezing fraction.

- 5.3.3 Upper and Lower Icing Limit: The location on the iced airfoil beyond which no ice adheres including non-contiguous ice accretions such as feathers, beads, and frost. The use of the x-coordinate (with x=0 at the leading edge) is preferred for code acceptance evaluations, with the values reported as a percentage of chord. The distance may also be measured as the surface or wrap distance normalized by the chord, with the same reference of 0 at the leading edge and also reported as a percentage of chord.
- 5.3.4 Upper and Lower Impingement Limit: The upper or lower impingement limit is the location on the upper or lower surface of the clean airfoil beyond which no water droplets impinge. This can include non-contiguous water impingement on complicated geometry. The distance is measured in the same way as the icing limits.
- 5.3.5 Total Water Catch Efficiency: The total water catch is the ratio of the forward freestream impingement streamtube width to the projected frontal height between the upper and lower impingement limits, i.e., the proportion of liquid mass flow based on the projected frontal height of the impingement limits that ultimately strikes the airfoil. An alternative (and equivalent) measurement is the weighted average of the water catch efficiencies (see Equation 3). This equation is more universal in that both Lagrangian and Eulerian techniques can use it.

$$E = \frac{\int \beta ds}{\int ds} \quad (\text{Eq. 3})$$

- 5.3.6 Maximum Local Water Catch Efficiency: The value of maximum water catch efficiency ($\beta_{\max}$) can be used to compare a test result to a code result. Thus the $\beta_{\max}$ difference is the $(\beta_{\max})_{\text{experiment}} - (\beta_{\max})_{\text{calculated}}$.
- 5.3.7 Water catch Efficiency Curve: A water catch efficiency curve comparison can be made by summing the water catch efficiencies as follows: $\Sigma [(\text{Water catch efficiency at location } x)_{\text{experiment}} - (\text{Water catch efficiency at location } x)_{\text{calculated}}]$.

5.4 Organization Comments on Parameter Ranking:

Comments on the parameter priority from those organizations surveyed varied widely, but most especially for those parameters that are less widely known. The highest ranked parameters were generally highly ranked by each organization surveyed. Summaries of two surveys are given below.

- 5.4.1 Industry Comments on Parameter Ranking: Upper peak thickness, angle at upper peak thickness and upper icing limit ranked consistently in the top three parameters. The lower icing limit, upper surface ice area, lower surface ice area, lower peak thickness, and angle at lower peak thickness consistently ranked next, but some reviewers considered leading edge minimum thickness to also rank highly. Upper impingement limit and lower impingement limit were ranked as next in importance. The remaining parameters were considered useful only for comparing details of codes, but not useful for ice shapes, or were considered to be of limited value altogether.

5.4.2 Certification Authorities Comments on Parameter Ranking: The most challenging use for the 2D ice prediction codes in certification work is as a tool in the determination of critical ice shapes. Recent work (particularly by the University of Illinois Urbana Champaign, Wichita State University, and NASA Glenn Research Center) suggests that the angle at upper peak thickness and upper peak thickness (protuberance location and protuberance height) are most important to the effect of the ice on aerodynamic performance. The location, shape, and surface texture at the tip of the protuberance and the general airfoil pressure loading may influence the severity of the protuberance's aerodynamic effects. Upper impingement limit and lower impingement limit are in a tie for 3rd because they are used in the determination of the limits of ice protection systems. Overall or total water catch efficiency, E , is directly proportional to the total water catch, which is important in determination of the parameters of thermal ice protection systems. Additional research is needed to establish a ranking of ice shape parameters confidently. The total ice area can be used to estimate water catch and furthermore, estimation of the ice size on a component may be significant in answering shedding questions.

6. GUIDELINES FOR THE USE OF DROPLET IMPINGEMENT AND ICE ACCRETION CODES:

6.1 Overview:

Research organizations, government laboratories, universities, and private companies have developed a variety of droplet impingement and ice accretion codes. The list of users is also varied, and includes corporations, individuals, laboratories, universities, and certification agencies. Blind comparisons of droplet impingement and ice accretion code results have shown that ice shape predictions are inconsistent among codes, users, versions of the same code, and even among users of the same version of a code. The intended capabilities of codes also vary, with some codes designed for specialized analyses while others have generalized capabilities. Certification authorities take into consideration the acceptability of droplet impingement and ice accretion code results when those results are used to demonstrate compliance with ice protection certification requirements. Certification regulations require flight testing of the airplane or its components in measured atmospheric icing conditions to verify the ice protection analyses, to check for icing anomalies, and to demonstrate that the ice protection system is effective.

Flight testing in measured icing conditions is costly, time consuming, and dependent on the availability of atmospheric icing conditions. In order to minimize the need to verify ice protection analyses and to conduct flight testing in atmospheric icing conditions, increased confidence and reliance on droplet impingement and ice accretion codes in the ice protection certification process are desired. Demonstrating the validity of droplet impingement and ice accretion codes is key to achieving the goal of minimizing the burdens associated with the ice protection regulations.

6.1 (Continued):

Many factors contribute to the acceptability of icing code results. These include the choice of icing codes, the capability of the code, the validity of the code, and the skill of the user. In general, the proper selection and use of codes is a significant factor in producing good results. The purpose of this section of the Droplet Impingement And Ice Accretion Computer Codes ARP is to provide guidelines, based on industry practices, for the use of droplet impingement and ice accretion codes.

Safety Through Conservative Analyses: A critical distinction should be made between code results which are accurate and those that are conservative in the sense that they err on the side of safety. While total validity/accuracy would be ideal for analyses, droplet impingement and ice accretion codes have not achieved this ideal. Therefore, the droplet impingement and ice accretion codes are evaluated for conservatism of the results they provide, with the goal of insuring safe aircraft inflight icing operations. Conservative results for droplet impingement and ice accretion codes, when compared to icing tunnel or flight results for the same flight and meteorological conditions will have one or more of the following criteria:

- a. cause a greater aircraft performance penalty
- b. have a more adverse handling qualities effect
- c. increase ice shedding hazard
- d. increase burden on the IPS
- e. other criteria which have unsafe effects for the application under consideration

The criteria for conservatism listed above may be employed independently or in combination to evaluate conservatism of a particular design. A balancing of accurate and conservative results may be necessary to achieve a design that is both cost-effective and safe. The choice of a code to be used for a given application plays a role in the conservatism of results, as does the proper use of the code.

The following sections include guidelines for investigating the proper use of codes and ensuring conservatism in the choice and application of codes and utilization of results.