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SAE Aerospace Applied Thermodynamics Manual
Ice, Rain, Fog, and Frost Protection

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the SAE Aerospace Applied Thermodynamics Manual. The manual was originally published in one volume as ARP1168. The manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

To maintain consistency with the other 13 reports, unit abbreviations were retained from the previous document, although they may not be the currently recommended abbreviation. An exception is that the current SAE guideline of using “lb” to refer pound mass has been followed. When the Thermodynamics Manual was originally written, most calculations were performed based on pound force and not pound mass. Since most of the equations in this document are more familiar using pound mass, pound mass is used. If using one of the other 13 reports, be aware that “lb” likely represents pound force.

The SAE Aerospace Applied Thermodynamics Manual comprises the following AIR documents.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures
AIR1168/3	Aerothermodynamic Systems Engineering and Design
AIR1168/4	Ice, Rain, Fog, and Frost Protection
AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement
AIR1168/6	Aircraft Fuel Weight Penalty Due to Air Conditioning

AIR1168/7	Aerospace Pressurization System Design
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning
AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids
AIR1168/11	Spacecraft Boost and Entry Heat Transfer
AIR1168/12	Spacecraft Thermal Balance
AIR1168/13	Spacecraft Equipment Environmental Control
AIR1168/14	Spacecraft Life Support Systems

F. R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the original 14 documents that comprise AIR1168.

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1. INTRODUCTION

The ability of aircraft to fly in adverse weather conditions is a requirement for most military and commercial aircraft. Ice buildups in critical areas can affect flight safety by adding drag and weight and thus adversely affecting stability.

Supercooled water drops may exist in clouds at ambient temperatures far below the freezing point. When the drops are disturbed by an aircraft flying through them, the drops will impinge and may freeze on airfoil surfaces, radomes, engine inlets, windshields, and other areas, resulting in weight and drag penalties or obstruction of vision through transparent surfaces. Some means, therefore, must be provided to prevent large ice buildups in critical areas.

The inner surfaces of most cockpit transparencies are susceptible to condensation in the form of fog or frost during most normal aircraft operation, particularly when descending from high altitude flight, unless fog and frost protection systems are provided. Fog will form on the inside surface of the windshield whenever that surface is below the cockpit air dew point. If the surface temperature is below 32 °F, frost will form.

Removal of rain from the windshields to maintain pilot visibility is accomplished by hot air jet blast or by windshield wipers. A rain repellent fluid is sometimes used in conjunction with either system for increased rain removal efficiency.

1.1 Scope

This section presents the basic equations for computing ice protection requirements for nontransparent and transparent surfaces and for fog and frost protection of windshields. Simplified graphical presentations suitable for preliminary design and a description of various types of ice, fog, frost, and rain protection systems are also presented.

1.2 Nomenclature

A/B	= Semi-length/maximum radius ratio of ellipsoid, dimensionless
A _c	= Area of cold side, ft ²
A _f	= Body frontal area, ft ²
A _F	= Windshield projected area (along line of flight), ft ²
A _h	= Area of hot side, ft ²
A _{pa}	= Airfoil passage cross-sectional area, ft ² /ft of span-surface
A _w	= Wetted surface area, ft ²
a	= Nozzle depth, feet
B	= Airfoil maximum thickness, feet
b	= Passage width, feet
C	= Airfoil chord length, or characteristic length, feet
C _{min}	= Minimum heat capacity between hot and cold side, Btu/h-°F
c _w	= Specific heat of water = 1.0 Btu/lb-°F
D _h	= Passage hydraulic diameter, feet
d _{med}	= Volume-median drop diameter, μm (3.94 x 10 ⁻⁵ inches)
d	= Passage depth, feet
e	= Base of the Napierian (natural) logarithm, 2.718
exp	= Exponent
E _m	= Total water catch efficiency, dimensionless
F	= Wettedness factor, dimensionless
G _f	= Percent freeze point depressant by weight in final mixture, %
G _i	= Percent freeze point depressant by weight in initial mixture, %
h _c	= Hot side heat transfer coefficient, Btu/h-ft ² -°F
h _i	= Internal (or passage) heat transfer coefficient, Btu/h-ft ² -°F
h _o	= External heat transfer coefficient, Btu/h-ft ² -°F
h _o S _o	= External film conductance, Btu/h-°F-ft of span per surface
k	= Thermal conductivity, Btu-in/h-ft ² -°F
k _a	= Thermal conductivity of air at nozzle, Btu/h-ft ² -°F
k _g	= Thermal conductivity of glass, 6 Btu-in/h-ft ² -°F
k _p	= Thermal conductivity of plastic 1.5 Btu-in/h-ft ² -°F
k _o	= Thermal conductivity of air at freestream static temperature, Btu/h-ft ² -°F
K _o	= Modified inertia parameter, dimensionless
K ₁	= Pressure correction (see Figure 11), dimensionless

K_a	= Average power/power at control point (Equation 48), dimensionless
K_h	= Power at hot spot/power at control point (Equation 49), dimensionless
K_m	= Average power/power at hot spot (Equation 50), dimensionless
L_e	= Latent heat of evaporation, Btu/lb
L_{eq}	= Equivalent passage length, feet
L_n	= Nozzle length, feet
LWC	= Cloud liquid water content, g/m ³
L_x	= Length, feet
M	= Total water catch, lb/h, or in the case of an airfoil, lb/h-ft of span
M_β	= Local water catch, lb/h-ft ²
M_n	= Mach number, dimensionless
M_w	= Windshield water catch, lb/h-ft ² of surface area
N_{Nu}	= Nusselt number, dimensionless
$N_{(Re,d)}$	= Freestream Reynolds number based upon water drop diameter, dimensionless
$N_{(Re,o)}$	= Freestream Reynolds number based upon body length, dimensionless
$N_{(Re,s)}$	= Local surface Reynolds number based upon surface distance from stagnation point, dimensionless
n	= Number of heat transfer passages per foot of span per surface
P_{cb}	= Cabin pressure, inch Hg
P_{amb}	= Ambient (freestream) static pressure, psia or inch Hg
p_{sk}	= Saturation pressure of vapor at t_{sk} , psia
p_w	= Saturation pressure of water vapor at t_w , psia
p_{ws}	= Saturation pressure of water vapor, inch Hg
Q_i	= Heat loss to inside, Btu/h-ft ²
Q_o	= Heat loss to outside, Btu/h-ft ²
Q_t	= Total heat loss, Btu/h-ft ²
q	= Heat flow, Btu/h
q_a	= Average heat flow to exterior surface, Btu/h-ft ²
r	= Maximum radius of conical body, feet
r	= Recovery factor, dimensionless
S	= Surface area, ft ²
S_b	= Impingement limit on any body, feet, inches
S_L	= Airfoil lower surface impingement limit, ratio to chord, dimensionless
S_o	= External heat transfer area, ft ² , or in the case of an airfoil, ft ² /ft of span per surface
S_L	= Airfoil lower surface impingement limit, feet, inches
S_m	= Total area of impingement divided by body frontal area, dimensionless
S_U	= Airfoil upper surface impingement ratio, ratio to chord, dimensionless
s	= Surface distance from stagnation point, feet, inches
S_U	= Airfoil upper surface impingement limit, feet, inches
T_{amb}	= Ambient (freestream) static temperature, °R
T_m	= Mean temperature between wall and fluid, °R
T_{bl}	= Temperature of boundary layer, °R
t_{aw}	= Adiabatic wall temperature, °F
t_c	= Temperature at control point, °F
t_{cb}	= Cabin temperature, °F
t_{ex}	= Passage exit air temperature, °F
t_{fa}	= Temperature of film average, °F
t_h	= Hot spot temperature, °F
t_{in}	= Passage inlet air temperature, °F
t_j	= Temperature at a point downstream of nozzle, °F
t_n	= Nozzle temperature, °F
t_s	= Effective outside surface temperature, °F
t_{si}	= Inside surface temperature, °F
t_{sk}	= Skin temperature, °F
t_w	= Total temperature of atmospheric water, °F
thick	= Thickness of piccolo tube
U_h	= Heat transfer coefficient hot side, Btu/h-ft ² -°F
U_i	= Heat transfer coefficient to inside, Btu/h-ft ² -°F
U_o	= Heat transfer coefficient to outside, Btu/h-ft ² -°F
U_{ov}	= Overall heat transfer coefficient, Btu/h-ft ² -°F

V	= Freestream velocity, ft/s
v	= Freestream velocity, knots TAS
V_j	= Velocity at distance x , ft/s
V_o	= Velocity at nozzle, ft/s
W	= Mass flow of air, lb/s
W_f	= Liquid flow rate, lb/h-ft ² surface area
W_s	= Moisture content, lb/lb dry air
w_{pa}	= Passage air flow, lb/h-ft of span per surface
ΔX	= Total windshield thickness, inches
x	= Distance from nozzle, feet
Δx_i	= Distance from film to inner surface, inches
Δx_o	= Distance from film to outer surface, inches
Y	= Correction factor for passage fin effect, dimensionless
Z	= Correction factor for passage aspect ratio, dimensionless
α	= Angle of attack, deg
β	= Local catch efficiency, dimensionless
β_{max}	= Local catch efficiency at stagnation line, dimensionless
Φ_o	= Cone semivertex angle, deg
Γ	= Local catch parameter on cones, dimensionless
μ_o	= Absolute viscosity of air at freestream static temperature or nozzle temperature, lb/s-ft
Ψ	= Scale modulus, dimensionless
η_t	= Decay ratio, dimensionless
ρ_o	= Ambient air density, lb/ft ³
ρ_w	= Water drop air density, lb/ft ³

1.3 Common Abbreviations

AAFTR	Army Air Forces Technical Report
AC	Alternating current
Aer	Bureau of Aeronautics, Department of the Navy
AF	Air Force
ASG	Aeronautical Systems Group
Btu	British thermal units
cc	Cubic centimeters
DC	Direct current
CFR	Code of Federal Regulations
deg	Degree(s)
exp	Exponent
°F	Degrees Fahrenheit
FAA	Federal Aviation Administration
ft	Feet
g	Gram(s)
Hg	Mercury
h	Hour(s)
in	Inch(es)
IVR	Inlet velocity ratio
lb	Pound(s) mass
lb _f	Pound(s) force
LE	Leading edge
LWC	Liquid water content
m	Meter(s)
max	Maximum (in tables)
min	Minute(s)
mph	Miles per hour
nmi	Nautical mile, international
NACA	National Advisory Committee for Aeronautics

%	Percent
p. (pp.)	Page(s)
Proc.	Proceedings
PS	Parting strip
psi	Pounds force per square inch
psia	Pounds force per square inch absolute
PT	Point
°R	Degrees Rankine
RM	Research Memorandum
s	Second(s)
SI	International System of Units
STAG.	Stagnation
TAS	True Air Speed
TEMP.	Temperature
TN	Technical Note
TR	Technical Report
Typ.	Typical
U.S.	United States
USAF	United States Air Force
W	Watt(s)
WADC	Wright Air Development Center
μm	Micrometer, 10 ⁻⁶ meter (formerly known as micron)

1.4 Definition of Terms

The following terms are used in this discussion:

1. **Icing Cloud:** A cloud containing supercooled water drops of sufficient concentration and size to produce ice on an airborne aircraft's surface.
2. **Liquid Water Content:** Liquid water content is the total mass of water contained in liquid drops within a unit volume or mass of cloud or precipitation, usually given in units of grams of water per cubic meter or kilogram of dry air (g/m³, g/kg) of air.
3. **Median Volumetric Diameter (MVD):** The drop diameter which divides the total liquid water content present in the drop distribution in half, i.e., half the water volume will be in larger drops and half the volume in smaller drops.
4. **Maximum Drop Size:** Maximum drop size is the size of a drop which is larger than 95% of the drops. It is approximately double the volume median drop size and is used to determine impingement limits.
5. **Local Water Catch:** Local water catch is the point-by-point distribution of water (or ice), in lb/h-ft² surface area, over the impingement area.
6. **Total Water Catch:** Total water catch is the total amount of water (or ice), in lb/h, that impinges on the aircraft surface. It is the integrated value of the local catch. For a two-dimensional body (for example, on a wing) the total catch is more conveniently expressed in terms of a unit span.
7. **Total Catch Efficiency:** Total catch efficiency is the total water catch on a body divided by the amount of water contained in the volume of air swept out by the frontal area of the body.
8. **Local Catch Efficiency:** Local catch efficiency is the local catch divided by that which would be caught on 1 ft² of surface area with a catch efficiency of unity.
9. **Impingement Limit:** The impingement limit is the farthest aft location on a body at which water drops impact. This applies to both the upper or lower surface for a body such as an airfoil. This distance can be measured either as the x distance from the leading edge or as the surface distance from the stagnation point.

10. Anti-ice: The prevention of ice accumulation on a protected surface.

11. Deice: The periodic shedding of ice accretions by destroying the bond between the ice and the protected surface.

2. ICE PROTECTION OF NONTRANSPARENT SURFACES

Various methods have been developed for aircraft ice protection of nontransparent surfaces. The earliest practical method was to use inflatable rubber pneumatic boots which, when inflated, broke the bond between the ice and the surface, thus allowing aerodynamic forces to blow the ice away. This method, because of its simplicity, is still employed on many aircraft.

Recent developments include electromechanical methods that break the bond of the ice to the surface. Since the pulse used is instantaneous and the power can be stored, this device requires a relatively small amount of total power to operate.

Another form of ice protection uses glycol or alcohol pumped in a thin film over the protected surface, thus lowering the freezing point and preventing the formation of ice.

An effective method of ice protection is to use thermal energy, either hot air or electrical. Many all-weather aircraft employ thermal ice protection systems.

The thermal energy required for ice protection can be obtained in two ways:

1. Hot air, either heated ram air or compressor bleed air, passed through passages integral with the surface being heated.
2. Electrical resistance heating elements embedded just below the surface being heated.

In either case, thermal ice protection results in aircraft weight and performance penalties related to system capability, and makes necessary the accurate prediction of ice protection required for a given application.

The calculation of ice protection requirements can be tedious, in some cases requiring extensive trial and error experiments or computer codes. It is possible, however, to rearrange the water catch and heat and mass transfer equations into forms that permit graphical presentation of the various parameters, thus reducing the number of calculations.

This AIR discusses these graphical presentations and includes illustrative problems of typical ice protection systems to enable the designer to make calculations of system requirements. The methods presented here, though approximate, have produced good correlation in both icing tunnel tests and natural icing flights. Even though more sophisticated computer programs are available, these methods are still in use and widely accepted. Reference 18 is dedicated to computer codes and lists many of the simulation codes and discusses their capabilities.

Analysis of thermal ice protection systems can be undertaken with those familiar with thermodynamics using the techniques provided in this AIR. Other types of ice protection systems require specialized tools developed by those supplying those systems. A more detailed description of other types of ice protection systems including those mentioned here can be found in Reference 33. This AIR will provide techniques and methods of analysis related only to thermal ice protection systems. As indicated other systems require specialized analysis tools that are often proprietary to the companies providing those systems.

3. METHODS OF THERMAL ICE PROTECTION

3.1 Fully Evaporative Anti-Icing

Fully evaporative anti-icing systems, either electrical or hot air, are used for wing and empennage surfaces and, in the case of turbine powered aircraft, for engine air intake systems. For electrical systems, electrical-resistance heating elements are installed on the aircraft in areas requiring ice protection. For hot air systems, heated air is directed at or along the inner surfaces of such areas. Energy requirements are determined by assuming full evaporation of all impinging water under the severest condition which the aircraft is expected to encounter (see Section 8).

In piston engine powered aircraft, ram air can be heated either by a combustion heater or by being passed through an engine exhaust air heat exchanger. However, ram air systems are limited in their evaporative capabilities, especially in light of the latest civil and military specifications. In turbine engine powered aircraft, compressor bleed air is usually utilized to provide adequate ice protection. Compressor bleed air systems are lighter than equivalent heated ram air systems, since they can use the same bleed manifolds required for engine starting.

3.2 Running Wet Anti-Icing

Heat requirements, either electrical or hot air for running wet anti-icing, are based upon the maintenance of a surface temperature just above freezing, thus allowing some of the impinging water to run back and freeze aft of the heated area. This technique is employed for surfaces where the effects of ice buildups aft of the heated area can be tolerated (e.g., radomes and spinners). It is also used in (1) turbine engine inlet ducts where the runback is permitted to enter the engine, and (2) on the duct lips of all-weather supersonic aircraft where only limited protection is required.

3.3 Cyclic Deicing

Cyclic deicing is the periodic shedding of small ice buildups. In thermal deicing, the ice-airfoil interface is melted by a high rate of heat input; the adhesion at the ice-airfoil interface becomes zero and aerodynamic or centrifugal forces remove the ice. With the advent of lightweight AC systems for aircraft application, electrical resistance heating elements are also used for deicing. Electrothermal systems are used primarily for airfoil surfaces (since small ice buildups here may not be detrimental to airplane performance or handling qualities) or on propeller and helicopter blades where other means are impractical. Electrothermal deicing requires the least amount of heat of all thermal ice protection systems, but this advantage is partially offset by the aerodynamic penalties incurred during the "heat-off" period.

4. EXTERNAL FACTORS AFFECTING HEAT REQUIREMENTS

4.1 Water Catch and Impingement Limits

4.1.1 Methods of Determination

Water catch parameters on a body may be determined either experimentally in an icing wind tunnel or analytically. The experimental technique (Reference 1) is to allow a short burst of dye spray of known quantity and drop distribution to impinge on blotting paper that has been taped to the body for this purpose. A colorimetric analysis of the paper is performed to determine the local and total catch efficiencies and impingement limits, the latter requiring correction for model scale effects. Alternately, the collection efficiency may be determined experimentally following icing exposure during rime conditions for a short period. The exposure time is just sufficient to measure reliably variations in ice thickness within the impingement area, and not long enough for secondary effects such as ice feather growth near the impingement limits. The local collection efficiency can be computed knowing the local ice thickness, the airspeed, the exposure time, and the freestream LWC.

The analytical approach (Reference 2) is the direct solution of the appropriate differential equations. This method has produced good correlation with icing tunnel results, both for water catch and impingement limits, when the flow field could be calculated accurately. Because of the high cost of tunnel programs, the bulk of available water catch data for simple body shapes has been obtained analytically.

4.1.2 Airfoils

4.1.2.1 Total Water Catch

The fundamental equation for total water catch is

$$M = 0.38vB(LWC)E_m \quad (\text{Eq. 1})$$

For a given volume median drop size, ambient temperature, and altitude, water catch efficiency, E_m , is a function of velocity, airfoil shape, and thickness. References 2 and 3 present curves for the determination of E_m for several 15% thick airfoils, obtained from a differential analyzer, based on two parameters, a drop Reynolds number $N_{(Re,d)}$, and a scale modulus Ψ . Large amounts of information have been accumulated for numerous classical shapes such as rectangles, ribbons, spheres, cylinders, and ellipsoids, as well as for airfoils.

A simplified parameter called a "Modified Inertia Parameter, K_o ," was developed in References 4 and 5. The use of this K_o parameter permits correlation into a set of universal K_o plots of most of the published drop trajectory data of (1) water catch efficiency (E_m), and upper and lower limits of ice impingement (S_u , S_L) for airfoils, rectangles, ribbons, spheres, cylinders, radomes, ellipsoids, elbows, cones, and engine inlets; and (2) local stagnation line impingement efficiency (β_{max}) for ellipsoids, spheres, cylinders, and rectangular half-bodies. Use of the K_o correlation is considered justified by the small loss in accuracy versus the large condensation in data presentation made possible by its use, however, the calculation of K_o is also feasible (see Equation 2).

Efficiency of water catch (E_m) data for airfoils, engine inlets, and many geometrical shapes is shown in Figure 1 (taken from References 6 and 7) as a function of the modified inertia parameter K_o . Each geometric shape is represented by a single curve. It should be noted that the efficiency of water catch can be greater than 1.0 (that is, >100%) because E_m is strictly defined as the dimensionless ratio of the amount of water intercepted by a body to the amount of water contained in the volume of cloud swept by the body when at $\alpha = 0$ degrees.

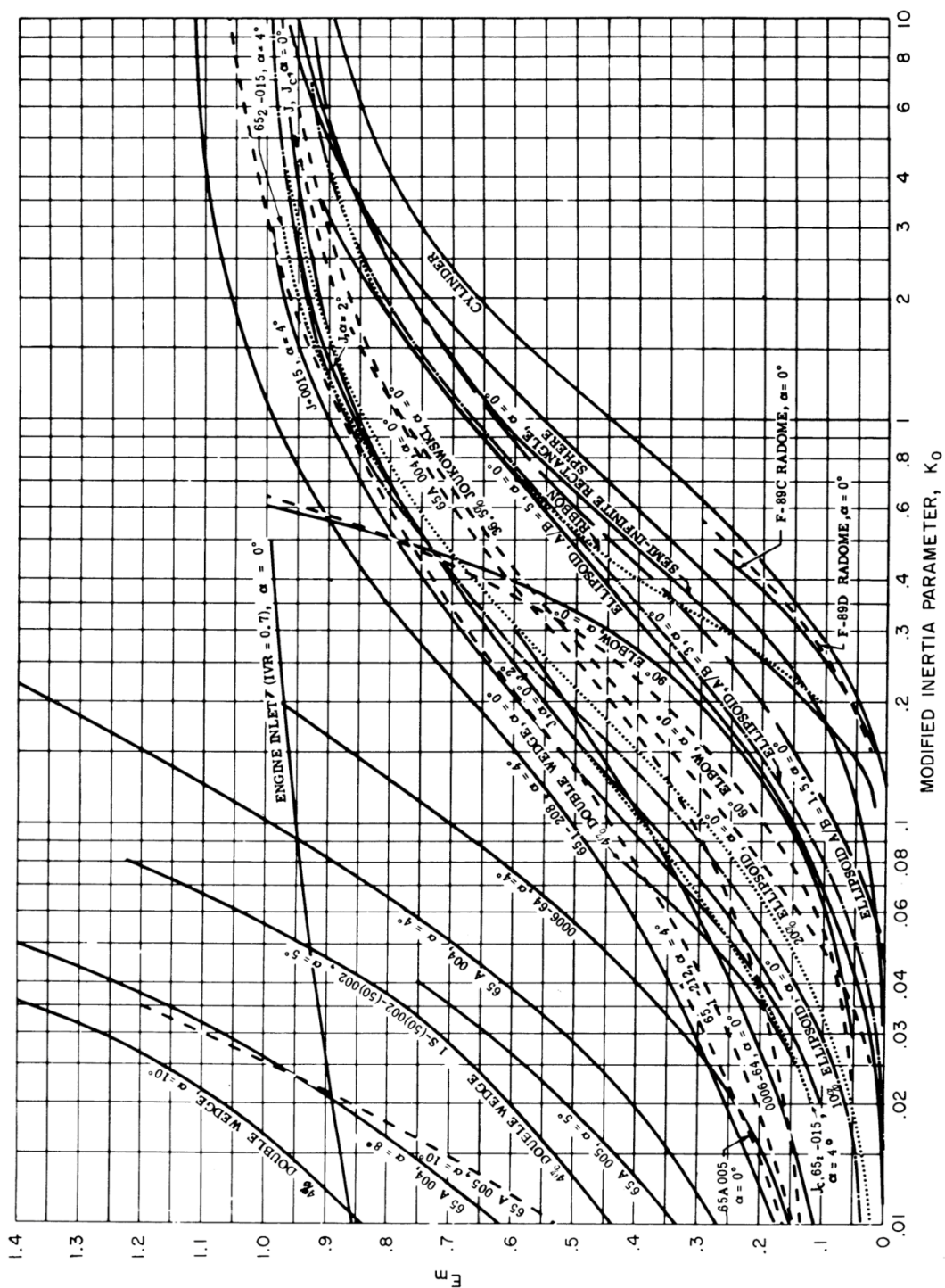
At angles of attack greater than 0 degrees, the amount of water intercepted by an airfoil may be larger than the amount of water contained in the volume of cloud swept out by the airfoil when at $\alpha = 0$ degrees. The plots shown in Figure 1 are generally within $\pm 10\%$ of the original data for the practical range of drop Reynolds numbers from 100 to 250.

The collection efficiency may be larger than 100%. As an example, drops that miss an aircraft radome and travel close to the fuselage and produce a local high concentration downstream may impact a portion of an air data probe that protrudes a short distance from the surface. These effects can be predicted with reasonable reliability by advanced computational tools that take into account the full three-dimensional flow and drop trajectory effects.

The K_o factor may be evaluated either using Figure 2 or by the following equation:

$$K_o = \left(\left[\frac{d_{med}^2 v \rho_w}{C \mu_o} \right] \right) \left[N_{(Re,d)}^{-2/3} - \frac{\sqrt{6}}{N_{(Re,d)}} \arctan \left(\frac{N_{(Re,d)}^{1/3}}{\sqrt{6}} \right) \right] \quad (\text{Eq. 2})$$

Figure 3 presents a plot of M/LWC for a 15% Joukowski airfoil as a function of true air speed and airfoil thickness, for $\alpha = 4$ degrees and 20 μm water drops. Plots of this type are accurate for only one angle of attack, drop diameter, altitude, and airfoil thickness ratio, but may be used as a range of altitudes and airfoil thickness ratios in making preliminary design first approximations for subsonic airfoils. The more refined K_o and E_m method is preferred for greater accuracy. A comprehensive summary, including experimental data, can be found in Reference 8. Alternately, recent computational tools have simplified the steps for these predictions, but they require familiarity and experience.



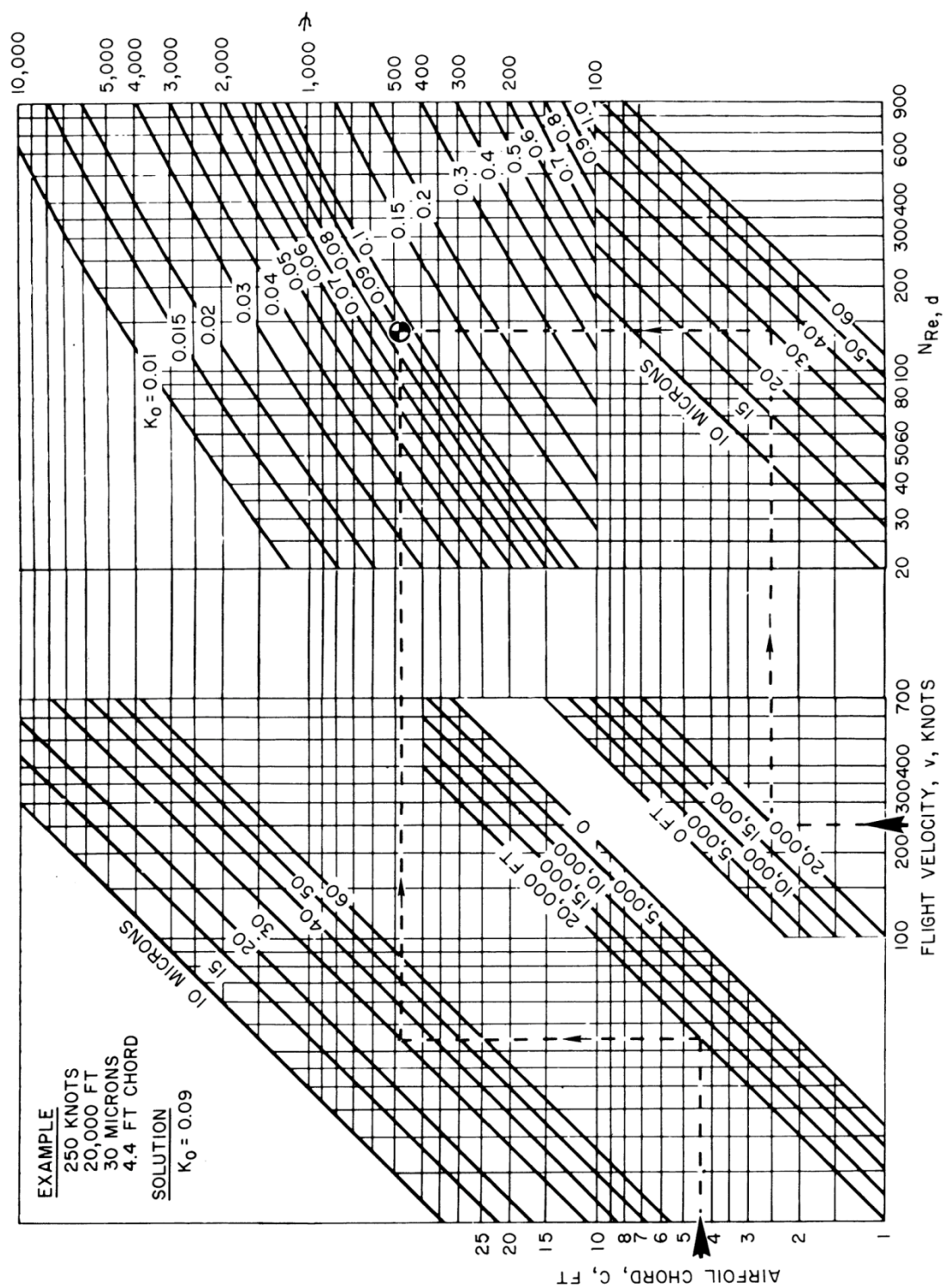


Figure 2 - Graphical solution of K_0 for 15 °F ambient air temperature (References 6 and 7)

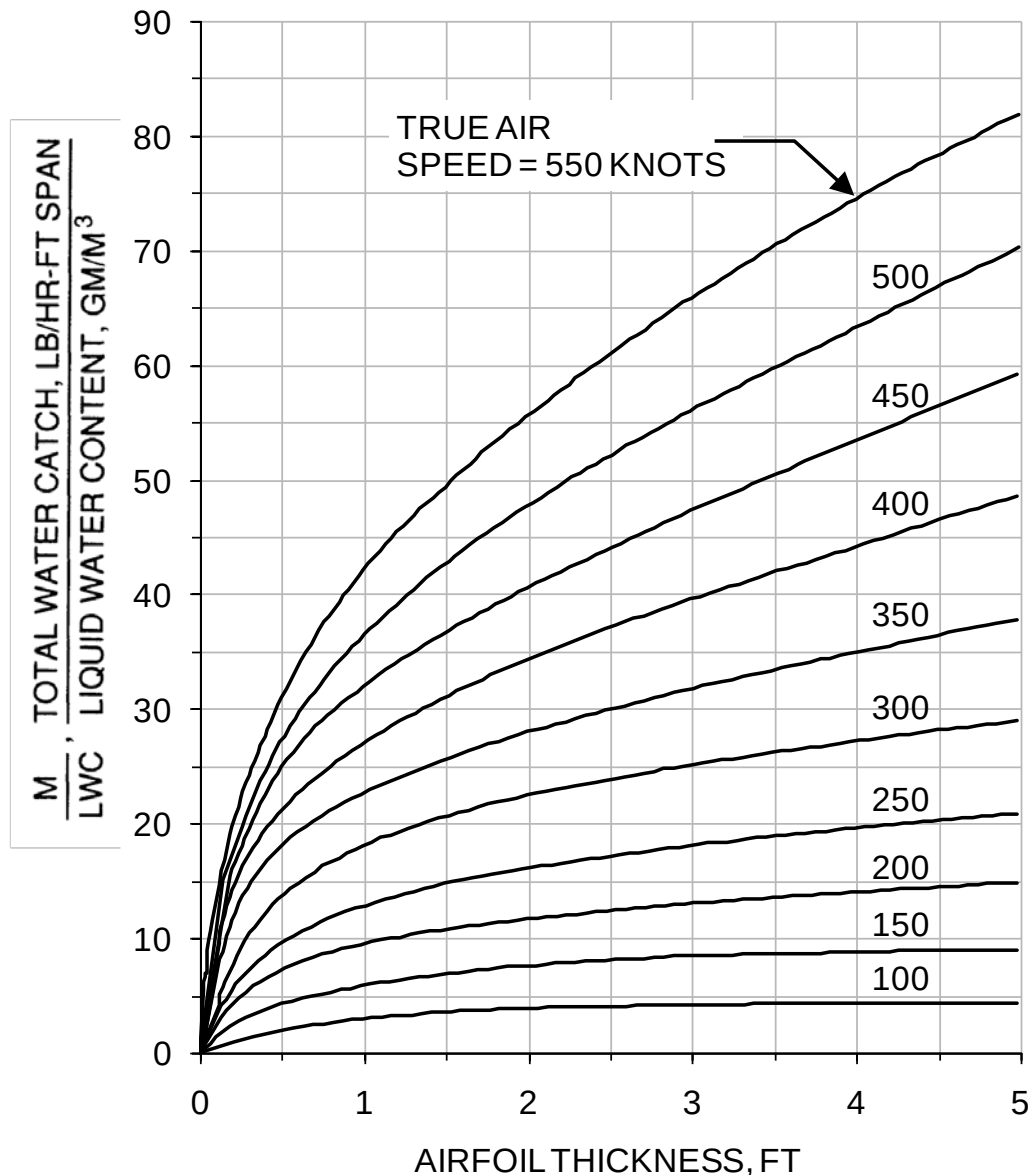


**Figure 3 - Airfoil total catch typical for 6 to 16% thick airfoils at $\alpha = 4$ degrees
20 μm volume median drops (all altitudes: strictly true for 10000 feet and approximately,
within 10%, true between sea level and 20000 feet)**

4.1.2.2 Local Water Catch Distribution and Impingement Limits

The formula for local water catch, analogous to Equation 1, is:

$$M_{\beta} = 0.38v(LWC)\beta \quad (\text{Eq. 3})$$

Local water catch efficiency, β , is a complex function of drop size, airfoil geometry, and freestream conditions. Consequently, it is not possible to construct a set of semi-universal curves using the method from Reference 9, as it is for total water catch. Reference 8 presents curves for determining local water catch efficiencies for several airfoil sections at various angles of attack. Figure 4 shows the maximum water catch efficiency at the stagnation line, β_{max} , versus the modified inertial parameter, K_o , for three ellipsoids and a sphere, cylinder, and rectangular halfbody (from References 6 and 7).

Airfoil impingement limits, too, are a complex function of maximum drop size, airfoil geometry, and freestream conditions. These limits are used to determine how far aft of the leading edge the surface requires protection. References 2 and 3 and 6 through 8 present curves for obtaining impingement limits for several airfoil sections at various angles of attack. Aviation regulatory agencies specify a drop size as a mean volumetric diameter within a distribution of drop sizes. In the determination of impingement limits, a single drop size or a distribution has been used. The procedure is simple using existing computational tools. It should be noted that large drops that exist near the edge of a distribution impinge farther aft on the surface compared to the nominal drop size. However, they contribute a small percentage of total cloud water content. The specific application dictates whether a single drop size or a distribution should be used in analyzing impingement limits.

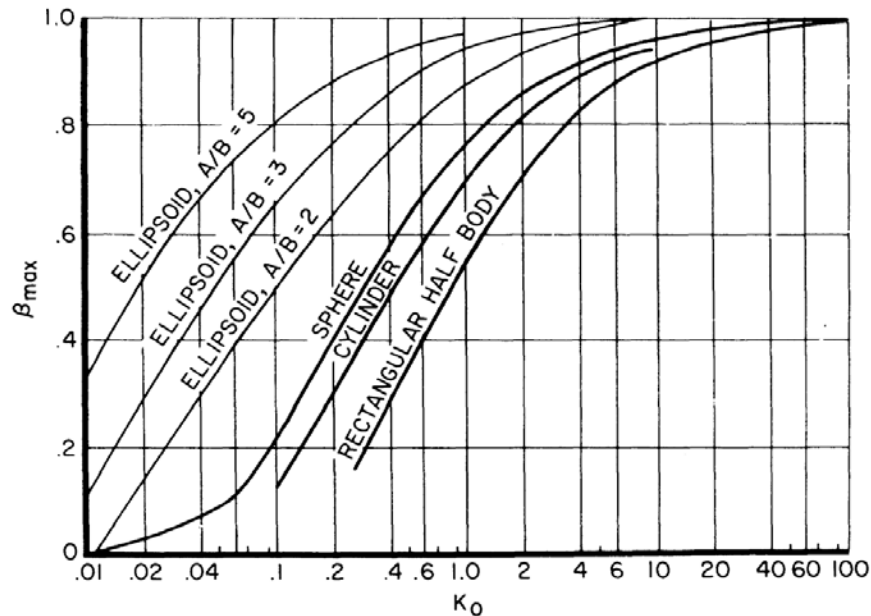


Figure 4 - Maximum water catch efficiencies at the stagnation line, $\alpha = 0$ degrees

As an example, Figure 5 shows the impingement limits for an NACA 65₂-015 airfoil at $\alpha = 4$ degrees, and for a symmetrical 15% airfoil at $\alpha = 0$ degrees. Over the range of airfoil geometries of interest, impingement limits appear to be only moderately sensitive to changes in percent thickness and camber, but are very sensitive to changes in angle of attack, this latter effect being roughly parabolic.

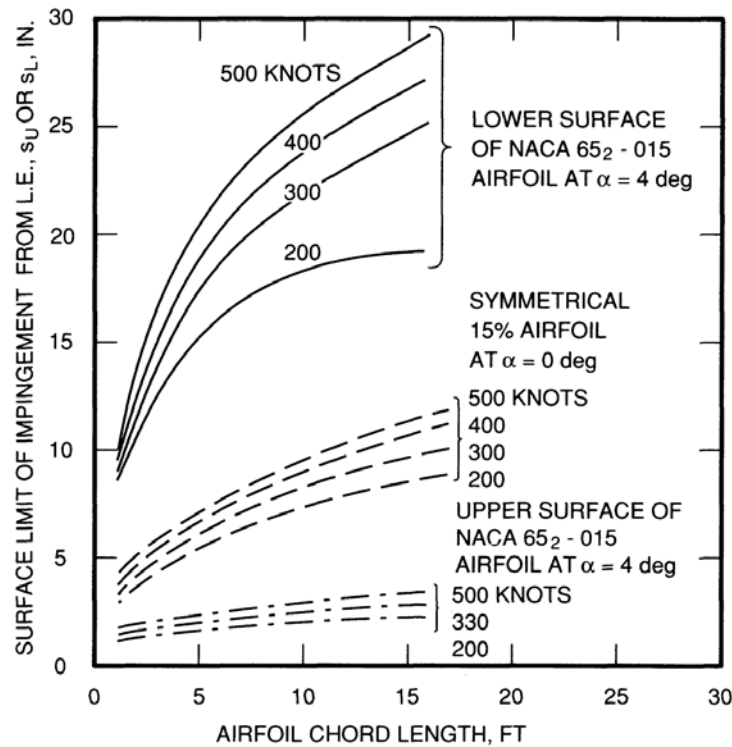
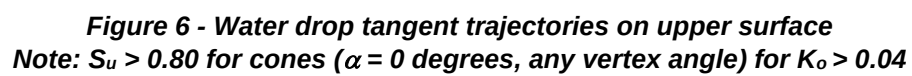


Figure 5 - Airfoil impingement limits for 40 μm maximum (20 μm volume median) drops
*(all altitudes: strictly true for a particular altitude and approximately,
 within 10%, true between sea level and 20000 feet)*

Figures 6 and 7 show the upper and lower limits of ice impingement (S_U , S_L), as simplified by the K_o correlation (taken from References 6 and 7). The tendency of thin airfoils, at large angles of attack ($\alpha \geq 4$ degrees), to accumulate ice up to the mid-chord on the lower surface under conditions of large K_o (large drop size, high speed, small chord length) is clearly apparent.

The method of presentation in Figures 1, 6, and 7 permits interpolation or extrapolation to other airfoil thicknesses and angles of attack for which water drop trajectory data are not known.



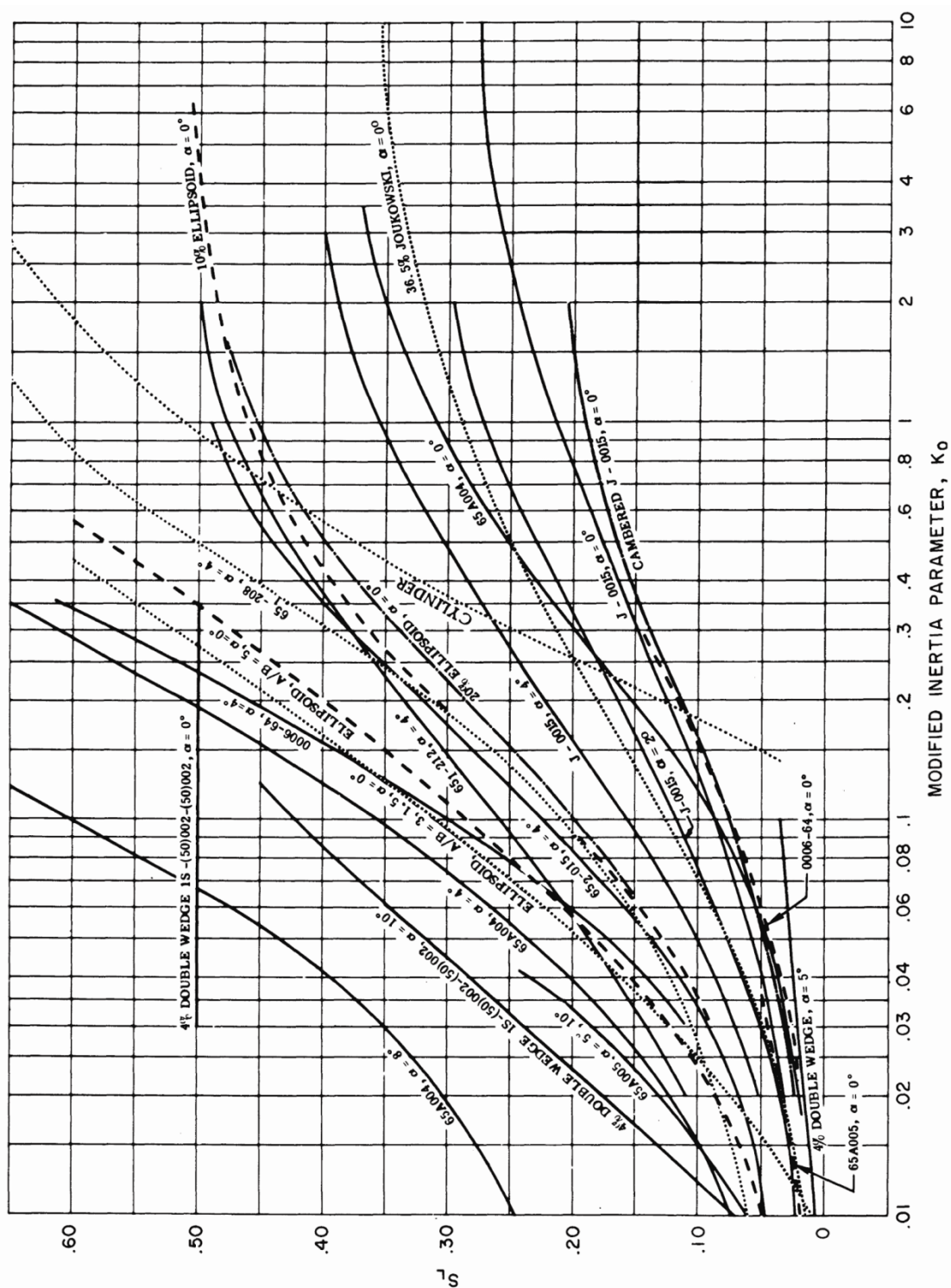


Figure 7 - Water drop tangent trajectories on lower surface

Note: $SL > 0.80$ for cones ($\alpha = 0$ degrees, any vertex angle) for $K_0 > 0.04$

4.1.3 Bodies of Revolution

The equation analogous to Equation 1 for bodies of revolution is

$$M = 0.38vA_r(LWC)E_m \quad (\text{Eq. 4})$$

where A_r is the frontal area of the body. Figure 8 shows cone water catch efficiencies as obtained from Reference 9, plotted as a function of velocity and body (radome, spinner, and so forth) length. In the same manner, it is possible to plot $\beta_{\max}/\sin\Phi_0$ where Φ_0 is the cone semivertex angle (Figure 8) and s_0 is the impingement limit (Figure 9).

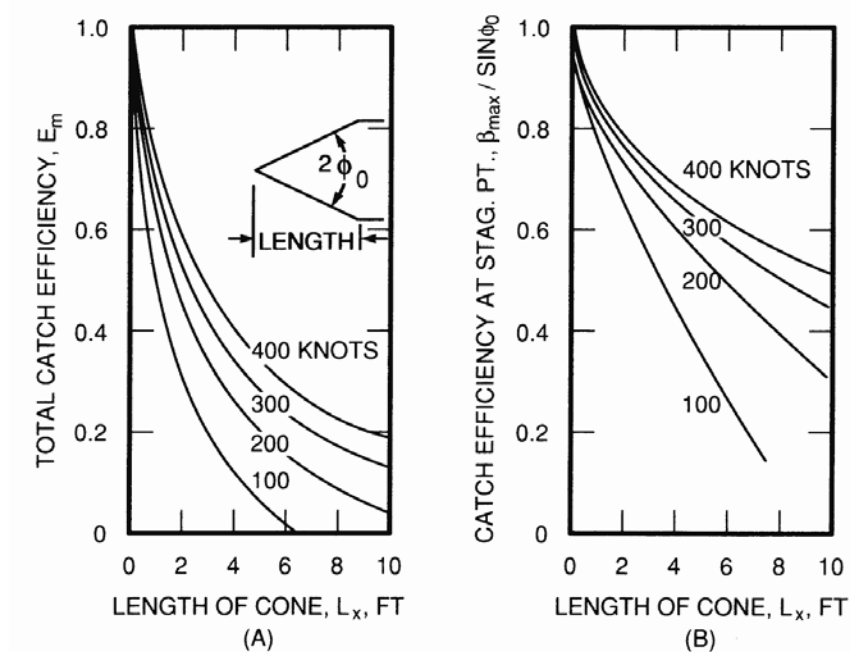


Figure 8 - Catch efficiency on cones for 20 μ m volume median drops (A) - Total, (B) - Stagnation point (all altitudes: strictly true for 10000 feet altitude and approximately, within 10%, true between sea level and 20000 feet)

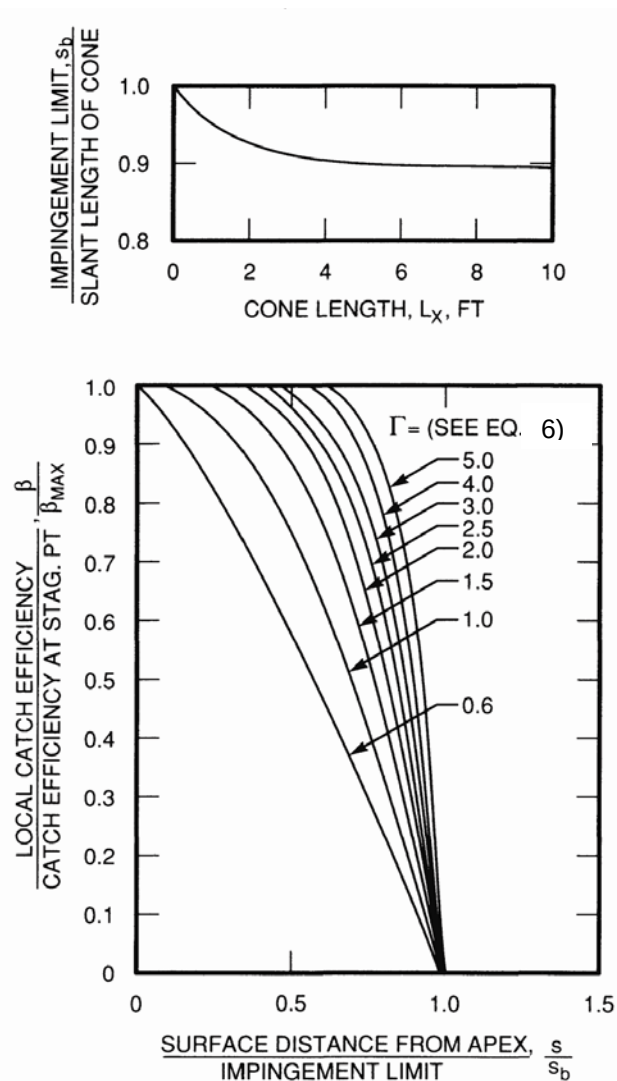


Figure 9 - Local catch distribution (bottom) and impingement limits (top) on cones for 20 μ m volume median drop diameter.
Note: impingement limits are fairly insensitive to changes in altitude and velocity.

The cones analyzed in Reference 9 are rounded at the base, as shown in Figure 10, where s_b = Impingement limit and $r = L_x \sin \Phi_0$.

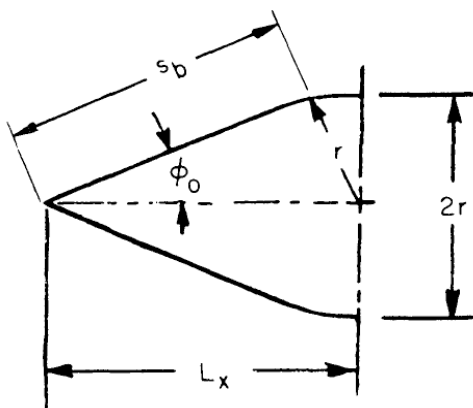


Figure 10 - Cone geometry

Then

$$A_i = \pi L_x^2 \sin^2 \Phi_o \quad (\text{Eq. 5})$$

To obtain local catch distributions (Figure 9), it is necessary to compute the quantity Γ , where

$$\Gamma = \frac{E_m}{\beta_{\max} S_m - E_m} \quad (\text{Eq. 6})$$

The factor S_m is the impingement area divided by the cone frontal area. Using the cone geometry of the sketch,

$$S_m = \frac{(S_b / L_x)^2}{\sin \Phi_o} \quad (\text{Eq. 7})$$

Catch rates for ellipsoids may be obtained from the previous figures and also from Reference 9.

4.2 External Heat Transfer Coefficients

4.2.1 Airfoils

4.2.1.1 Local

The calculation of local heat transfer coefficients requires knowledge of the velocity and static pressure distributions over the airfoil. Since this latter subject is covered in Reference 10 as well as in standard aerodynamic textbooks, it will not be presented here.

Laminar heat transfer coefficients are computed by using the Eckert wedge solution, which assumes that laminar heat transfer coefficients on an airfoil are the same as those on a wedge at the same distance from the stagnation point, provided the stream velocity and its gradient on the wedge and the airfoil are the same at the given location. This is covered in AIR1168/2, 3.5.2 and also in Reference 11.

Turbulent heat transfer coefficients are computed from flat plate theory, using the local velocity. For air at normal temperature,

$$\text{Turbulent } h_o = 0.51(T_m)^{0.3} \cdot \frac{[1.69 \rho_o v]^{0.8}}{S^{0.2}} \quad (\text{Eq. 8})$$

Transition from laminar to turbulent flow is dependent upon local pressure gradients, local Reynolds number, and local surface roughness that may be a result of ice formation. In the absence of strong pressure gradients, transition will start where the local surface Reynolds number $N_{(Re,S)}$ is 0.5×10^6 and will end at $N_{(Re,S)} = 2.0 \times 10^6$. A strong favorable pressure gradient (decreasing static pressure with increasing distance from the leading edge) will delay transition.

Conversely, an unfavorable pressure gradient (increasing static pressure with increasing distance) will promote transition. Impingement limits have no apparent effect on transition for an anti-iced surface.

4.2.1.2 Average

The average external heat transfer curves are based on the assumption of fully turbulent flat plate flow. Owing to this simplified treatment, it is not possible to take into account the effect of airfoil camber or angle of attack. It is probable, however, that such effects fall within the accuracy of the formula used.