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Ice, Rain, Fog, and Frost Protection

PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. 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.

In the Third Edition, no attempt was made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained, insofar as possible.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs comprising the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(1A,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)

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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 Third Edition.

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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 droplets may exist in clouds at ambient temperatures far below the freezing point. When the droplets are disturbed by an aircraft flying through them, the droplets 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_f = Body frontal area, ft²

A_F = Windshield projected area (along line of flight), ft²

A_{pa} = Airfoil passage cross-sectional area, ft²/ft of span-surface

a = Nozzle depth, ft

B = Airfoil maximum thickness, ft

b = Passage width, ft

C = Airfoil chord length, or characteristic length, ft

c_w = Specific heat of water = 1.0 Btu/lb-°F

D_h = Passage hydraulic diameter, ft

d_{med} = Volume-median waterdrop diameter, μ (3.94×10^{-5} in.)

d = Passage depth, ft

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_i	= Internal (or passage) heat transfer coefficient, Btu/hr-ft ² -°F
h_o	= External heat transfer coefficient, Btu/hr-ft ² -°F
$h_o S_o$	= External film conductance, Btu/hr-°F-ft of span per surface
k_a	= Conductivity of air at nozzle, Btu/hr-ft-°F
k_g	= Thermal conductivity of glass, 6 Btu-in./hr-ft ² -°F
k_p	= Thermal conductivity of plastic 1.5 Btu-in./hr-ft ² -°F
k_o	= Thermal conductivity of air at freestream static temperature, Btu/hr-ft-°F
K_o	= Modified inertia parameter, dimensionless
K_1	= Pressure correction (see Fig. 3F-11), dimensionless
K_a	= Average power/power at control point (Eq. 3F-22), dimensionless
K_h	= Power at hot spot/power at control point (Eq. 3F-23), dimensionless
K_m	= Average power/power at hot spot (Eq. 3F-24), dimensionless
L_e	= Latent heat of evaporation, Btu/lb
L_{eq}	= Equivalent passage length, ft
L_n	= Nozzle length, ft
LWC	= Cloud liquid water content, gm/m ³
L_x	= Length, ft
M	= Total water catch, lb/hr, or in the case of an airfoil, lb/hr-ft of span
M_β	= Local water catch, lb/hr-ft ²
M_n	= Mach number, dimensionless
M_w	= Windshield water catch, lb/hr-ft ² of projected 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 ft of span per surface
P_{cb}	= Cabin pressure, in.Hg
P_{amb}	= Ambient (freestream) static pressure, psia or in.Hg
p_s	= Saturation pressure of water vapor, in.Hg
p_{sk}	= Saturation pressure of vapor at t_{sk} , psia
p_w	= Saturation pressure of water vapor at t_w , psia
Q_i	= Heat loss to inside, Btu/hr-ft ²
Q_o	= Heat loss to outside, Btu/hr-ft ²
Q_t	= Total heat loss, Btu/hr-ft ²
q	= Heat flow, Btu/hr
q_a	= Average heat flow to exterior surface, Btu/hr-ft ²

r	= Maximum radius of conical body, ft
r	= Recovery factor, dimensionless
S	= Surface area, ft ²
s_b	= Impingement limit on any body, ft, in.
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, ft, in.
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, ft, in.
s_U	= Airfoil upper surface impingement limit, ft, in.
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
U_i	= Heat transfer coefficient to inside, Btu/hr-ft ² -°F
U_o	= Heat transfer coefficient to outside, Btu/hr-ft ² -°F
U_{ov}	= Overall heat transfer coefficient, Btu/hr-ft ² -°F
V	= Freestream velocity, ft/sec
v	= Freestream velocity, knots TAS
V_j	= Velocity at distance x, ft/sec
V_o	= Velocity at nozzle, ft/sec
W	= Mass flow of air, lb/sec
W_f	= Liquid flow rate, lb/hr-ft ² surface area
W_s	= Moisture content, lb/lb dry air
w_{pa}	= Passage air flow, lb/hr-ft of span per surface
ΔX	= Total windshield thickness, in.
x	= Distance from nozzle, ft
Δx_i	= Distance from film to inner surface, in.

- Δx_o = Distance from film to outer surface, in.
 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/sec-ft
 Ψ = Scale modulus, dimensionless
 η_t = Decay ratio, dimensionless
 $(\rho g)_o$ = Ambient air density, lb/ft³

1.3 Common Abbreviations

- AAFTTR — Army Air Forces Technical Report
 AC — Alternating current
 Aer — Bureau of Aeronautics, Department of the Navy
 AF — Air Force
 ASG — Aeronautical Systems Group
 ASHRAE — American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
 Btu — British thermal units
 cc — Cubic centimeters
 DC — Direct current
 deg — Degree(s)
 Eq. (Eqs.) — Equation(s)
 exp — Exponent
 °F — Degrees Fahrenheit
 FAA — Federal Aviation Agency
 FAR — Federal Air Regulations
 Fig. (Figs.) — Figure(s)
 fps — Feet per second
 ft — Feet
 gm — Gram
 Hg — Mercury
 hr — Hour
 in. — Inch
 IVR — Inlet velocity ratio
 lb — Pound
 L.E. — Leading edge
 LWC — Liquid-water content
 m — Meter

max	— Maximum
min	— Minute(s)
mph	— Miles per hour
NACA	— National Advisory Committee for Aeronautics
%	— Percent
p. (pp.)	— Page(s)
Par. (Pars.)	— Paragraph(s)
Proc.	— Proceedings
PS	— Parting strip
psi	— Pounds per square inch
psia	— Pounds per square inch absolute
PT.	— Point
°R	— Degrees Rankine
Ref.(Refs.)	— Reference (s)
RM	— Research Memorandum
sec	— Second
SI	— International System of Units
STAG.	— Stagnation
std	— Standard
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
WADC	— Wright Air Development Center
μ	— Microns, 10 ⁻⁶ meter

1.4 Definition of Terms

The following terms are used in this discussion:

- (1) **Icing Cloud:** Icing clouds are those containing supercooled water droplets in sufficient concentration to produce ice on an aircraft surface.
- (2) **Liquid Water Content:** Liquid water content is the amount of supercooled water in grams of water per m³ of air, contained in an icing cloud.
- (3) **Volume Median Droplet Size:** Volume median droplet size is the droplet diameter, in microns (μ), (10⁻⁶ m), such that one-half the water in an icing cloud is contained in droplets smaller than the volume median droplet size.
- (4) **Maximum Droplet Size:** Maximum droplet size is the size of a droplet which is larger than 95% of the droplets. It is approximately double the volume median droplet 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/hr-ft² surface area, over the impingement area.
- (6) Total Water Catch: Total water catch is the total amount of water (or ice), in lb/hr, 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 location farthest aft on a body at which ice impinges. It governs the extent of protection to be provided.
- (10) Anti-Icing: Anti-icing is the prevention of ice buildup on the protected surface, either by evaporating the impinging water or by allowing it to run back and freeze on noncritical areas.
- (11) De-Icing: De-icing is the periodic shedding, either by mechanical or thermal means, of small ice buildups 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.

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.

The most effective method of ice protection is to use thermal energy, either hot air or electrical; consequently most of the currently designed 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 calculations involved in computing ice protection requirements usually are extremely tedious, in some cases requiring extensive trial and error experiments. 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 section discusses these graphical presentations and includes illustrative problems of typical ice protection systems to enable the designer to make preliminary estimates of system requirements. The methods presented here, though approximate, have produced good correlation in both icing tunnel tests and natural icing flights.

3. METHODS OF THERMAL ICE PROTECTION

3.1 Hot Air Evaporative Anti-Icing

Hot air evaporative anti-icing systems are used for wing and empennage surfaces and, in the case of turbine powered aircraft, for portions of the engine air intake systems. With this type of protection, hot air is passed through passages integral with the surface being heated. Air flow requirements are determined by assuming full evaporation of all impinging water under the severest condition which the aircraft is expected to encounter (see Par. 8).

In piston 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. With the advent of turbine powered aircraft, compressor bleed air is usually utilized to provide adequate ice protection. Compressor bleed air systems are lighter than equivalent 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 radomes and propeller spinners where the effects of ice buildups aft of the heated area can be tolerated. 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 De-Icing

Cyclic de-icing is the periodic shedding of small ice buildups. In thermal de-icing, the ice-airfoil interface is melted by a high rate of heat input; the adhesion at the ice-airfoil interface becomes zero and aerodynamic forces remove the ice. With the advent of lightweight, 400 hertz, three phase AC systems for aircraft application, electrical resistance heating elements are also used for de-icing. Electrothermal systems are used primarily for airfoil surfaces (since small ice buildups

here are not detrimental to airplane performance) or on propeller and helicopter blades where other means are impractical. Electro-thermal de-icing requires the least amount of heat of all thermal ice protection systems, but this advantage is partially offset by the drag 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 using the differential analyzer. The experimental technique (Ref. 1) is to allow a short burst of dye spray of known quantity and droplet 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.

The analytical approach (Ref. 2) is the direct "brute force" 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

$$M = 0.38 \nu B (LWC) E_m \quad (3F-1)$$

For a given volume median droplet size, ambient temperature, and altitude, water catch efficiency, E_m , is a function of velocity, airfoil shape, and thickness. Refs. 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 droplet 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 Refs. 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 waterdrop 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; (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.

Efficiency of water catch (E_m) data for airfoils, engine inlets, and many geometrical shapes is shown in Fig. 3F-1 (taken from Refs. 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 $\alpha=0$ deg.

At angles of attack greater than 0 deg, 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 $\alpha=0$ deg. The plots shown in Fig. 3F-1 are generally within $\pm 10\%$ of the original data for the practical range of Reynolds numbers from 100-250.

The K_o factor may be evaluated either by the graph of Fig. 3F-2 or by the following equation (correct within $\pm 5\%$):

$$K_o = (1.87)(10^{-7}) \left(\frac{1.15 v}{\mu_o} \right)^{0.6} \left[\frac{d_{med}^{1.6}}{12 C (g\rho)_o^{0.4}} \right] \quad (3F-2)$$

Fig. 3F-3 presents a plot of M/LWC for a 15% Joukowski airfoil as a function of true air speed and airfoil thickness, for $\alpha=4$ deg, and 20μ water drops, the water-drop diameter called out in military specifications. Plots of this type are accurate for only one angle of attack, droplet 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 Ref. 8.

4.1.2.2 Local Water Catch Distribution and Impingement Limits

The formula for local water catch, analogous to Eq. 3F-1, is:

$$M_\beta = 0.38 v (LWC) \beta \quad (3F-3)$$

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, as it is for total water catch. Ref. 8 presents curves for determining local water catch efficiencies for several airfoil sections at various angles of attack. Fig. 3F-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 Refs. 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. Refs. 2 and 3 and 6-8 present curves for obtaining impingement limits for several airfoil sections at various angles of attack.

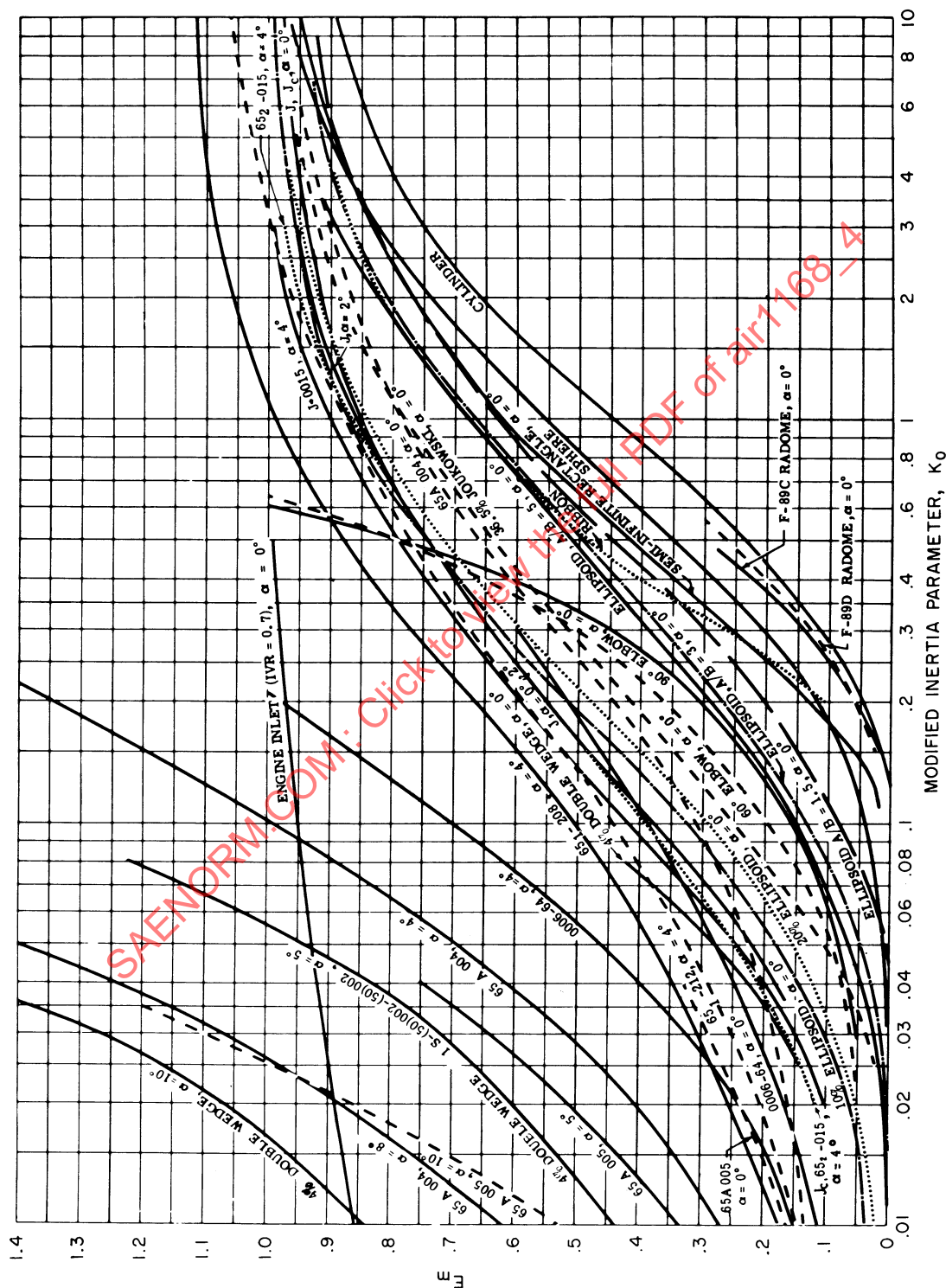
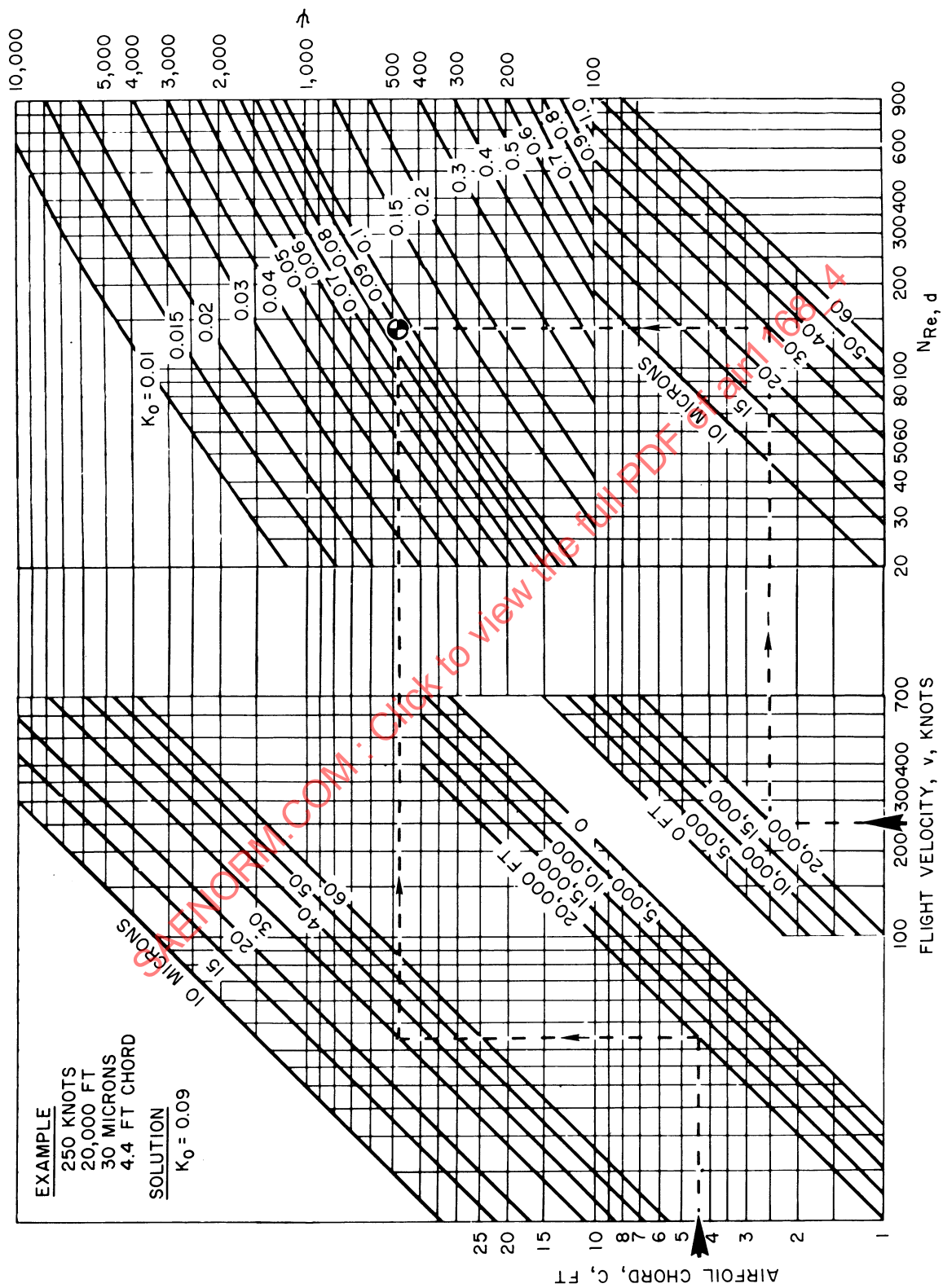


Figure 3F-1 - Water Catch Efficiencies For Various Airfoils and Geometric Shapes (J refers to Joukowski 0015 airfoil, subscript c means cambered; Refs. 6 and 7)

Figure 3F-2 - Graphical Solution of K_0 For 15°F Ambient Air Temperature (Refs. 6 and 7)

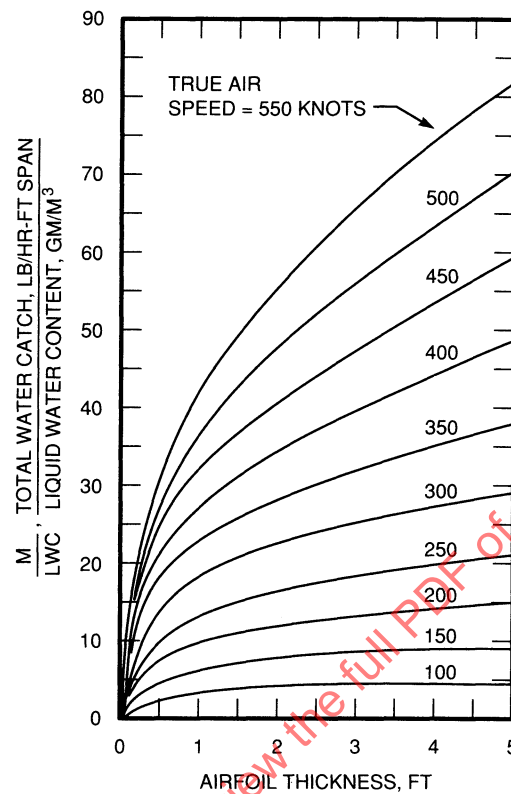


Figure 3F-3 - Airfoil Total Catch Typical For 6-16% Thick Airfoils At $\alpha=4$ deg. 20μ Volume Median Drops (All altitudes: Strictly true for 10,000 ft and approximately, within 10%, true between sea level and 20,000 ft)

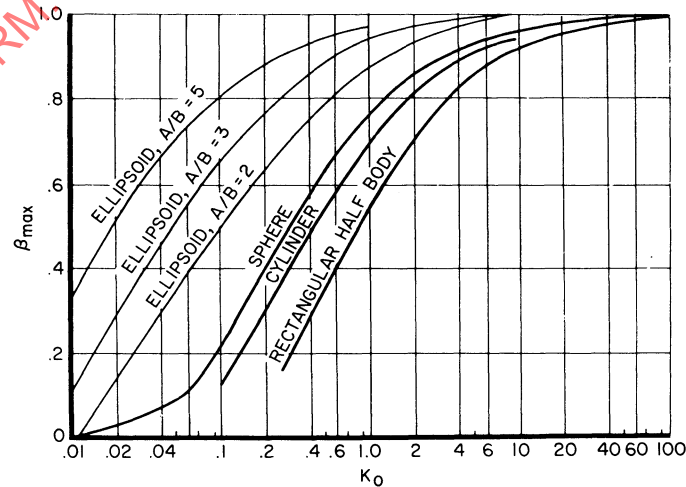


Figure 3F-4 - Local Impingement Efficiencies At the Stagnation Line, $\alpha=0$ deg

As an example, Fig. 3F-6 shows the impingement limits for an NACA 65₂-015 airfoil at $\alpha=4$ deg, and for a symmetrical 15% airfoil at $\alpha=0$ deg. 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.

Figs. 3F-7 and 3F-8 show the upper and lower limits of ice impingement (S_U, S_L), as simplified by the K_o correlation (taken from Refs. 6 and 7). The tendency of thin airfoils, at large angles of attack ($\alpha \geq 4$ deg), to accumulate ice up to the mid-chord on the lower surface under conditions of large K_o (large droplet size, high speed, small chord length) is clearly apparent.

The method of presentation in Figs. 3F-1, 3F-7, and 3F-8 permits interpolation or extrapolation to other airfoil thicknesses and angles of attack for which waterdrop trajectory data are not known.

4.1.3 Bodies of Revolution

The equation analogous to Eq. 3F-1 for bodies of revolution is

$$M = 0.38 v A_f (LWC) E_m \quad (3F-4)$$

where A_f is the frontal area of the body. Fig. 3F-9 shows cone water catch efficiencies as obtained on the differential analyzer (Ref. 9), plotted as a function of velocity and body (radome, spinner, and so forth) length. In the same manner, it is possible to plot $\beta_{max}/\sin \Phi_o$ (Fig. 3F-9), where Φ_o is the cone semivertex angle, and impingement limits (Fig. 3F-10).

The cones analyzed in Ref. 9 are rounded at the base, as shown in Fig. 3F-5, where

$$s_b = \text{Impingement limit and } r = L_x \sin \Phi_o$$

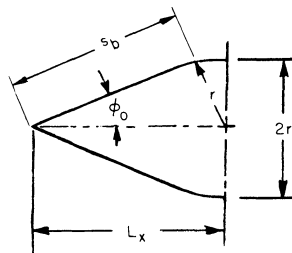


Figure 3F-5 - Cone Geometry

$$\text{Then } A_f = \pi L_x^2 \sin^2 \Phi_o \quad (3F-5)$$

To obtain local catch distributions (Fig. 3F-10), it is necessary to compute the quantity Γ , where

$$\Gamma = \frac{E_m}{\beta_{max} S_m - E_m} \quad (3F-6)$$

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

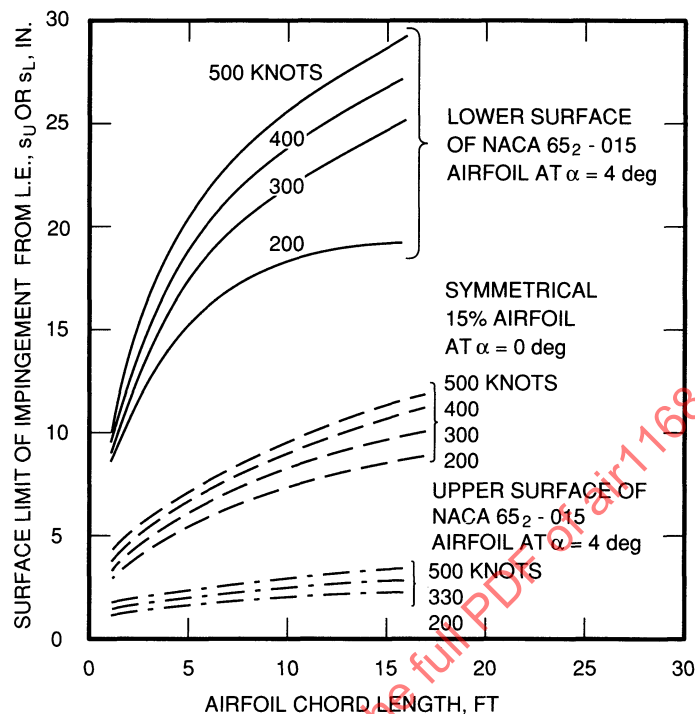


Figure 3F-6 - Airfoil Impingement Limits For 40μ Maximum (20μ volume median) Drops (All altitudes: Strictly true for a particular altitude and approximately, within 10%, true between sea level and 20,000 ft)

$$S_m = \frac{(s_b/L_x)^2}{\sin \Phi_o} \quad (3F-7)$$

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

4.2 External Heat Transfer Coefficients

4.2.1 Airfoils

4.2.1.1 Local

The calculation of local heat transfer coefficients requires a knowledge of the velocity and static pressure distributions over the airfoil. Since this latter subject is covered in Ref. 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, Par. 3.5.2 and also in Ref. 11.

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

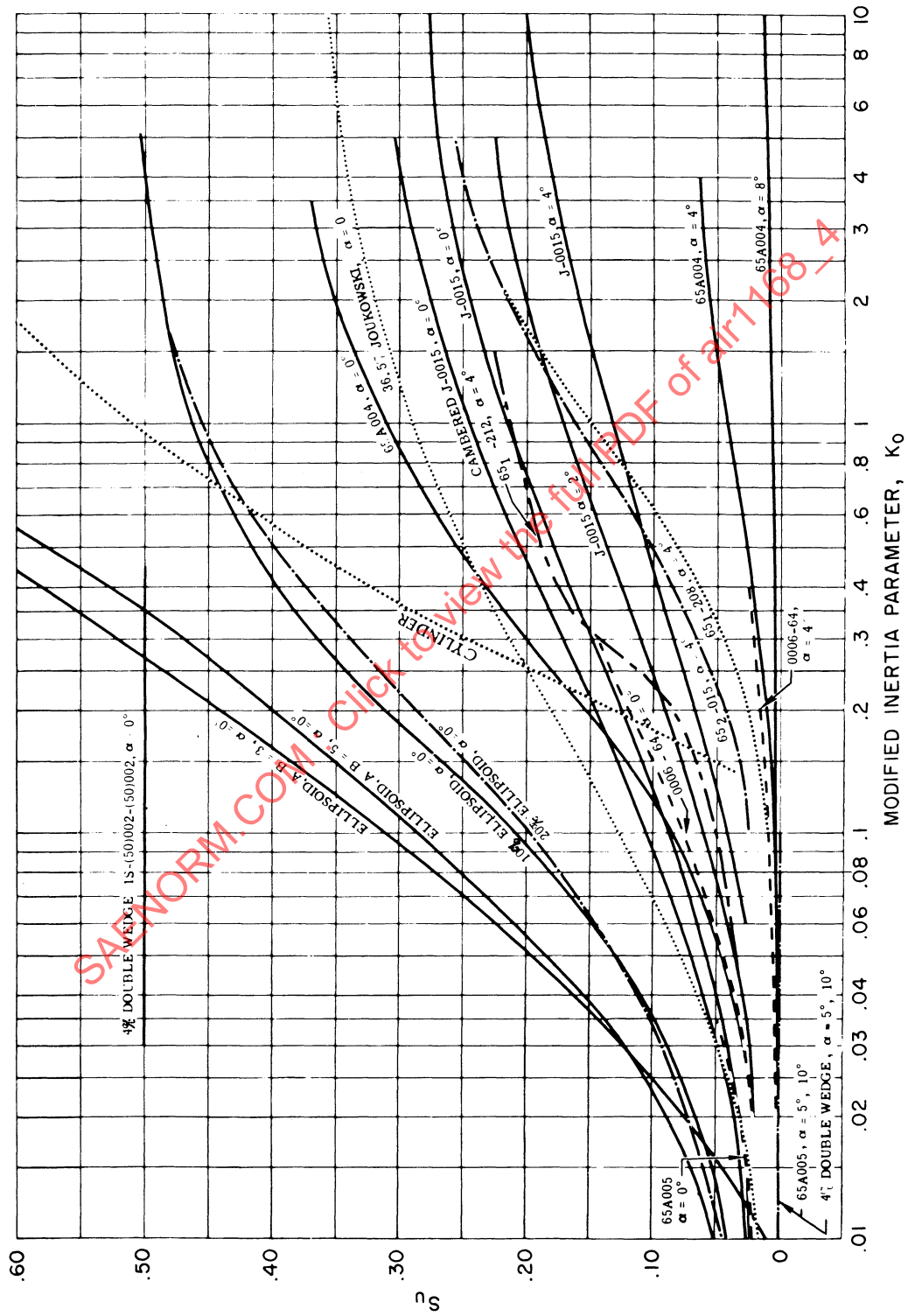


Figure 3F-7 - Water Drop Tangent Trajectories On Upper Surface. Note: $S_u > 0.80$ for cones ($\alpha = 0^\circ$ deg, any vertex angle) for $K_0 > 0.04$

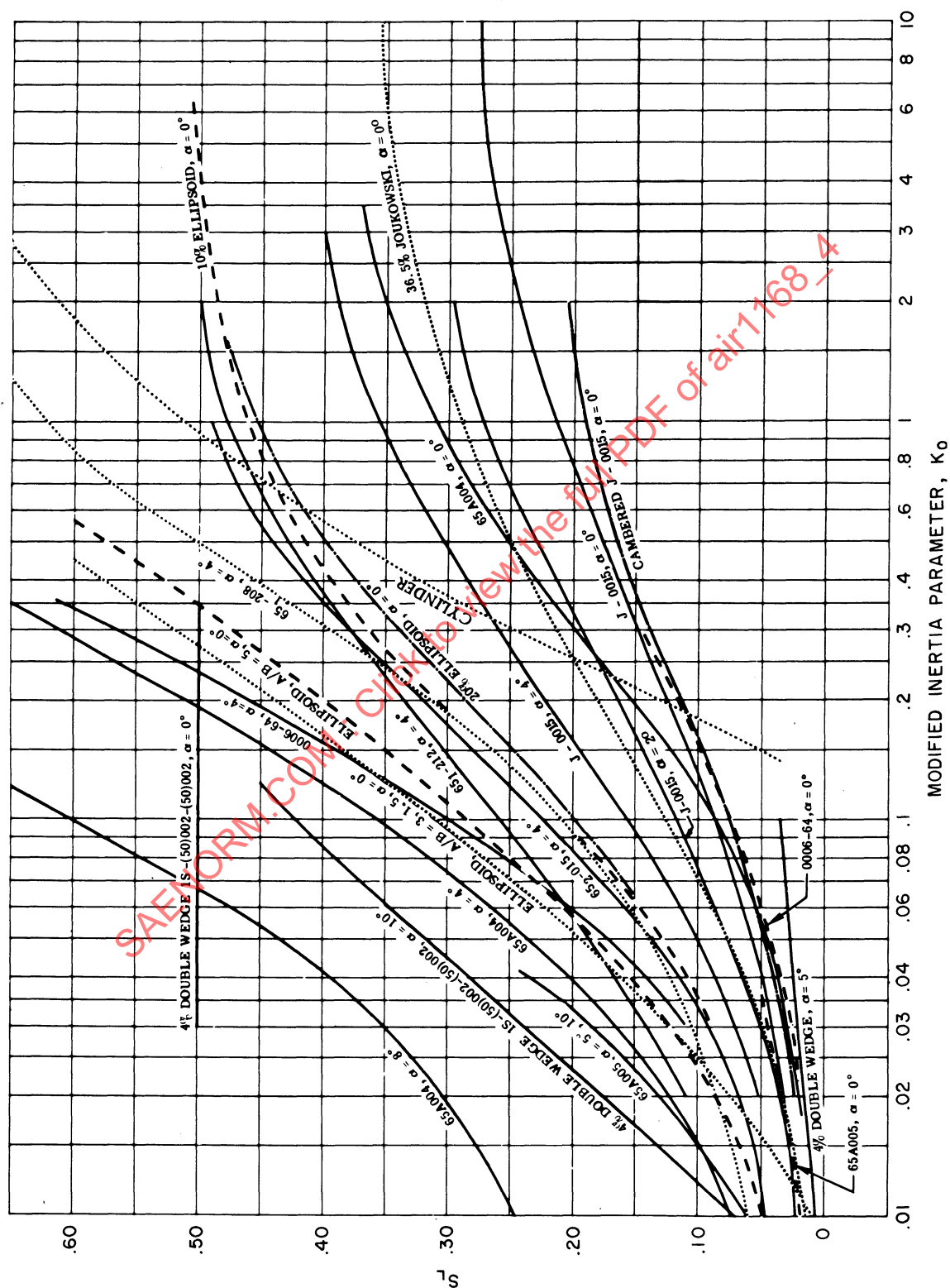


Figure 3F-8 - Water Drop Tangent Trajectories On Lower Surface. Note: $S_L > 0.80$ for cones ($\alpha = 0$ deg; any vertex angle) for $K_o > 0.04$

$$\text{Turbulent } h_o = 0.51 (T_m)^{0.3} \cdot \frac{[1.69 (\rho g)_o v]^{0.8}}{s^{0.2}} \quad (3F-8)$$

Transition from laminar to turbulent flow is dependent upon local pressure gradients and local Reynolds number. 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. In all probability an iced surface will be fully turbulent from the stagnation point.

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.

The equation for the average heat transfer coefficient over a distance L_x from the leading edge is

$$\text{Average } h_o = 0.64 (T_m)^{0.3} \cdot \frac{[1.69 (\rho g)_o v]^{0.8}}{L_x^{0.2}} \quad (3F-9)$$

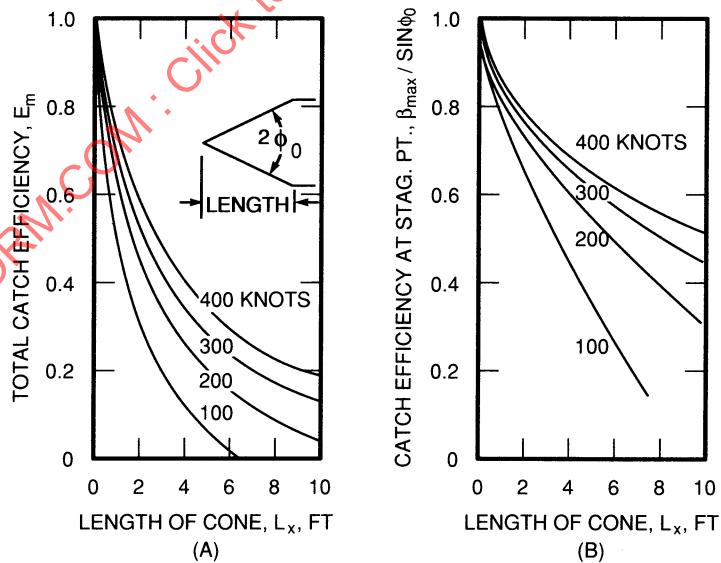


Figure 3F-9 - Catch Efficiency On Cones For 20μ Volume Median Drops (A) - Total, (B) - Stagnation Point (All altitudes: Strictly true for 10,000 ft altitude and approximately, within 10%, true between sea level and 20,000 ft)

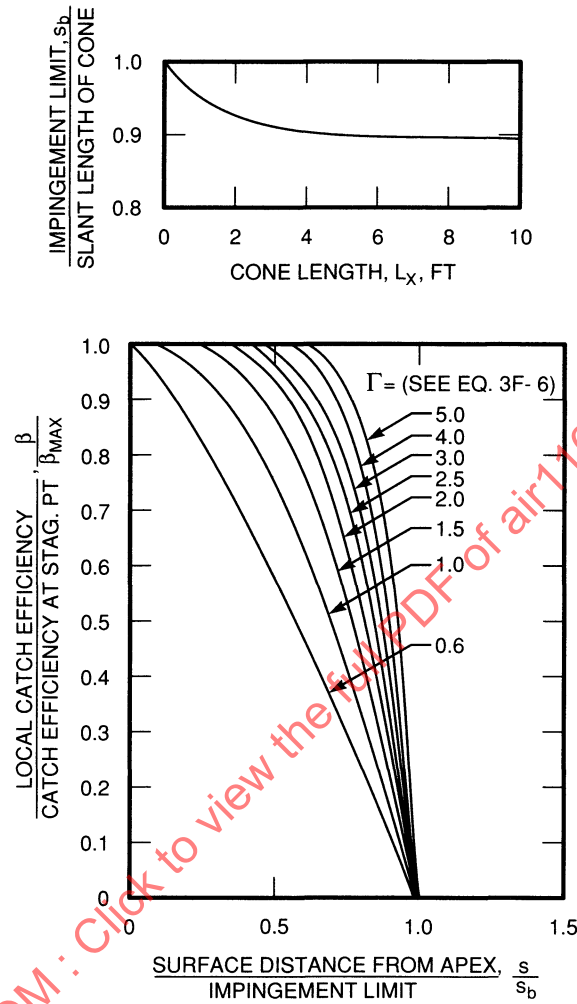


Figure 3F-10 - Local Catch Distribution (Bottom) and Impingement Limits (Top) On Cones For 20μ Volume Median Drops. Note: impingement limits are fairly insensitive to changes in altitude and velocity

Taking the area per ft of span per surface = $L_x(1) = S_o$, and putting in the equation of state, Eq. 3F-9 becomes (for $T_m = 520^\circ\text{R}$),

$$h_o S_o = 6.32 \left[(\rho g)_o v L_x \right]^{0.8} \quad (3F-10)$$

Although h_o is a function of T_{amb} , the change in h_o over the range of ambient temperatures for which icing can occur can be neglected. Hence, $h_o S_o$ may be plotted as a function of v and L_x for various altitudes (for $T_{amb} = 460^\circ\text{R}$) as presented in Fig. 3F-11.

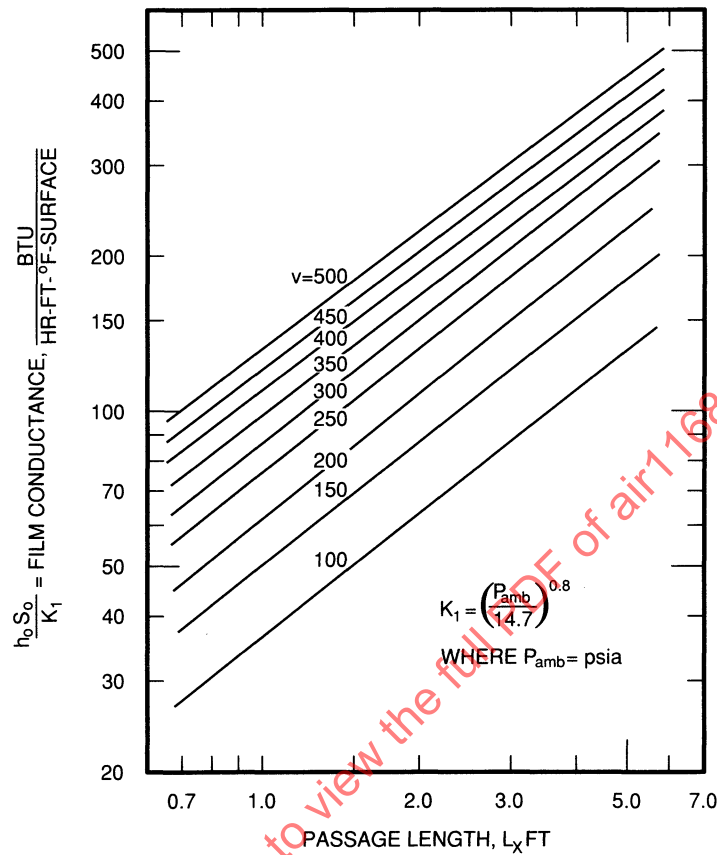


Figure 3F-11 - Average External Film Conductance For Fully Turbulent Flow Over Airfoils (v = velocity, knots TAS)

4.2.2 Bodies of Revolution

Figs. 3F-12 and 3F-13 (taken from Ref. 9) present curves for the determination of local laminar and turbulent heat transfer coefficients over cones. Transition from laminar to turbulent flow may be assumed to occur at

$$N_{(Re,o)} \left(\frac{s}{L_x} \right) \cos \Phi_o = 1.5 \times 10^6 \quad (3F-11)$$

where $N_{(Re,o)}$ is based upon freestream conditions and body length. Heat transfer coefficients over ellipsoids can be obtained from Ref. 9. For Figs. 3F-12 and 3F-13,

$$N_{Nu} = \frac{h_o L_x}{k_o} \quad \text{and} \quad N_{(Re,o)} = \frac{1.69 (\rho g)_o v L_x}{\mu_o}$$

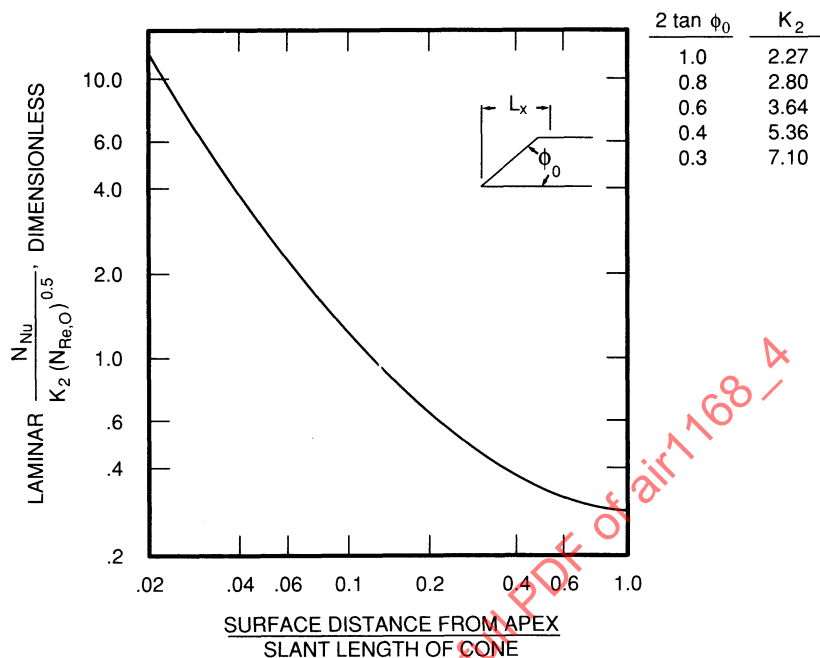


Figure 3F-12 - Laminar Heat Transfer Coefficients Over Cones

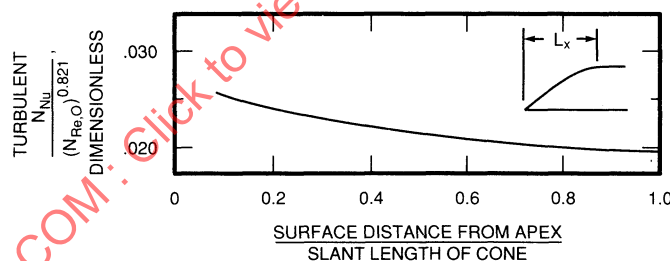


Figure 3F-13 - Turbulent Heat Transfer Coefficients Over Cones

5. AIRFOIL EVAPORATIVE ANTI-ICING

5.1 Wet Surface Temperature

5.1.1 Wettedness Factor

Wettedness factor, F , is a measure of the surface area over which evaporation occurs, and is related to the impingement limit. Forward of the impingement limit, the water (on a heated surface) tends to form a solid film, and the wettedness factor is unity. Aft of the impingement limit the water flows in rivulets and the wettedness factor F is taken as 0.2. Consequently, the overall wettedness factor could vary from 0.2 to 1.0, depending upon the ratio of impingement limit to heated chord. However, an overall value of 0.6 can be used for computing air flow requirements.

5.1.2 Evaporation Rate

For evaporative anti-icing, the rate of evaporation is equal to the rate of water catch, or

$$M = \frac{2.9 h_o S_o F (p_{sk} - p_w)}{p_{amb} - p_{sk}} \quad (3F-12)$$

Rearranging Eq. 3F-12 and putting in $F=0.6$,

$$\frac{M}{h_o S_o} = 1.74 \frac{p_{sk} - p_w}{p_{amb} - p_{sk}} \quad (3F-13)$$

Since $p_{sk} \gg p_w$ for the skin temperatures of interest, and since p_{sk} is a function of skin temperature only, it is possible to plot required skin temperature as a function of $M/h_o S_o$ for various altitudes, as is presented in Fig. 3F-14.

5.2 Anti-Icing Heat Load

The requirements of a hot air evaporative anti-icing system are determined by the rate at which heat must be supplied to balance the heat losses from the protected surface, which result from three concurrent processes: convective cooling, evaporation, and sensible heating (heating of the impinging water to the skin temperature). The heat load equation is

$$\frac{q}{h_o S_o} = (t_{sk} - t_{aw}) + \left[\frac{M}{h_o S_o} c_w (t_{sk} - t_w) \right] + \left(\frac{M}{h_o S_o} L_e \right) \quad (3F-14)$$

convection sensible heat evaporation

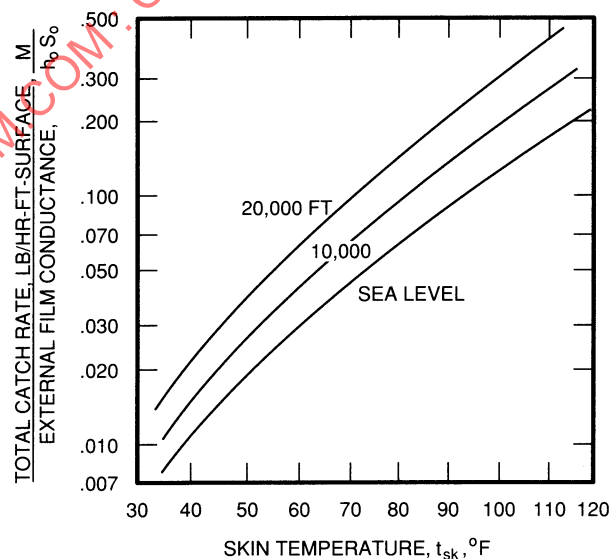


Figure 3F-14 - Skin Temperature Required For Evaporative Anti-icing

Using a constant value of L_e of 1060 Btu/lb, and rearranging terms,

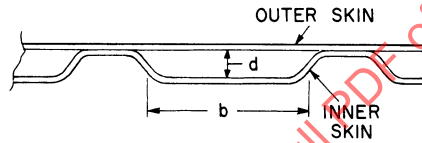
$$\frac{q}{h_o S_o} = (t_{sk} - t_{aw}) + \frac{M}{h_o S_o} \cdot [1060 + (t_{sk} - t_w)] \quad (3F-15)$$

Since $(t_{sk} - t_w) \ll L_e$, the difference between t_w and t_{aw} can be neglected, and hence it is possible to plot $q/h_o S_o$ against $(t_{sk} - t_{aw})$ for various values of $M/h_o S_o$, as shown in Fig. 3F-15.

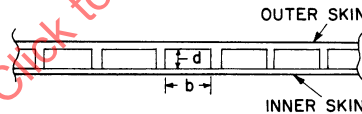
5.3 Determination of Air Flow Requirements

5.3.1 Passage Design

The most commonly employed hot air passages are the corrugated double skin and the machined skin. In the former a second, or inner, skin forms the heat transfer passages as shown in the sketch below.



In the machined skin, chordwise slots are milled in the leading edge and a second flat sheet is used to back up the passages, as shown in the next figure.



This construction is used where very shallow passages (≈ 0.05 in. deep) are desired.

5.3.2 Internal Heat Transfer Coefficient

The internal heat transfer coefficient for turbulent flow in a passage is

$$h_i = 5.4 \times 10^{-4} \left(\frac{T_m^{0.3}}{D_h^{0.2}} \right) \left(\frac{w_{pa}}{A_{pa}} \right)^{0.8} \quad (3F-16)$$

From the two preceding sketches,

$$A_{pa} = n b d$$

$$D_h = 2 \left(\frac{b d}{b + d} \right) = 2 \left(\frac{d}{1 + (d/b)} \right)$$

Also, we can define the correction factor for passage aspect ratio:

$$Z = \left(1 + \frac{d}{b} \right)^{0.2}$$

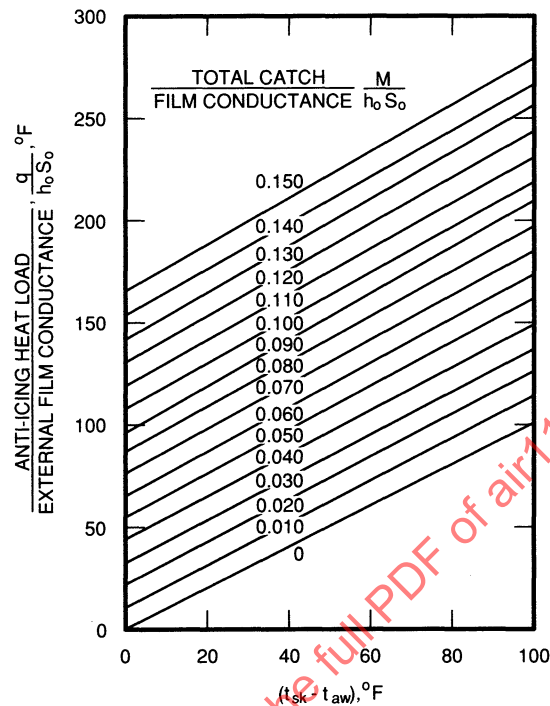


Figure 3F-15 - Airfoil Evaporative Anti-icing Energy Requirements

Combining these equations,

$$h_i = 5.4 \times 10^{-4} \left(\frac{T_m^{0.3}}{(2d)^{0.2}} \right) \left(\frac{Z}{(bd)^{0.8}} \right) \left(\frac{w_{pa}}{n} \right)^{0.8} \quad (3F-17)$$

5.3.3 Passage Heat Balance

The energy required to satisfy the requirements of Eq. 3F-15 is supplied by the enthalpy drop of the passage air, or

$$q = w_{pa} c_p (t_{in} - t_{ex}) \quad (3F-18)$$

The air temperatures are related to the skin temperature by Eq. 3F-19:

$$\frac{t_{ex} - t_{sk}}{t_{in} - t_{sk}} = e \exp \left(- \frac{h_i n b Y L_x}{w_{pa} c_p} \right) \quad (3F-19)$$

The factor Y in Eq. 3F-19 is the correction for passage fin effect brought about by conduction from the inner skin, which effectively increases the internal heat transfer area. The determination of Y is discussed in detail in Reference 34. In the case of a corrugated aluminum passage, Y is approximately 1.6. Insertion of Eq. 3F-17 into Eq. 3F-19 leads, after considerable rearrangement, to (for $T_m \approx 660^\circ\text{R}$)

$$\frac{q}{nb(t_{in} - t_{sk})} = 0.24 \left(\frac{w_{pa}}{nb} \right) \left\{ 1 - e \exp \left(-0.0137 \frac{L_{eq}}{d} \left(\frac{nb}{w_{pa}} \right)^{0.2} \right) \right\} \quad (3F-20)$$

where $L_{eq} = L_x YZ$ and is defined as the "equivalent passage length." In Fig. 3F-16, $q/nb(t_{in} - t_{sk})$ has been plotted as a function of w_{pa}/nb for values of L_{eq}/d . Values of Z are shown as a function of d/b in Fig. 3F-17.

6. RUNNING WET ANTI-ICING

Energy requirements for running wet anti-icing are found by combining Eqs. 3F-12 and 3F-14 and setting $F=1.0$, or

$$\frac{q}{h_o S} = (t_{sk} - t_{aw}) + \frac{M_\beta}{h_o} c_w (t_{sk} - t_w) + \frac{2.9 L_e (p_{sk} - p_w)}{P_{amb} - p_{sk}} \quad (3F-21)$$

The choice of unity wettedness factor results from the assumption of a solid film of water over the entire heated area. The use of this equation differs from that of the preceding section in that a desired skin temperature (35-50°F) is selected beforehand and the energy requirements computed directly.

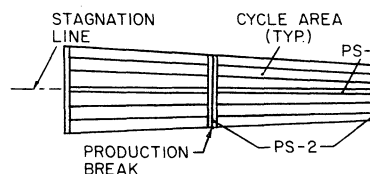
Another difference is that, whereas evaporative anti-icing requirements were based upon average quantities, running wet anti-icing requirements are computed using the local values of water catch rate and heat transfer coefficients. Fig. 3F-18 shows $q/h_o S$ plotted against velocity and M_β/h_o for a skin temperature of 40°F (a conservative value) and an ambient temperature of 0°F (specification requirement).

The values in Fig. 3F-18 assume 100% heating efficiency; that is, no heat loss to the structure. Heating efficiency normally varies from 60 to 100%, depending upon the type of construction, proximity of unheated areas, and similar factors. Because of the varying requirements from point to point, running wet anti-icing lends itself to the use of electrical resistance elements for the energy supply. In this case, heating efficiency may be taken as 70% along the edge of the heated area, and may be increased roughly exponentially to unity at approximately 8 in. in from the edge.

7. ELECTROTHERMAL CYCLIC DE-ICING

7.1 Description

With the development of lightweight 400 hertz alternators, electrothermal de-icing has found many applications on new aircraft designs as a power conservation measure. The leading edge area to be protected is divided into several spanwise and chordwise areas, with each area energized sequentially or, at most, with corresponding areas on opposite sides of the airplane energized simultaneously. A possible heater layout is sketched below.



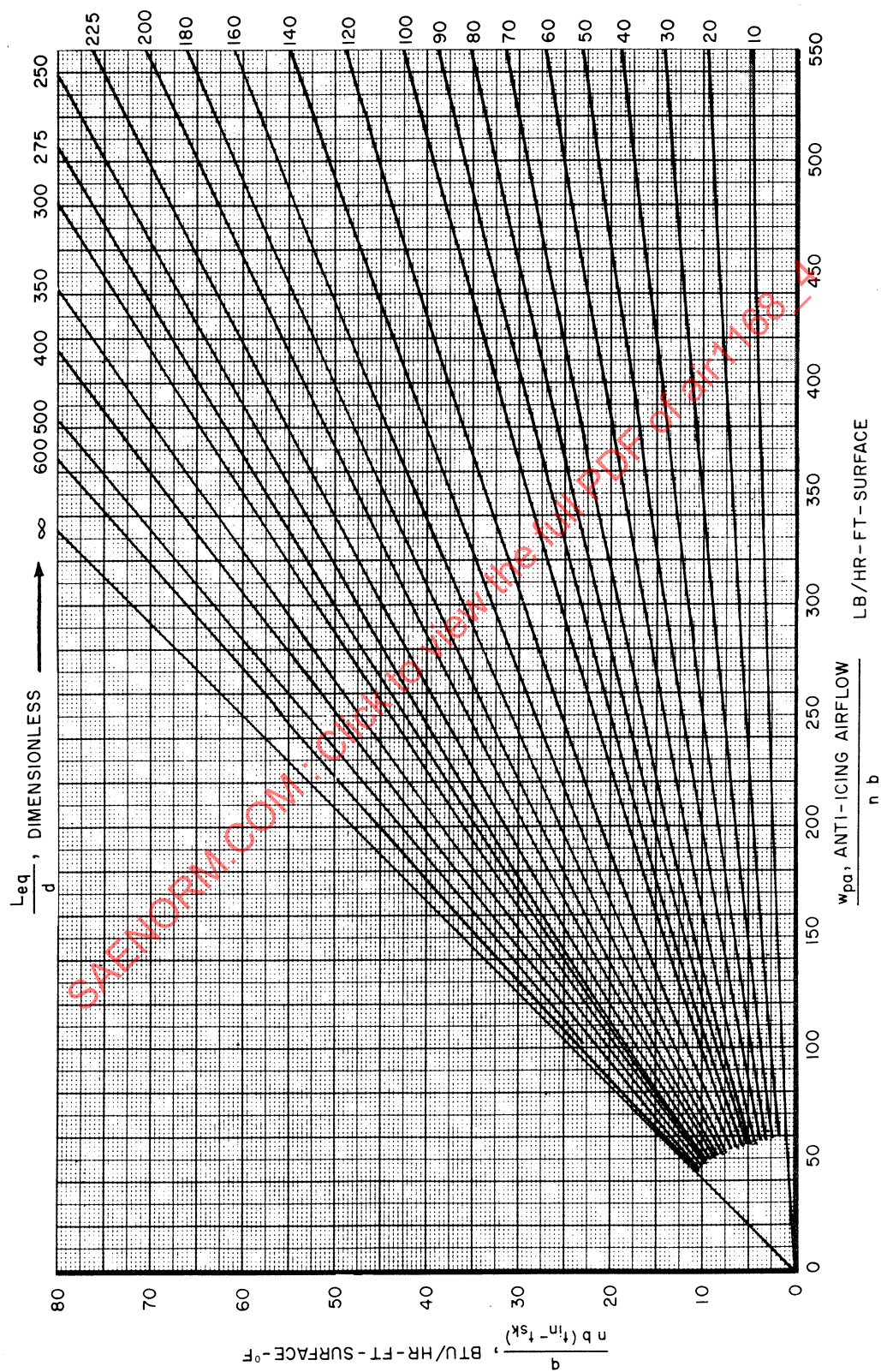


Figure 3F-16 - Air Flow Required For Evaporative Anti-icing

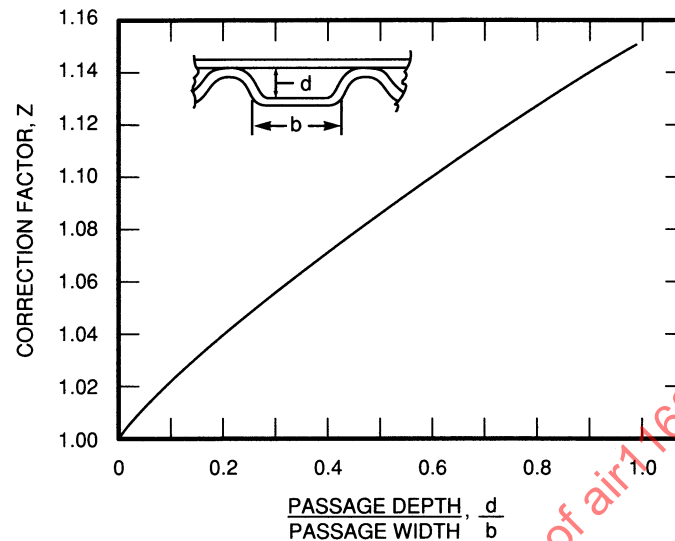


Figure 3F-17 - Correction Factor For Passage Aspect Ratio, $Z = (1 + d/b)^{0.2}$

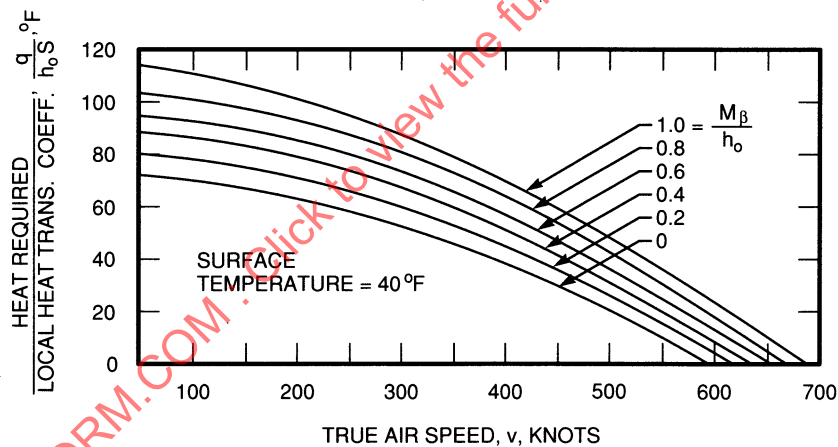


Figure 3F-18 - Energy Requirements For Running Wet Anti-icing. Surface temperature = 40°F, 10,000 ft at 0°F ambient. To obtain values for other altitudes: subtract 11.0 for sea level, add 15.0 for 22,000 ft

For slightly swept airfoils a 1 in. wide, continuously heated parting strip (PS-1) is provided along the stagnation line to prevent ice from bridging over between the top and bottom surfaces and to allow aerodynamic forces to remove the ice. In addition, 3/4 in. wide chordwise parting strips (PS-2) should be added adjacent to the unprotected areas and on either side of production breaks.

The cycled area may be divided into two or three chordwise areas, the cycling sequence being from front to rear. Usually, but not always, the rearmost element is aft of the impingement limits to clear off any runback ice (formed while the recently shed areas are still above freezing and the impinging water merely runs back along the surface).

On highly swept airfoils, the spanwise parting strip (PS-1) may not be necessary because the spanwise components of the aerodynamic forces may be sufficient to cause the ice to shed spanwise. Under these circumstances, only one chordwise shedding area need be employed, with the farthest edge area being shed first.

7.2 Heater Construction

The basic heater construction consists of electrical resistance elements sandwiched between two layers of dielectric material, with some form of rain and hail resistant material applied to the external surface. Heater de-icing performance is measured in terms of a de-icing efficiency, which is defined as the heat leaving the surface integrated over the "ON" time divided by the total heat input. De-icing efficiency is, in turn, influenced by the heater construction, typical values ranging from 20-40% for various designs. Heater de-icing efficiency is reduced by improper heater design in several ways:

- (1) Not all the heat input goes out the external surface; some of it goes back into the leading edge skin and plenum areas.
- (2) The heater itself absorbs heat while being heated up to the temperature required for de-icing.
- (3) Discrete heater elements, such as ribbons or wires, result in nonuniform heating of the external surface, and thus power inputs must be increased to ensure that the areas between the heater elements are sufficiently heated.

The optimum heater buildup is one that maximizes de-icing efficiency and at the same time is light in weight and has good rain and hail resistance.

The most recent heater designs utilize glass cloth impregnated with epoxy or phenolic resins as the dielectric material. Erosion resistance is provided by a sheet of metal (either 0.010 in. thick aluminum or 0.005 in. thick stainless steel), which also helps reduce the problem of nonuniform heat sources and adds some structural rigidity to the sandwich, thus reducing the leading edge skin thickness. A cross section of this type of construction is shown in Fig. 3F-19.

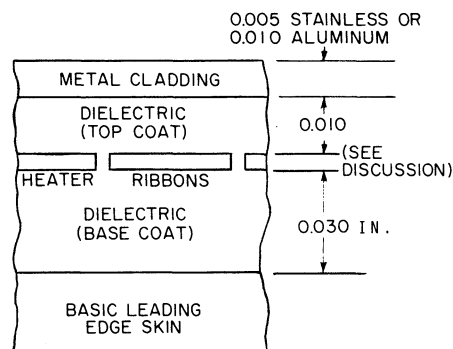


Figure 3F-19 - Heater Construction

Heater ribbon thickness varies with the material used, ribbon width, and desired resistance. The thickness is usually in the neighborhood of 0.003-0.005 in. Although the metal cladding will help spread the heat, the heater ribbon should be at least five and preferably ten times as wide as the allowable gap between ribbons, to ensure uniform surface temperature. With a maximum gap width of 0.05 in., this means a ribbon width of 0.25-0.5 in. The ratio of base coat to top coat thickness of 3:1 has been found to be a good compromise between heater efficiency and heater weight. For this particular construction the de-icing efficiency is approximately 40%.

7.3 Parting Strip Power Requirements

Parting strip power requirements are computed in much the same manner as those for running wet anti-icing (Par. 6). The basic difference is that the presence of ice layers on the adjacent cycled areas materially affects parting strip power requirements. Because of conduction into the cycled areas, a surface temperature of 50°F at the center of the parting strip is necessary to ensure a finite ice-free area and prevent adjacent ice formations from bridging over. Generally, 12 W/in.² (5900 Btu/hr-ft²) will suffice for a 0°F ambient, while 20 W/in.² are required for a -22°F ambient. These values are approximate and depend on the heater construction. In particular, thicker skins and cladding or thinner base coats may increase the power requirements by 10 to 20%. Consequently, the actual powers used should be verified by tests.

7.4 Cyclic Requirements

Cyclic requirements are a function of impingement limits, power available, and total cycle time (number of elements times the "ON" time for each element). The required power intensity is primarily a function of the unheated equilibrium temperature (Par. 8.3) and the heat-on time; the heat-off time, ice thickness, catch rate, and heat transfer coefficient have second order effects.

For the most efficient removal of ice, minimum runback ice, and minimum total energy input, high power intensities (40 W/in.²) for very short periods (2-3 sec) give the best results. However, for a given total power available, this results in a large number of elements and the consequent increase in weight and timer complexity.

As a compromise, a power input of 22 W/in.² for 9 sec can be used to obtain good de-icing performance. For total cycle time, 3 min has been found to be the best compromise for total power requirements (the more elements, the lower the total power), with the drag occurring during the heat-off period. Again, these numbers are approximate, since heater construction plays a major role in de-icing performance; therefore, the final design should be verified by tests.

8. DETERMINATION OF THE NEED FOR ICE PROTECTION

8.1 Design Point

Regardless of the type of ice protection employed (evaporative, running wet, or cyclic), it is necessary to design the system to meet the severest icing condition the airplane is anticipated to encounter. This is determined by superimposing the airplane mission on the applicable government requirements (Par. 8.2) and computing the energy requirements for several flight conditions. In addition, an envelope should be drawn, using the methods of Par. 8.3, showing the flight

conditions for which ice protection is not required because the unheated equilibrium temperature is above freezing. The following paragraphs present some general statements regarding the selection of a design point.

In general, hot air systems, which rely primarily on ram pressure for adequate air flow, must be sized for the highest altitude at which ice is expected, usually 20,000 to 22,000 ft. Systems employing compressor bleed air must be sized for the lowest engine power settings (in some cases, descent power) because of reduced bleed temperatures, pressures, and available air flow. Generally, the condition of lowest ambient temperature is the most critical, from a heat requirement consideration, but in the case of the civil requirement the increase in required liquid water content with ambient temperature (Fig. 3F-20) may more than offset the reduced convective losses.

Since the energy available from electrothermal systems, either running wet or cyclic, is constant, they must be sized for maximum energy requirements. For running wet systems, this usually occurs in the vicinity of 250-350 knots true air speed at sea level. At velocities greater than this, the increase in equilibrium temperature due to the kinetic rise offsets the increased convective losses. This is presented only as a guide and should be verified for the particular application.

Since cyclic requirements are primarily a function of unheated equilibrium temperature (Par. 7.4), such a system should be designed for the condition where this temperature is a minimum (see Fig. 3F-23).

8.2 Government Regulations

8.2.1 Commercial Transports

The ice protection requirements for commercial transports are specified in the Federal Air Regulations (FAR), Part 25 (Ref. 12). Two regimes are considered: continuous and intermittent maximums, as defined below and as plotted in Figs. 3F-20 and 3F-22 (continuous) and in Fig. 3F-21 (intermittent).

The continuous maximum icing condition (Figs. 3F-20 and 3F-22) is characterized by exposure to moderate-to-low liquid water content for an extended period of time. It is applicable to those components such as wing and tail surfaces that are affected by continuous flight in icing conditions but which can tolerate brief and intermittent encounters with conditions of greater severity. The FAR does not specify infinite extent, but does specify a standard horizontal extent of 20 miles (Fig. 3F-20), with a correction factor to be applied to liquid water content for other ranges (Fig. 3F-22).

The intermittent maximum icing condition (Figs. 3F-21 and 3F-22) is characterized by exposure to high liquid water contents for a short period, usually superimposed upon the continuous maximum. It is applicable to those components such as engine inlets and guide vanes where ice accretions, even though slight and of short duration, cannot be tolerated. The standard horizontal extent for this condition is 3 miles, as compared with 20 miles for the continuous maximum.

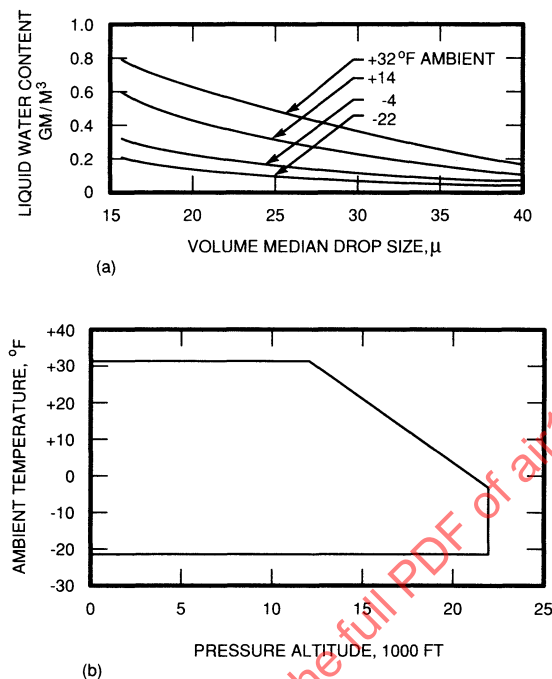
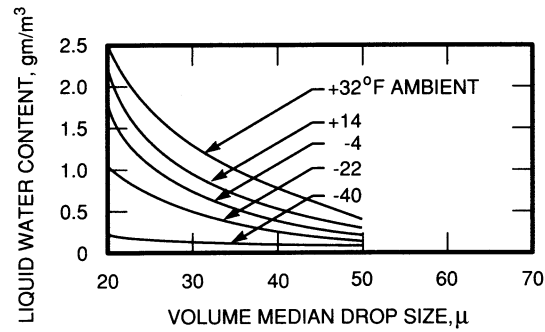


Figure 3F-20 - Continuous Maximum Icing Condition. Altitude: sea level to 20,000 ft; maximum vertical extent, 6500 ft; horizontal extent, 20 miles. (a) liquid water content, (b) envelope of icing temperature.

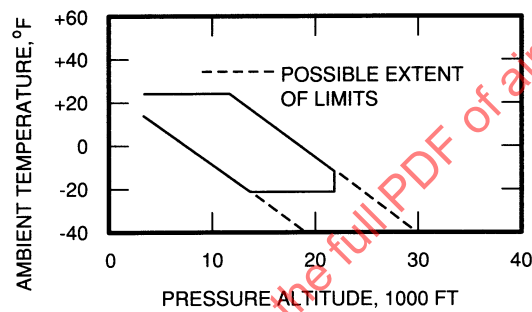
8.2.2 Military Aircraft

The military requirements for airfoil ice protection (Refs. 13 and 14) differ in some respects from those of the FAR. The Air Force design icing condition (Ref. 13) is 0.50 gm/m³ of 20μ volume median drops for all altitudes up to 20,000 ft. To comply with this specification, the system must provide complete evaporation of all impinging water at 15°F ambient temperature, with a minimum running wet surface temperature of 35°F at 0°F ambient. The Navy requirement (Ref. 14) states that the system should maintain an ice-free surface in a cloud containing 0.5 gm/m³ of 15μ volume median drops at an ambient temperature of 15°F for all altitudes up to 20,000 ft. Anti-icing requirements for turbine engines are specified in Refs. 15 and 18. These engines are required to operate satisfactorily with a power loss not to exceed 5% of military power between normal and military power, or 5% of normal power between flight idle and normal power, and 5% increase in fuel consumption at all operating conditions or above flight idle for the meteorological conditions given in Table 3F-1.

Although not applicable to thermal systems, it is appropriate to mention Ref. 17, which is the general specification for pneumatic boot de-icing systems. These systems are to be capable of removing ice formed under conditions at least equivalent in severity to 0.5 gm/m³ of 20μ volume median drops at 15°F ambient temperature. Chordwise coverage should be adequate for all flight conditions from minimum cruise or loiter to the maximum speed of the aircraft.



(a)



(b)

Figure 3F-21 - Intermittent Maximum Icing Condition. Altitude: 4000-22,000 ft; horizontal extent: 3 miles, (a) liquid water content, (b) envelope of icing temperature

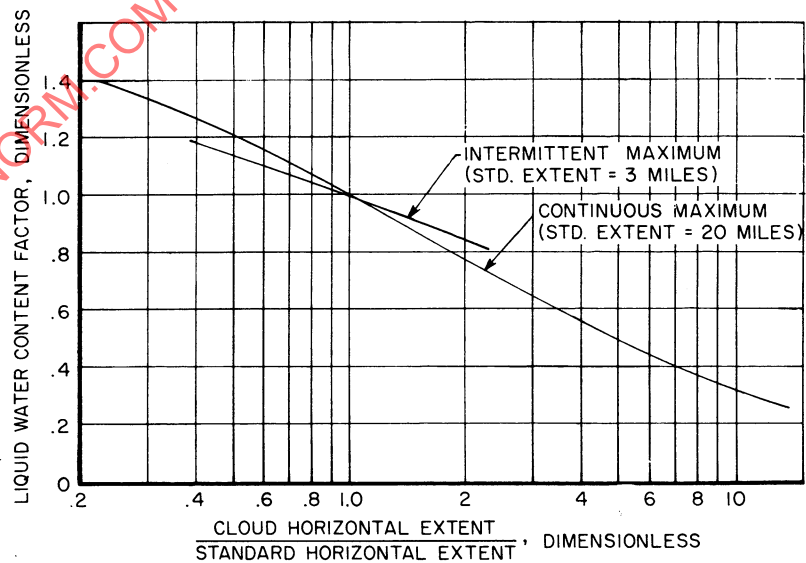


Figure 3F-22 - Variation of Liquid Water Content With Cloud Horizontal Extent

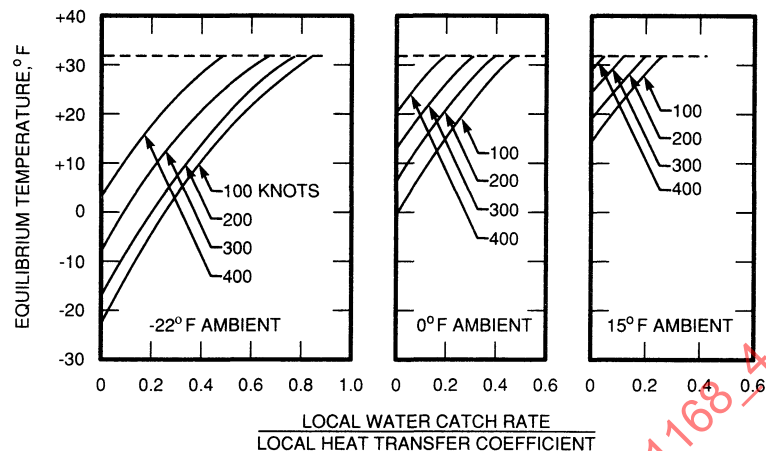


Figure 3F-23 - Unheated Equilibrium Temperature of an Iced Surface, All Altitudes

Table 3F-1 - Meteorological Operating Conditions for Turbine Engines

Quantity	Condition I	Condition II
Liquid Water Content	1.0 gm/m ³	2.0 gm/m ³
Ambient Air Temperature	-4°F	+23°F
Flight Velocity	Static	Static
Altitude	Sea level	Sea level
Volume Median Drop Size	15μ	25μ

8.3 Unheated Equilibrium Temperature of an Iced Surface

8.3.1 Surface Temperature Below Freezing

The surface of an unheated body flying in an icing condition will assume an equilibrium temperature that just balances convection, sensible heating, and sublimation (Par. 5). This temperature may be obtained by setting $q/h_o S_o$ in Eq. 3F-14 to zero and replacing the latent heat of evaporation with the latent heat of sublimation (approximately 1220 Btu/lb) to solve for the skin temperature. This leads to the family of curves shown in Fig. 3F-23. It must be remembered that these curves apply only to surface temperatures below 32°F.

8.3.2 Surface Temperature Above Freezing

Of more specific applicability to the question of the need for ice protection are the flight regimes for which the unheated equilibrium temperature is above freezing (Fig. 3F-20). For any given icing condition, ice protection is not required for velocities above those shown in Fig. 3F-24. The significance of the axis representing zero catch rate is that it indicates for what conditions any runback aft of the impingement area will not freeze. Fig. 3F-24 shows that all-weather supersonic aircraft do not need ice protection except during low speed operation (that is, landing, take-off, loiter, etc.), and hence require only limited protection on engine inlets and no protection on wing and tail surfaces.

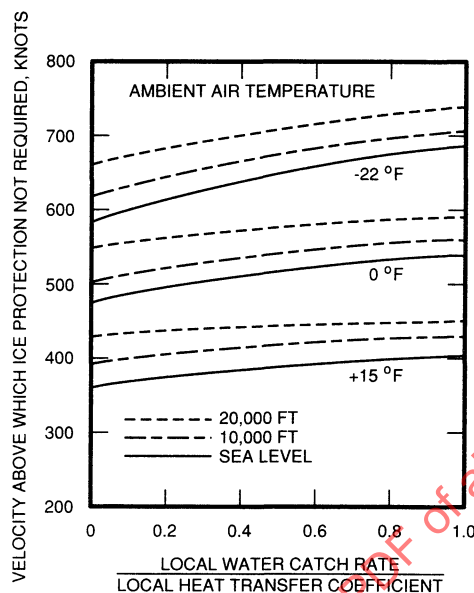


Figure 3F-24 - Velocity Above Which Ice Protection Is Not Required

9. ILLUSTRATIVE EXAMPLES

9.1 Airfoil Hot Air Evaporative Anti-Icing

The anti-icing provisions of a commercial transport are to be determined in compliance with the FAR for 300 knots true air speed at 20,000 ft, with a design icing condition of 20μ volume median drops and $+15^{\circ}\text{F}$ ambient air temperature. From Fig. 3F-20, the FAR continuous maximum requirement is 0.44 gm/m^3 . The airfoil geometry is listed in Table 3F-2.

Table 3F-2 - Airfoil Geometry

Quantity	Value
Airfoil Section	NACA 65 ₂ -015
Chord Length (Mean Aerodynamic)	150 in.
Maximum Thickness	22.5 in. (= 1.87 ft)
Passage Length, L_x (for front spar at 19% chord)	27 in. (= 2.25 ft)
Number of Passages per ft-span/surface, n	4
Passage Width, b	2.0 in.
Passage Depth, d	0.125 in.

In addition, a passage inlet air temperature of 280°F will be assumed. Normally, this temperature will have to be determined for the particular installation.

- (1) Compute passage equivalent length. From the airfoil geometry in Table 3F-2,

$$nb = \frac{4 \times 2.0}{12} = 0.667$$

$$\frac{d}{b} = \frac{0.125}{2.0} = 0.0625$$

From Fig. 3F-17, $Z=1.014$, and hence (from Par. 5.3.3),

$$\frac{L_{eq}}{d} = \frac{(L_x)(Y)(Z)}{d} = \frac{27 \times 1.6 \times 1.014}{0.125} = 350$$

- (2) Compute total water catch. From Fig. 3F-3,

$$\frac{M}{LWC} = 22.0$$

or

$$M = \frac{22.0 \times 0.44}{2} = 4.84 \text{ lb/hr-ft of span per surface}$$

The factor of 2 in the preceding equation accounts for the split of the water catch about the stagnation point; that is, half the water catch is assumed for each top and bottom surface.

- (3) Compute external film conductance. From Fig. 3F-11, at $L_x=2.25$ ft,

$$\frac{h_o S_o}{K_1} = 165 \text{ Btu/hr-°F-ft of span per surface}$$

For 20,000 ft, $K_1=0.5365$,

and therefore $h_o S_o = 165 \times 0.5365 = 88.5 \text{ Btu/hr-°F-ft of span per surface}$

- (4) Compute required skin temperature. Using data obtained in steps 2 and 3,

$$\frac{M}{h_o S_o} = \frac{4.84}{88.5} = 0.055$$

From Fig. 3F-14, $t_{sk} = 59^\circ\text{F}$.

- (5) Compute anti-icing heat load. For 300 knots TAS and +15°F ambient,

$$t_{aw} = 43^\circ\text{F}$$

or

$$(t_{sk} - t_{aw}) = 59 - 43 = 16^\circ\text{F}$$

From Fig. 3F-15,

$$\frac{q}{h_o S_o} = 86$$

Therefore $q = 86 \times 88.5 = 7611$ Btu/hr-ft of span per surface

(6) Compute anti-icing air flow. Using data obtained in steps 1, 4, and 5,

$$\frac{q}{nb(t_{in} - t_{sk})} = \frac{7611}{(0.667)(280 - 59)} = 51.6$$

From Fig. 3F-16, at $L_{eq}/d = 350$,

$$\frac{w_{pa}}{nb} = 270 \text{ lb/hr-ft of span per surface}$$

and hence the required air flow for both top and bottom surfaces is

$$270 \times 0.667 \times 2 = 360 \text{ lb/hr-ft of span}$$

To obtain the total airplane requirements it is necessary merely to repeat this procedure at several stations and integrate the results.

9.2 Engine Inlet Electrothermal Running Wet Anti-Icing

The engine inlet duct of an all-weather supersonic aircraft is to have a 40°F running wet surface temperature at a design icing condition of 0.50 gm/m³ of 20μ volume median drops at 0°F ambient. The annular inlet has a 2.0 ft long central conical spike having a semivertex angle (Φ_o) of 21.8 deg. Because of the annular inlet, the cone anti-icing efficiency may be assumed to be unity. The analysis will be performed at a surface distance of 15.0 in. from the apex of the cone.

Selection of a design point for this system requires a knowledge of the power requirement as a function of flight speed and altitude. However, for the purpose of illustration, this example will be restricted to 250 knots at sea level.

(1) Compute water catch. From Fig. 3F-9, at $L_x = 2$ ft (24.0 in.),

$$E_m = 0.52$$

and

$$\frac{\beta_{max}}{\sin \Phi_o} = 0.77 \text{ or } \beta_{max} = 0.286$$

From Fig. 3F-10, $s_b/\text{slant length} = 0.92$; since slant length = $L_x/\cos \Phi_o$,

$$s_b = \frac{0.92 \times 24.0}{\cos 21.8 \text{ deg}} = 23.7 \text{ in. from apex}$$

Using Eq. 3F-7,

$$S_m = \frac{(23.7/24.0)^2}{\sin 21.8 \text{ deg}} = 2.62$$

and hence (using Eq. 3F-6),

$$\Gamma = \frac{0.52}{(0.286)(2.62) - 0.52} = 2.26$$

For a surface distance s of 15.0 in.,

$$\frac{s}{s_b} = \frac{15.0}{23.7} = 0.623$$

From Fig. 3F-10,

$$\frac{\beta}{\beta_{max}} = 0.87$$

and therefore $\beta = 0.248$.

Using Eq. 3F-3, the local water catch is

$$M_\beta = 0.38 \times 250 \times 0.50 \times 0.248 = 11.8 \text{ lb/hr-ft}^2$$

(2) Compute freestream Reynolds number. Freestream air properties are

$$(\rho g)_o = \frac{2116}{(53.3)(460)} = 0.0865 \text{ lb/ft}^3$$

$$\mu_o = 1.10 \times 10^{-5} \text{ lb/sec-ft}$$

$$k_o = 0.0132 \text{ Btu/hr-ft-}^\circ\text{F}$$

$$\text{Therefore } N_{(Re,o)} = \frac{1.69 \times 0.0865 \times 250 \times 2.0}{1.10 \times (10^{-5})} = 6.65 \times 10^6$$

From Eq. 3F-11, transition occurs at

$$s = \left(\frac{1.5 \times 10^6}{6.65 \times 10^6} \right) \left(\frac{24.0}{\cos 21.8 \text{ deg}} \right) = 5.75 \text{ in.}$$

Therefore $s = 15.0 \text{ in.}$ is in the turbulent region.

(3) Compute local heat transfer coefficient. From Fig. 3F-13,

$$\frac{N_{Nu}}{(N_{(Re,o)})^{0.821}} = 0.0210$$

$$\text{and therefore } h_o = \frac{0.0210 (6.65)^{0.821} \times 10^{4.92} \times 0.0132}{2.0} = 52.1 \text{ Btu/hr-ft}^2$$

(4) Compute power requirements. Using data obtained in steps 1 and 3,

$$\frac{M_{\beta}}{h_o} = \frac{11.8}{52.1} = 0.226$$

From Fig. 3F-18,

$$\text{Local } \frac{q/S}{h_o} = 67 - 11 = 56$$

Since $1 \text{ W/in.}^2 = 492 \text{ Btu/hr-ft}^2$, the required local power intensity is

$$\frac{q}{S} = \frac{56 \times 52.1}{492} = 5.9 \text{ W/in.}^2$$

10. WINDSHIELD ICE PROTECTION

10.1 Introduction

Anti-icing protection is usually provided for the forward-facing windshield panels on both military and commercial aircraft that are required to operate in all-weather conditions. The most widely used system is electrical anti-icing, whereby electric current is passed through a transparent conductive film that is part of the laminated windshield. The heat from the anti-icing film also prevents internal fogging for most configurations. Use of electrical heat also maintains the windshield interlayers (of a glass/vinyl laminated windshield) at near the optimum temperature for resistance to bird strikes (birdproofing).

Where adequate electric power is not available or when the windshield configuration does not allow use of electrical anti-icing at a feasible cost, the most common alternates are use of an external air blast system (that may also be used for rain removal) or use of a fluid anti-icing system using freeze-point depressant solutions (such as glycol or alcohol) to prevent freezing of impinging water. Hot air flowing through a double pane windshield has been used for anti-icing in the past, but is seldom used currently because of problems of installation, noise, collection of dirt between panes, and other undesirable effects.

The following paragraphs describe in detail the various methods of providing windshield ice protection, with typical examples. Methods of analysis, equations, and typical results are also shown.

10.2 Methods of Protection

10.2.1 Electrical Anti-Icing

Heating is accomplished by applying electric power to a conductive transparent film located on the inner surface of the outer ply. This ply is usually limited to 0.18 in. thickness if the surface is glass (or 0.06 in. if plastic), to avoid excessive internal temperatures. Power supply bus bars and the temperature control sensor are usually located as shown in Fig. 3F-25.

Power input must be adequate to maintain a running wet surface (35°F) under the design icing condition. A power input of 3-4.5 W/in.² is normally used, and will give satisfactory protection for most icing conditions. Higher heat inputs may have an adverse effect on windshield service life because of increased thermal stresses resulting when power is applied and removed. Thus the minimum heat input that will give icing protection should be used.

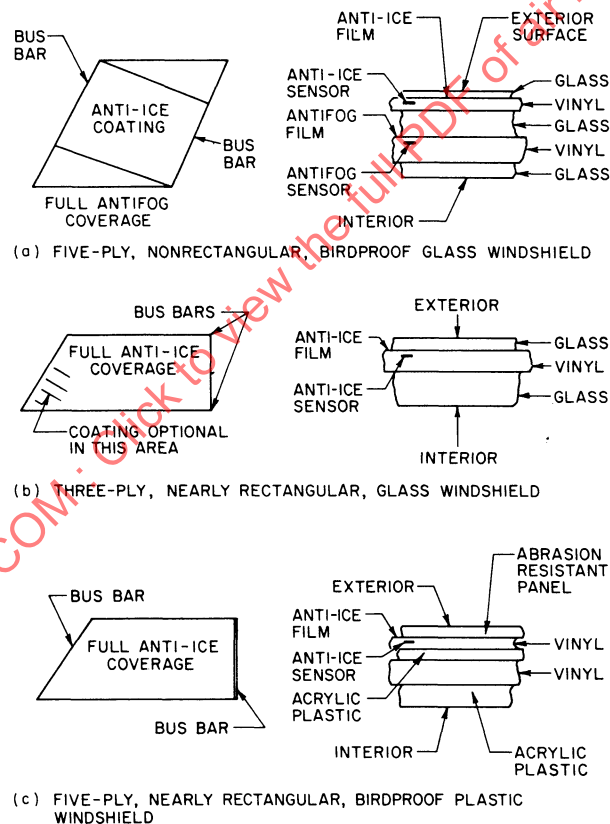


Figure 3F-25 - Typical Windshield Panels Heated Electrically

Power supply is normally from an AC generator; however, if only DC power is available, an inverter can be used to produce the required voltage. The temperature control is set at a value high enough to produce the design heat requirement without overheating the interlayer. Usually a setting of 110 to 120°F will fulfill both the anti-icing and antifog temperature requirements. The most common control turns full power on and off as necessary to maintain the set temperature within a 10°F deadband. Controlling in this manner may result in cyclic thermal stresses that

have adverse effects on windshield service life. Some current aircraft are using modulating controls that vary power as a function of temperature sensor demand, to reduce thermal stresses.

Successful design of a windshield having electrical heating requires careful integration of all factors involved. The most important are: providing good coating uniformity (use of nearly rectangular areas), limiting heat input to the minimum acceptable level, and, if possible, using a modulating control to eliminate cyclic thermal stresses. Methods of calculating the heat required and temperature control setting are shown in Par. 10.3.1 together with a calculation method to determine temperature of the interlayer.

10.2.2 Hot Air Anti-Icing

10.2.2.1 Double Pane Anti-Icing System

Although seldom used, the double pane system (Fig. 3F-26) is a possible alternative to electrical anti-icing. A source of hot air is needed (such as a combustion heater, or compressor bleed diluted or cooled to an acceptable temperature), with a control valve and appropriate ducting. Surface heat requirements are the same as for an electrical system; however, the total heat input will be two or three times as large, depending on air gap width and resulting channel efficiency. Methods of analysis shown in Par. 5.3 for airfoil anti-icing may be used to determine air flow requirements.

Special attention must be given to solution of the problems of noise, duct installation, leakage, accumulation of dirt, dust, and oil, and stress problems resulting from temperature gradients in the windshield panes.

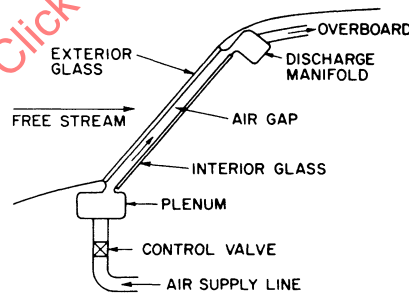


Figure 3F-26 - Double Pane Hot Air Windshield Anti-icing System

10.2.2.2 External Air Blast Anti-Icing

For many high performance aircraft, an external jet blast rain removal system employing compressor bleed air is used in place of windshield wipers. (See Par. 12.) The bleed air is discharged at the base of the windshield by a wide, narrow depth nozzle that directs air parallel to the windshield surface (Fig. 3F-27). Design of such systems is empirical to a large degree; however, general recommendations may be found in SAE AIR 805 (Ref. 19). Air flow rates required are usually between 2 and 7 lb/min-in. (width) of cleared area, with values of 4.5 to 7 lb/min-in. giving the most satisfactory results for rain removal.

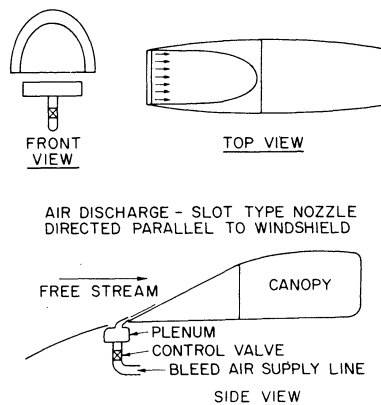


Figure 3F-27 - External Air Blast Windshield Anti-icing and Rain Removal System

In most cases, rain removal air flow requirements will exceed windshield anti-icing requirements. Typical surface temperatures are discussed in Par. 10.3.2.2. Care must be exercised in designing such a system, to avoid blowing excessively hot air across the windshield. This can cause overheating of the interlayer or cracking of the outer glass ply.

10.2.3 Fluid Anti-Icing

For many applications, electric power or hot air may not be available in sufficient amounts for anti-icing, and a fluid anti-icing system may be a suitable alternative. It is a simple system for retrofit applications, and the weight increase for non-icing flight missions is small because the fluid can be drained. The fluid system prevents ice by spreading sufficient fluid over the windshield so that the impinging water plus anti-icing fluid has a freezing point lower than the windshield surface temperature. Typical fluids are ethylene glycol, isopropyl alcohol, ethyl alcohol, and methyl alcohol. Various proprietary fluids are also available.

The fluid is most commonly distributed by a small "piccolo" tube with evenly spaced holes, or by one or more spray nozzles, or by a porous metal strip. Pressure to force the fluid through the distribution system may be supplied by a small pump or bleed air, if available.

Although designed for anti-icing protection (that is, the system is turned on when icing is encountered), the fluid system may also be used for de-icing, to remove ice accumulations. In this case the fluid and ice form a slush that is swept away by aerodynamic forces.

10.3 Analysis of System Requirements

10.3.1 Electrical Anti-Icing

Windshield water catch may be determined by Eq. 3F-4:

$$M_w = 0.38 v A_F (LWC) E_m$$

where M_w = lb/hr-ft² of projected area.

In this case A_F is the windshield projected area (along the line of flight). The impingement efficiency E_m is normally obtained from data for a semi-infinite rectangle. The graphs of Figs. 3F-28 and 3F-29 allow rapid determination of E_m . Because impingement rate is of secondary importance in a running wet anti-icing system, further refinement of water catch is usually unnecessary.

The heat transfer coefficient at the center of the windshield heated area must also be determined. Experience has shown that, for windshields, the turbulent flow equation for a flat plate may be used. Eq. 3F-9 may be used to obtain the heat transfer coefficient at the center of the windshield; or the graph of Fig. 3F-11 may be used if the value for h_o from Eq. 3F-9 is multiplied by 0.8. The distance L_x is the distance from the base of the windshield to the center for nearly vertical windshields; or from the nose of the aircraft for inclined windshields (that is, where the angle between fuselage and windshield is not so severe as to generate a new boundary layer).

The heat required for a 35°F surface temperature may be calculated using Eq. 3F-21. Typical values are shown in Fig. 3F-30. Anti-icing requirements for transparent areas, that is, windshields, are covered in Ref. 16. The requirements are a function of normal cruise speed, as shown in Table 3F-3. (The corresponding watt intensities are included for reference only and do not imply that the system must be electrical. A hot air external jet blast is often used as a combination anti-icing and rain removal system.)

Table 3F-3 - Heat Requirements at Various Cruise Speeds

Normal Cruise Speed, Knots	Heat Requirement	
	Btu/hr-ft ²	W/in. ²
100	1200	2.44
150	1700	3.45
200	1900	3.86
250	2000	4.06
300	2100	4.26
Over 300	2100	4.26

An additional correction is needed for inward heat flow to the cabin. This may be calculated after the anti-icing film temperature has been determined. In most windshields and for normal cabin temperatures, the inward heat loss is about 5% of the outward heat flow.

The characteristics of the anti-icing film are normally arrived at through consideration of practical conductive film manufacturing tolerances, the maximum hot spot temperature that must be set to avoid damage to the vinyl or glass, and the tolerances in control point temperature produced by the windshield temperature controller. These film characteristics are defined as the following power constants:

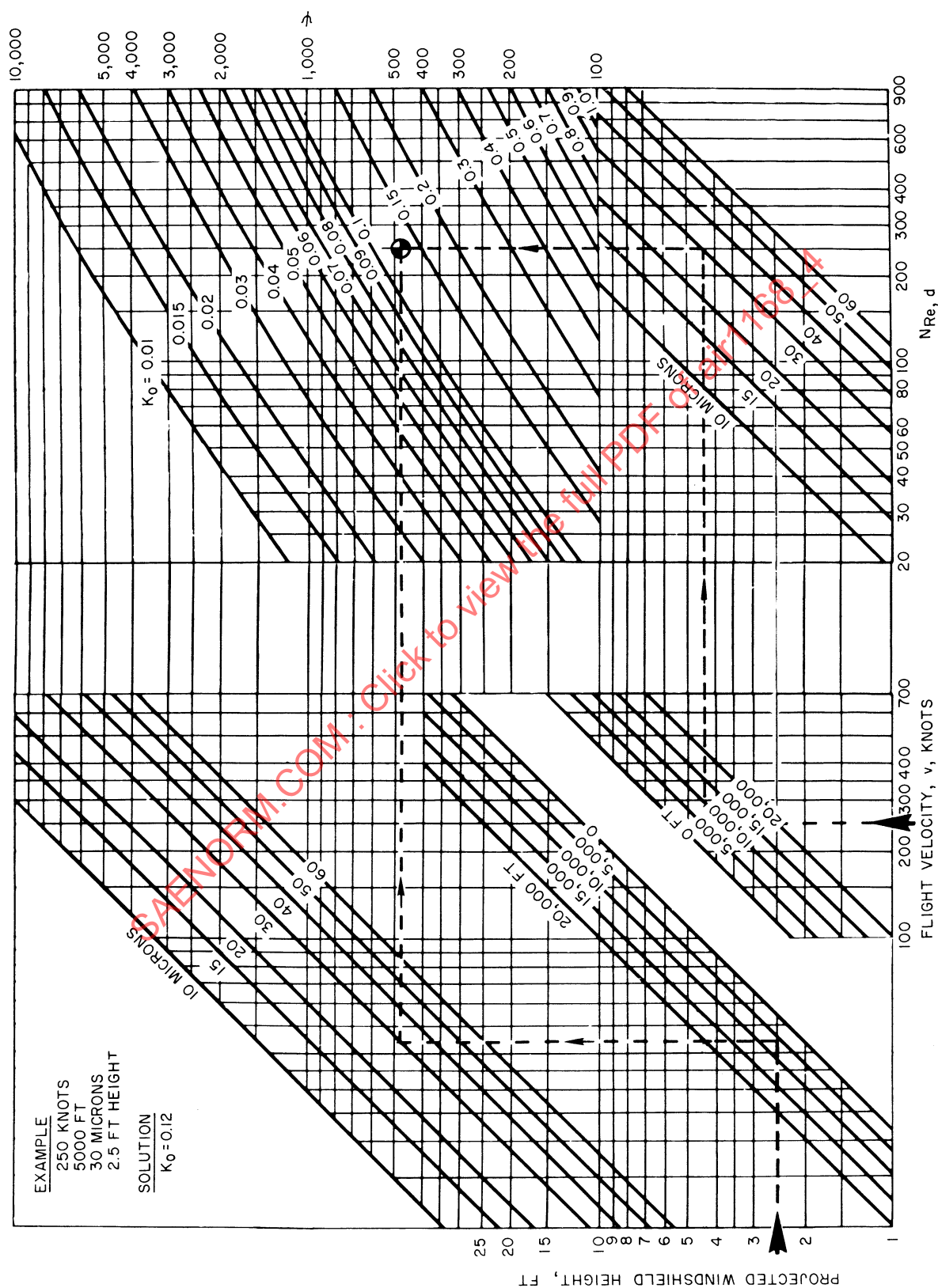


Figure 3F-28 - Graphical Solution of K_0 For 15°F Ambient Air Temperature (Refs. 6 and 7)

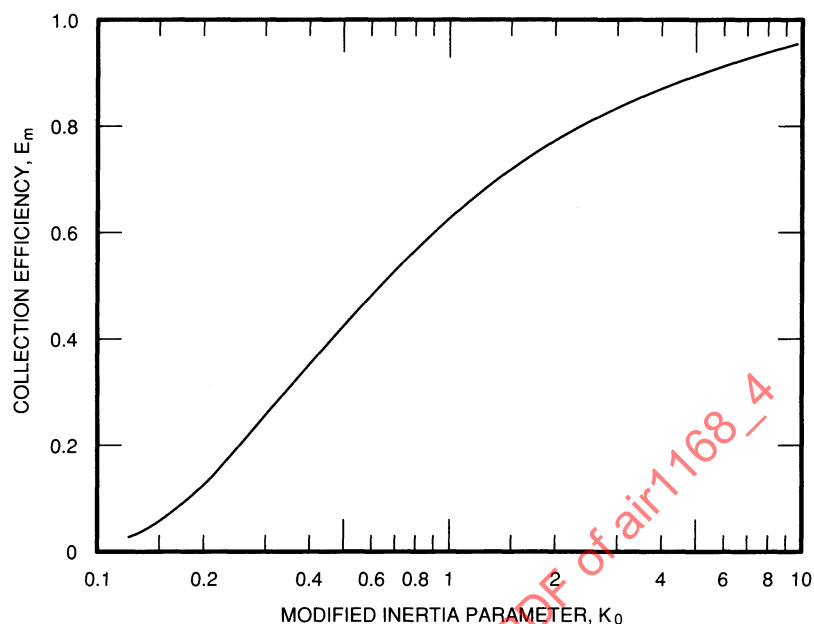


Figure 3F-29 - Collection Efficiency of Windshields (Based on Semi-infinite Rectangle)

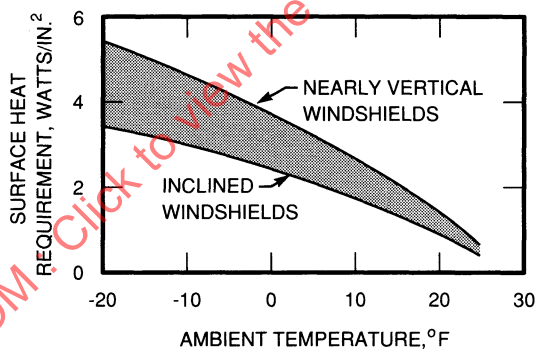


Figure 3F-30 - Variation of Windshield Surface Heat Requirement With Ambient Temperature (calculated for 7000 ft cruise at 205 mph true air speed)

$$K_a = \frac{\text{Average power}}{\text{Power at control point}} = \frac{t_{fa} - t_s}{t_c - t_s} \quad (3F-22)$$

(Recommended $K_a = 0.80$ or greater.)

$$K_h = \frac{\text{Power at hot spot}}{\text{Power at control point}} = \frac{t_h - t_s}{t_c - t_s} \quad (3F-23)$$

(Recommended $K_h = 1.3$ or less.)

$$K_m = \frac{\text{Average power}}{\text{Power at hot spot}} = \frac{K_a}{K_h} \quad (3F-24)$$

(Recommended $K_m = 0.7$ or greater.)

For ideal (uniform) heating, the constants would be unity.

With known power (average) requirement and power constants, the film temperature at the control point and at the hot spot may be calculated. The average film temperature is

$$t_{fa} = t_s + \frac{q_a \Delta x_o}{k_g} \quad (3F-25)$$

for glass, where k_g is replaced by k_p if plastic is considered.

Similarly, the temperature of the film at the control point and hot spot may be found if K_a and K_h are known. Temperature at the hot spot is usually limited to 160°F, to avoid damage to the vinyl.

For a windshield on a subsonic jet transport the recommended power constants will provide average outside windshield surface temperatures above 35°F in the most probable icing conditions up to an altitude of 22,000 ft with a control point setting of 105-110°F and a conductive coating of 2100 Btu/hr-ft².

The control sensor is usually mounted in the adjacent interlayer, 0.04 in. or less from the film. Sensor temperature will be within 2°F of the film temperature at this point.

Interlayer temperatures may be calculated, if needed for windshield bird-impact considerations, from the film temperature, average total heat flow, and conventional two-dimensional heat transfer equations. A heat transfer coefficient of $h = 2$ is usually appropriate for the inside face of the windshield.

Windshield power control may use either of two principles. Most common is the "on-off" cycling control, which turns full power on and off as needed to maintain a desired control temperature (typically $\pm 5^\circ\text{F}$ around the control point). A more complex control may be used to modulate power according to sensor demand, and may include a "warmup" control to apply power gradually to a cold windshield. This control minimizes the cyclic thermal stresses that cause glass breakage.

10.3.2 Hot Air Anti-Icing

10.3.2.1 Double Pane Hot Air Anti-Icing

Heat requirements for a double pane hot air anti-icing system are obtained by the method described for electrical anti-icing. With a selected source of hot air, the problem is simply that of varying the air flow rate and air gap until a satisfactory compromise is made between heat release and pressure drop. A heat exchanger efficiency of 50% is a realistic goal. Internal heat transfer coefficients may be calculated from equations presented in Par. 5.3.

Air flow should be from the base of the windshield upward, so that maximum heat release is achieved at this point. Assuming that the gap must be of uniform thickness for optical reasons, the heat release rate will decrease with distance along the windshield.

10.3.2.2 External Air Blast Method

The external air blast system will normally be designed for rain removal by either laboratory development or use of empirical design data such as Refs. 19 and 20. The problem remaining usually is the analytical evaluation of the rain clearing system under icing conditions. As a first approximation, the data of Fig. 3F-31 may be used to estimate surface temperatures. For other configurations, consult Ref. 20. In most cases, air flow and temperature requirements for anti-icing are less severe than for rain clearing.

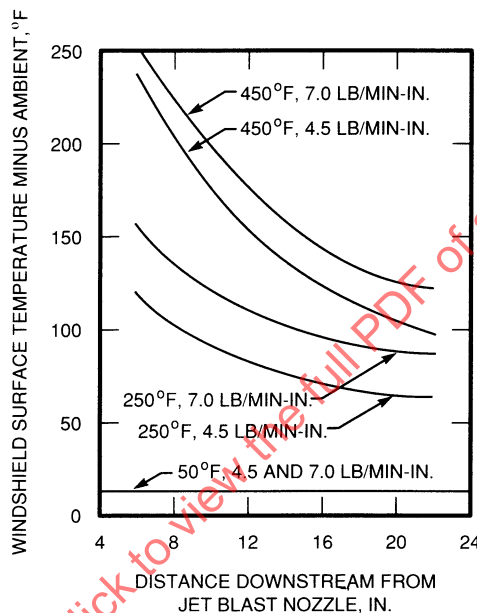


Figure 3F-31 - Windshield Surface Temperature In Icing For External Air Blast Anti-icing System. Flight velocity, 225 knots; liquid content, 1.0 gm/m³; nozzle velocity, Mach 1; drop size 20μ, continuous slot nozzle

10.3.3 Fluid Anti-Icing

The water catch on the windshield per unit area of windshield surface must be determined, as discussed in Par. 10.3.1. The reference (datum) temperature may be determined from the approximate graph of Fig. 3F-32. From Fig. 3F-33 (obtained from Ref. 8), the percent of freezing point depressant by weight (G_f) may be found. This is the amount of fluid required to mix with impinging water to result in the selected freezing temperature. The flow rate required is

$$W_f = \frac{G_f M_w}{G_i - G_f} \quad (3F-26)$$

Thus, for a datum temperature of 0°F and 0.57 lb/hr-ft² impingement (for 50/50 ethylene glycol/water, $G_i = 50\%$), and from Fig. 3F-33, at 0°F, ethylene glycol, $G_f = 35\%$. Then

$$W_f = \frac{(35)(0.57)}{50 - 35} = 1.33 \text{ lb/hr-ft}^2$$

For two 18 in. square windshield sections, the flow for 4.5 ft² is 6.0 lb/hr. Actual flow may have to be 1.2 to 1.5 times greater, depending on distribution efficiency.

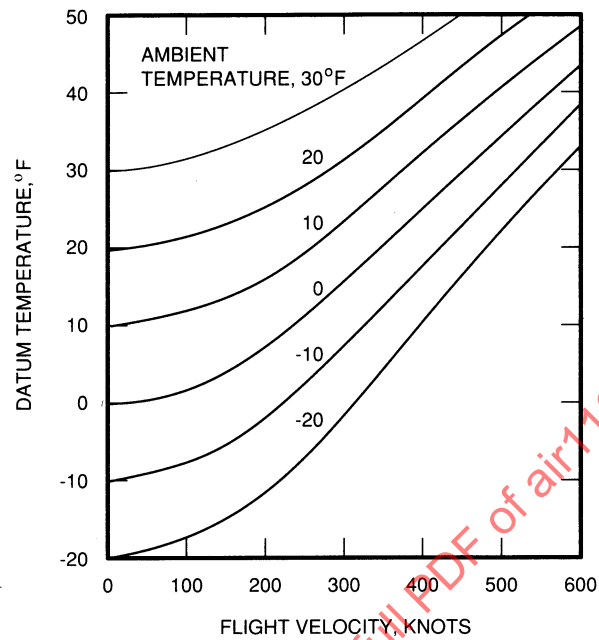


Figure 3F-32 - Datum Temperature Versus Flight Velocity (values shown at 10,000 ft and are approximately correct for 0 to 20,000 ft; see Ref. 8)

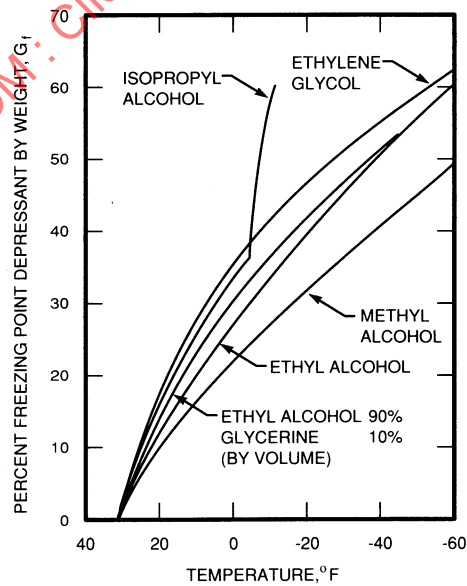


Figure 3F-33 - Freezing Points For Aqueous Solutions of Several Fluids

Tank capacity must be adequate for expected duration in icing plus a reserve. Continuous icing conditions seldom exist for a distance exceeding 200 miles. Hold in icing must also be considered; 15 min departure and 30 min destination holds are currently considered maximum.

11. WINDSHIELD AND CANOPY FOG AND FROST PROTECTION

11.1 Introduction

The inner surfaces of most cockpit transparencies are susceptible to condensation in the form of fog or frost during normal aircraft operation, particularly when descending from a high altitude flight, unless fog and frost protection systems are provided.

Two distinct approaches can be taken to provide the flight crew with clear vision areas. One is to keep the inner surface of the transparency continuously above the maximum anticipated cabin dew point; this is the "antifog" system. The other approach is to energize the system only after fog or frost has formed; this is the "defog" system. As a general rule, antifog systems are preferred because they keep windows clear at all times.

The two most common and practical methods are the use of electrical heating and the "free jet" hot air blast system. In many cases use of the electrical anti-icing system for a windshield will keep the inner surface warm enough to provide fog and frost protection. Electrically heated panels offer the best protection with the least effect on cabin temperature, and generally provide quite uniform temperatures. Cost of installation and in-service replacement of the heated panels and controls are the major objections to use of electrical heating.

The "free jet" system is commonly used where a source of compressor bleed air is available. Bleed air is mixed with cabin air by an ejector to yield a safe air temperature (usually below 200°F). The mixed air is discharged through a slot type of nozzle over the inner surface of the windshield, and will maintain an area clear for about 1-3 ft (depending on flow rate and design conditions). Although simple to install, the free jet hot air system has the disadvantage of noise, increased cabin temperature, and increased cabin free air velocity.

Other possibilities, depending on the specific application, are double pane hot air heating, use of dehydrated air, infrared heating, and "antifog" chemical coatings.

The following paragraphs describe the two main methods of fog protection (electrical and free jet hot air), methods of analysis, and typical electric power and air flow requirements. A discussion of the other methods is also included, with comments on specific applications.

11.2 Methods of Fog Protection

11.2.1 Electrical Heating

If electrical heating has been selected for windshield birdproofing or ice protection, the antifog problem is reduced to that of an analysis of inside surface temperature and cabin dew point for low ambient temperature conditions. The object is to determine whether the control temperature setting for anti-icing will maintain the inside surface temperature above the cabin dew point. Data on electrical anti-icing has been presented previously in Pars. 10.2.1 and 10.3.1.

Even though a steady-state analysis will often show that the anti-ice coating will provide inside surface temperatures above the cabin dew point, the addition of an antifog coating may be desirable to reduce the time needed to reach birdproofing temperatures prior to take-off.

For a canopy, windshield, or camera window that is not already electrically heated for anti-icing or birdproofing, electrical antifog protection may be used. A typical laminated plastic panel with antifog electrical coating is shown in Fig. 3F-34. Bus bars are located in noncritical vision areas. Because the power input is low ($1/2$ to 1 W/in.^2), nonrectangular areas may be protected with little danger of overheat. Temperature uniformity is always best for rectangular areas, however.

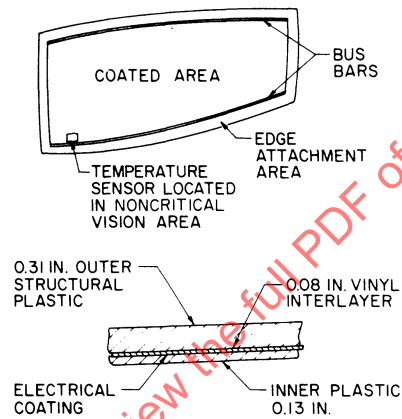


Figure 3F-34 - Antifog Coating and Bus Bar Arrangement For Electrical Antifog On Plastic Canopy (or Windshield) Panel

Power input and sensor temperature setting must be greater than that required for the most severe combination of ambient temperature, humidity, flight speed, and cabin temperature. For high performance aircraft, 1 W/in.^2 and 90°F , respectively, are typical values, with lesser requirements for less severe flight profiles, or with thicker structural plies outboard of the conductive coating (which reduce the external heat losses). Methods of calculating requirements are given in Pars. 11.3.2 and 11.3.3.

For windshields or canopies having the conductive coating located near the inner surface, a simple temperature control system can be used, consisting of a bimetallic surface-mounted snap switch wired in series with the conductive coating. This eliminates the need for more costly and heavy relays and controllers. Where the plastic coating is located more than about 0.15 in. from the inner surface, or about 0.4 in. for glass, or where more accurate temperature regulation is desired, internal sensing elements connected to appropriate controllers and relays are needed.

11.2.2 Free Jet Air Blast

The free jet air blast system is commonly used in jet aircraft because of the ease of installation, lower cost of the non-electrical windshield and canopy panels, and availability of engine compressor bleed air. The normal installation uses bleed air, reduced to about 8-10 psi above cabin pressure and driving an ejector that draws in sufficient cabin air to produce a mixed temperature (200°F), below the softening point of plastic.