WADC TECHNICAL REPORT 55-262

STUDY OF LIMITED-TYPE ICE REMOVAL AND PREVENTION SYSTEMS

(MECHANICAL PHASE)

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FOREWORD

This report was prepared by Research, Incorporated, and was written by Messrs. H.C. Johnson and E.G. Johnson. The program was conducted under USAF contract No. AF 33(616)-2548 and administered under the direction of the Equipment Laboratory, Wright Air Development Center with Mr. L.S. Lomas acting as project engineer.

In addition to the authors as noted above, Messrs. A.E. Abramson, W.L. Torgeson, J.E. O'Neil, and J.R. Anderson also participated in the program.

The guidance and helpful suggestions of Messrs. L.V. Larson and L.S. Lomas of WADC are gratefully acknowledged.

ABSTRACT

The requirements of aircraft icing protective systems have been gradually modified with the advent of the supersonic aircraft. A preliminary study is conducted herein of various methods of insuring that such an aircraft can be maintained sufficiently free of ice accretions to enable it to complete its basic mission. The study is limited to exclude thermochemical devices since these are being investigated by another agency.

Charts and graphs are presented describing impingement characteristics, heat requirements, etc., to aid in system development. In addition, a section is included describing various components which comprise an icing system.

The systems are analyzed from three viewpoints: the type of ice removal or preventive action at the icing surface, the duration of the period over which the system functions, and the degree of surface protection afforded. Conclusions are drawn wherever possible as to the feasibility of the various systems presented. However, a large percentage require experimental evaluation because of their simplified nature.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Scott

for ROBERT A. BARRERE
COLONEL, USAF
CHIEF, EQUIPMENT LABORATORY

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INTRODUCTION

The requirements of aircraft icing protective systems for fixed aerodynamic surfaces have been gradually modified with the development of the supersonic aircraft. While it has been the practice to date to equip aircraft with systems capable of operation continuously throughout an entire mission, present and projected aircraft performance allows the use of protective systems which need function only once or twice or for a small portion of the total flight time, providing that the mission allows a normal climb and letdown through an icing atmosphere.

It may also be noted that it is becoming increasingly difficult to fit conventional systems to modern aircraft. Limitations of space within the aerodynamic surfaces, maximum performance requirements, and the advent of thick-skinned airfoils all tend to complicate the design and installation of such systems. The above is particularly true of non-piloted aircraft where remotely controlled or automatic systems of a greatly simplified nature are required.

The following study was instituted for the purpose of conducting a preliminary investigation of the various methods of insuring that an aircraft be maintained sufficiently free of ice accretions to enable it to complete its basic mission. Special emphasis is given to systems and methods of minimum fixed weight, which can be easily installed in areas where space is a critical factor, and to systems which can be attached to previously fabricated surfaces. The use of chemical heat release devices is considered outside the scope of the program since this is being investigated by another agency.

Although the problems associated with providing icing protection are well known, effort in the past has been concentrated primarily toward development of continuous-type protective systems. Although some of the historical approaches may be adapted to meet present needs, the newness of the noncontinuous concept is such that little can be found in the literature regarding it. Because of this, most of the systems contained herein must be considered to be of a preliminary nature requiring further development before their full advantage can be utilized.

SECTION I

DESIGN CRITERIA

A. System Definitions

There are several different fundamental actions by which ice may be prevented from forming on the fixed surfaces of a moving aircraft or by which ice may be removed once it has formed. An ice removal or prevention system is defined herein by the time at which it is activated and the duration of its operation. It is further defined by the type of action at the icing surface and the extent of surface protection afforded.

Systems defined on a time basis may be designated as initial prevention, one-shot, limited duration, and continuous sytems. Thus initial prevention systems provide icing protection during pre-launch, take-off, and climb of an aircraft. As such, they are pre-programmed and should be capable of providing protection for at least five minutes. One-shot protective systems remove ice only once at any specified time during a particular mission. Limited duration systems provide protection for a specified period of time during a mission. They should be capable of being activated at any time and of removing ice at least twice or of providing anti-icing protection for an accumulated period of 20 to 30 minutes. Continuous systems provide protection throughout an entire mission, being limited only by the severity of the icing encounter.

Systems defined by their action are generally designated as thermal dry anti-icing, thermal wet anti-icing, freeze-point depressant anti-icing, thermal de-icing, and mechanical de-icing.

In a thermal dry anti-icing action, all the impinging droplets are evaporated by a high heat input to the impingement zone of the icing surface. Thus, when the direct impingement water is evaporated, the entire surface remains dry and ice-free. Where the heated area is small, the energy requirements are most directly sensitive to the rate of water catch (a function of liquid water content, airspeed, and catch efficiency) as given in reference 1.

A thermal wet anti-icing action requires only that enough heat be supplied to prevent impinging droplets from freezing on the icing surface. The entire surface must be kept about 32 °F for complete protection. Running wet energy requirements are about equally sensitive to ambient air temperature and rate of water catch.

Freeze-point depressant anti-icing is essentially a running wet action in which the impinging droplets are prevented from freezing by lowering their freezing point below the local surface temperature. This is usually achieved by exuding a chemical through the icing surface which mixes with the surface water to depress its freezing point. Since a nonfreezing mixture is formed in the impingement zone, the after surfaces are not subject to runback freezing.

Thermal de-icing action consists of periodically allowing ice to accumulate to a tangible thickness on a surface and then shedding it by heating the exterior wing surface above freezing. Reductions in energy requirements are possible with such a system because only a small fraction of the impinging water is melted and it is rarely necessary to protect more than the direct impingement portion of the icing surface. Some drag penalty is inherent in the de-icing action because of the ice build-up and thus a double load is imposed on the aircraft. Most thermal de-icing systems heat only a small portion of the icing surface at one time to conserve energy. The boundaries between the upper and lower surface are usually maintained ice-free through the use of continuously heated parting strips. It should be pointed out that for an efficient de-icing action the time rate of cycling must be controlled according to the total temperature. This requires that some complexity be introduced into the overall system.

Mechanical de-icing also involves a cyclic action where the ice interface is broken periodically by mechanical force. The inflatable boot system falls into this category and involves a minimum of energy for its operation. Some drag penalty is inherent as with any de-icing action.

Systems defined on the basis of extent of surface protection are designated as partial systems. Generally, in this case, protection is given only to the areas considered to be critical in flight. Any of the systems or actions defined in the preceding paragraphs may be applied on a partial basis.

B. Meteorological and Other Standards

Criteria were established early in the program from which the energy and extent requirements could be determined for any particular system. Three parameters are used: typical flight paths (to establish time in icing), meteorological conditions (to establish severity), and hypothetical aircraft layouts (to provide a basis for calculations).

Typical flight paths are shown in figure 1. The dashed paths (1, 2, and 3) are given for use in evaluating initial and one-shot systems. These are normally considered applicable to missiles and interceptor type aircraft. The solid paths (4, 5, 6, 7, and 8) are used in evaluating limited duration systems and are used in conjunction with bomber type aircraft. The paths are selected to serve as conservative examples of performance for the three types of aircraft.

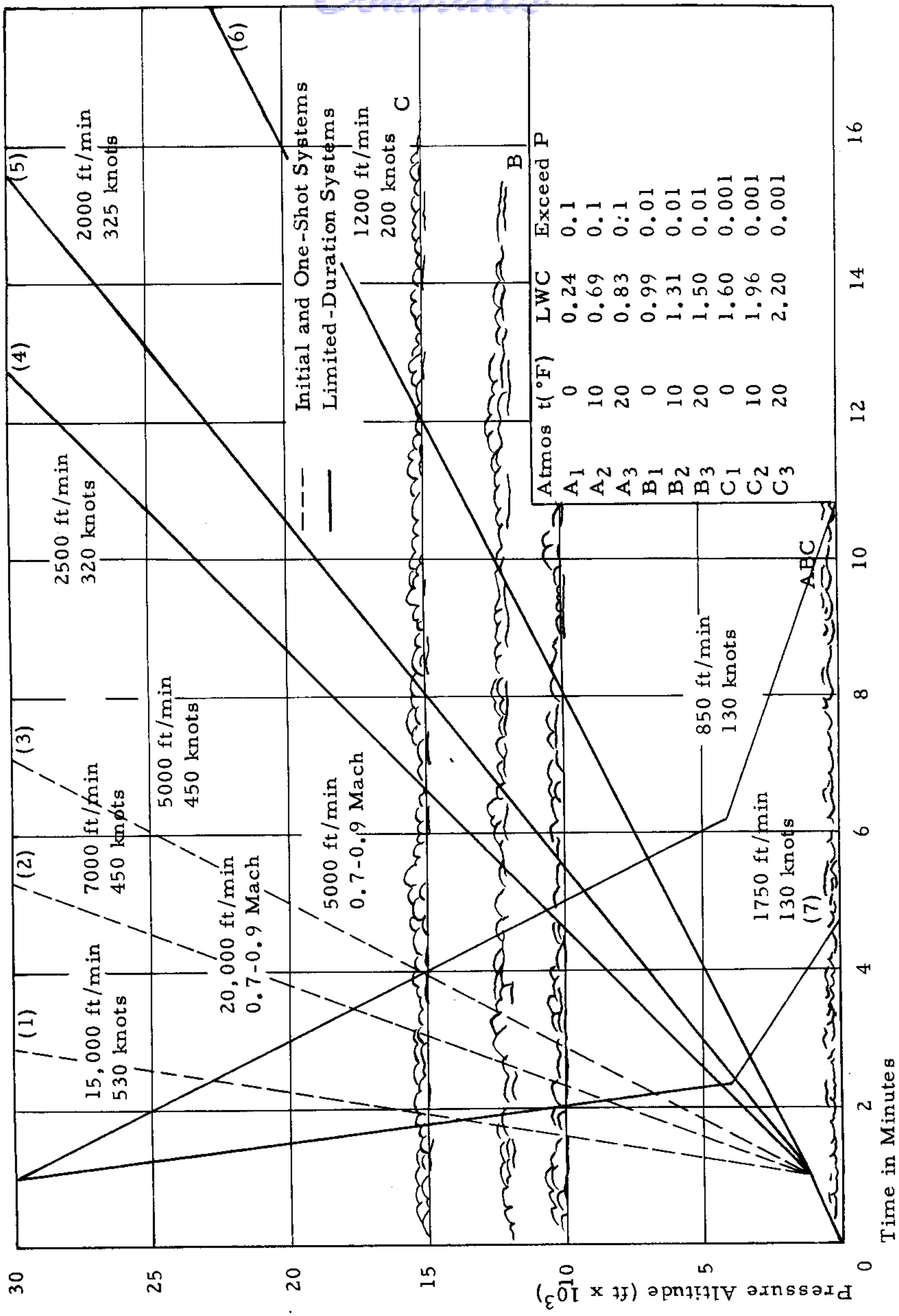
The meteorological conditions are also shown in figure 1. Three basic temperatures are used and three cloud density factors (liquid water contents) of different severities are used in conjunction with each temperature. The liquid water contents are established according to statistical probability. That is, if a specified value is expected to be exceeded only once in ten encounters, it may be said that it has an exceedance probability of 0.1. Similarly, if a specified value is exceeded only once in 100 encounters, it has an exceedance probability of 0.01, and so on. Three series are used herein. The A series has an exceedance probability of 0.1. The B series has an exceedance probability of 0.01; and the C series, 0.001. These choices are based upon the data of reference 2.

It will be noted that the liquid water contents shown are quite high compared with what is normally expected and most, in fact, exceed the Air Force specification for anti-icing systems. This specification calls for a design point of 0.5 grams per cubic meter at 20°F as given in reference 3.

The cloud depth associated with each of the basic atmospheres is also specified and shown in figure 1. The cloud is assumed to extend from the ground up to 10,000 feet for the A series, from the ground to 12,000 feet for the B series, and from the ground to 15,000 feet for the C series.

Reference to figure 1 will illustrate that even for the conservative performances indicated the longest period of exposure to icing is only 12 minutes with the great majority of the cases being only about half that amount.

A hypothetical bomber and interceptor were developed to serve as standards for the determination of requirements and evaluation of systems. Descriptions of these aircraft are given in figures 2 and 3. In order to properly evaluate the space requirements of any system installation, some concept of the full-scale airfoil dimensions is necessary. Figures 4 and 5 illustrate full-size wing leading edge regions for the interceptor and bombers as plotted for various points along the spans.



Atmos	t(°F)	LWC	Exceed P
A_1	0	0.24	0.1
A_2	10	0.69	0.1
A_3	20	0.83	0.1
B_1	0	0.99	0.01
B_2	10	1.31	0.01
B_3	20	1.50	0.01
C_1	0	1.60	0.001
C_2	10	1.96	0.001
C_3	20	2.20	0.001

FIGURE 1: SPECIFIED FLIGHT PATHS AND METEOROLOGICAL DATA

Hypothetical Fighter Specifications

Power plant:	Two 6000 pound thrust jet engines
Wing span:	30 feet
Sweepback:	50°
Airfoil:	NACA 65_1-208
Wing root chord:	9.4 feet
Wing tip chord:	2.76 feet
Leading edge radius:	0.004 percent of chord
Total ice-protected area:	72 square feet (including wing and tail surfaces)
Gross weight:	30,000 pounds

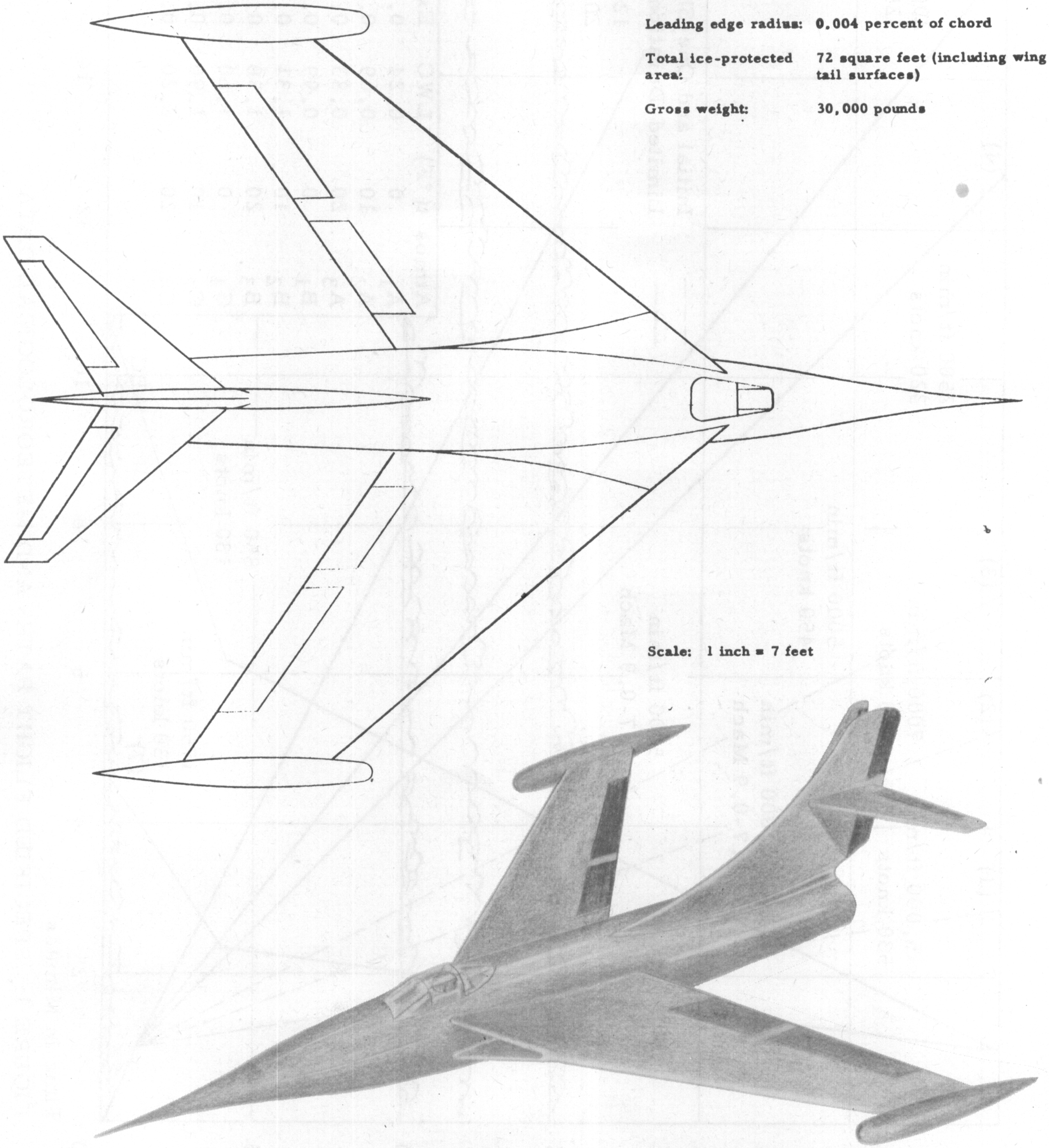


FIGURE 2 HYPOTHETICAL FIGHTER

Hypothetical Bomber Specifications

Power plant:	Eight 6000 pound thrust jet engines
Wing span:	100 feet
Sweepback:	50° (delta)
Airfoil:	NACA 65A-004
Wing root chord:	50 feet
Wing tip chord:	5.9 feet
Leading edge radius:	0.001 percent of chord
Total ice-protected area:	700 square feet (including wing and tail surfaces)
Gross weight:	150,000 pounds

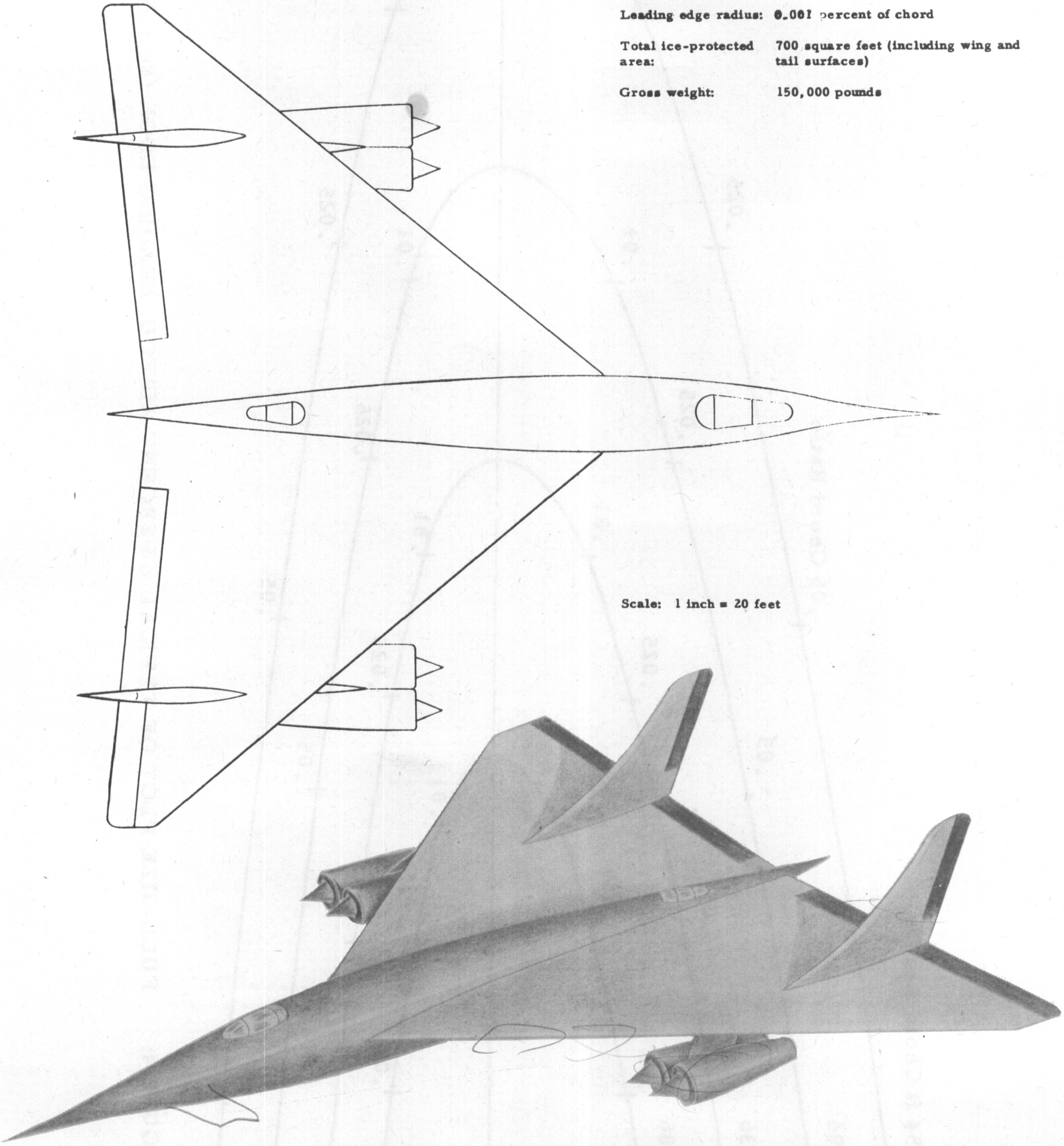

Scale: 1 inch = 20 feet

FIGURE 3 HYPOTHETICAL BOMBER

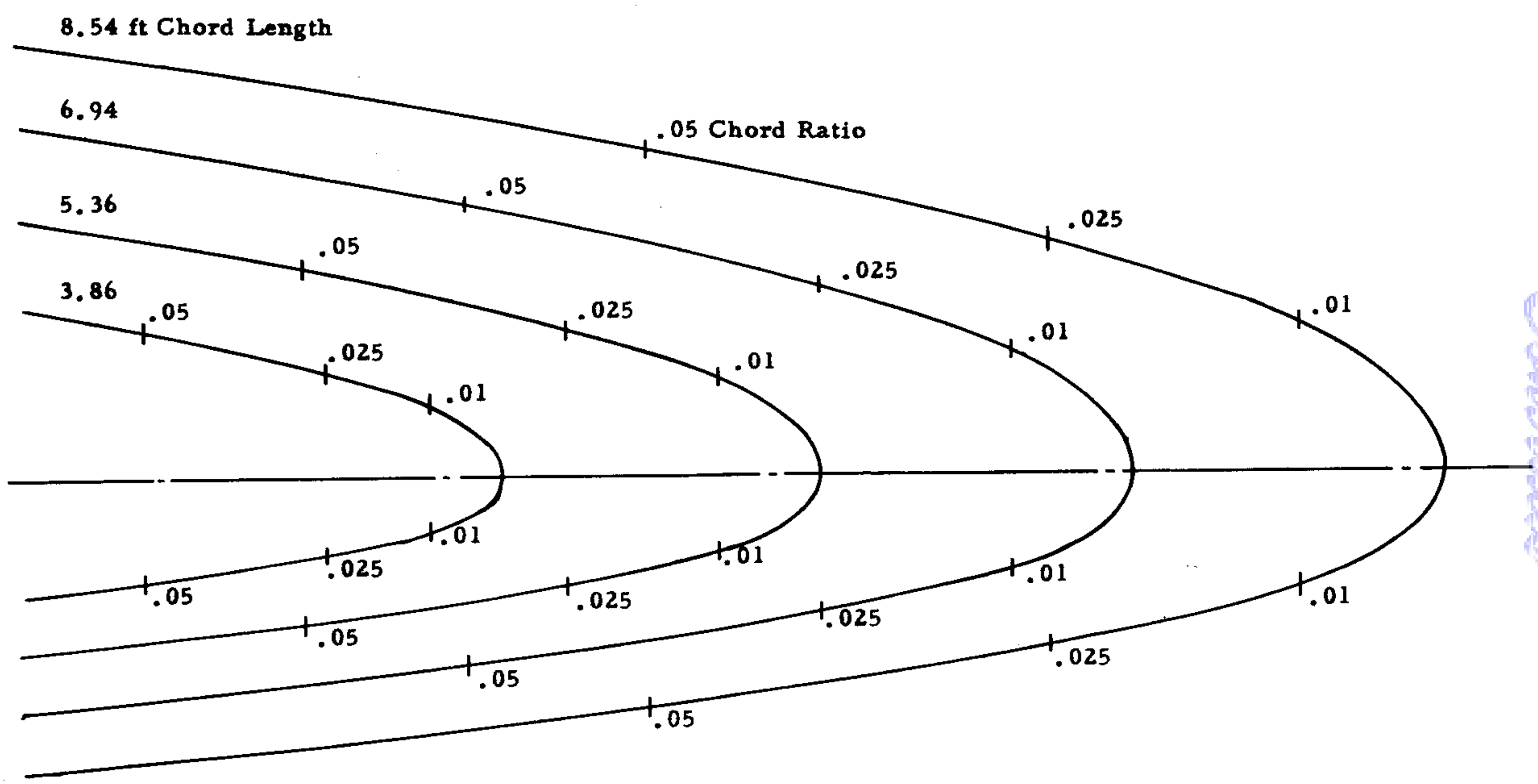


FIGURE 4: FULL-SIZE PLOT OF TYPICAL 8 PERCENT AIRFOIL LEADING EDGE (NACA 65_1-208)

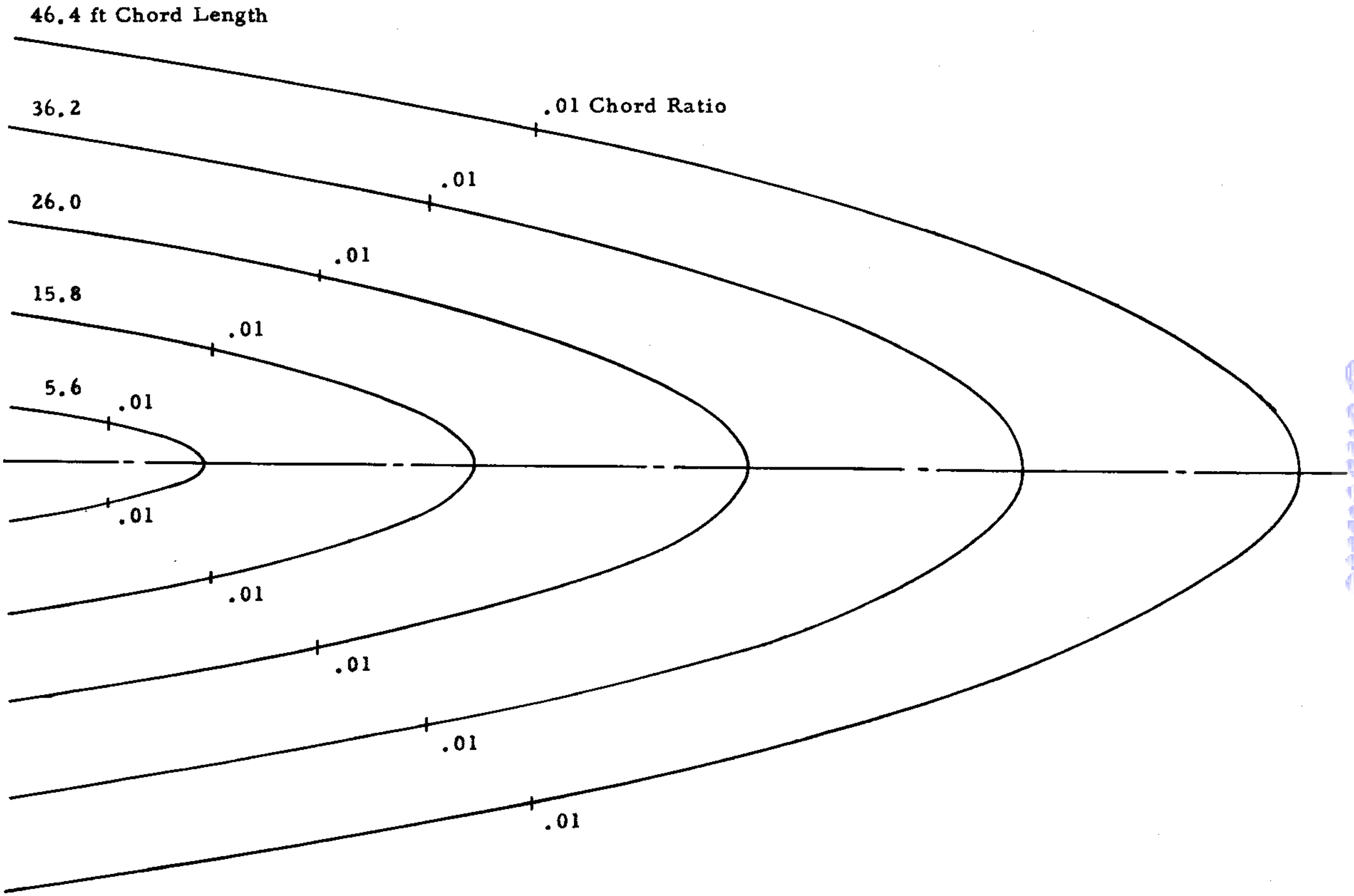


FIGURE 5: FULL-SIZE PLOT OF TYPICAL 4 PERCENT AIRFOIL LEADING EDGE (NACA 65_A-004)

C. System Requirements

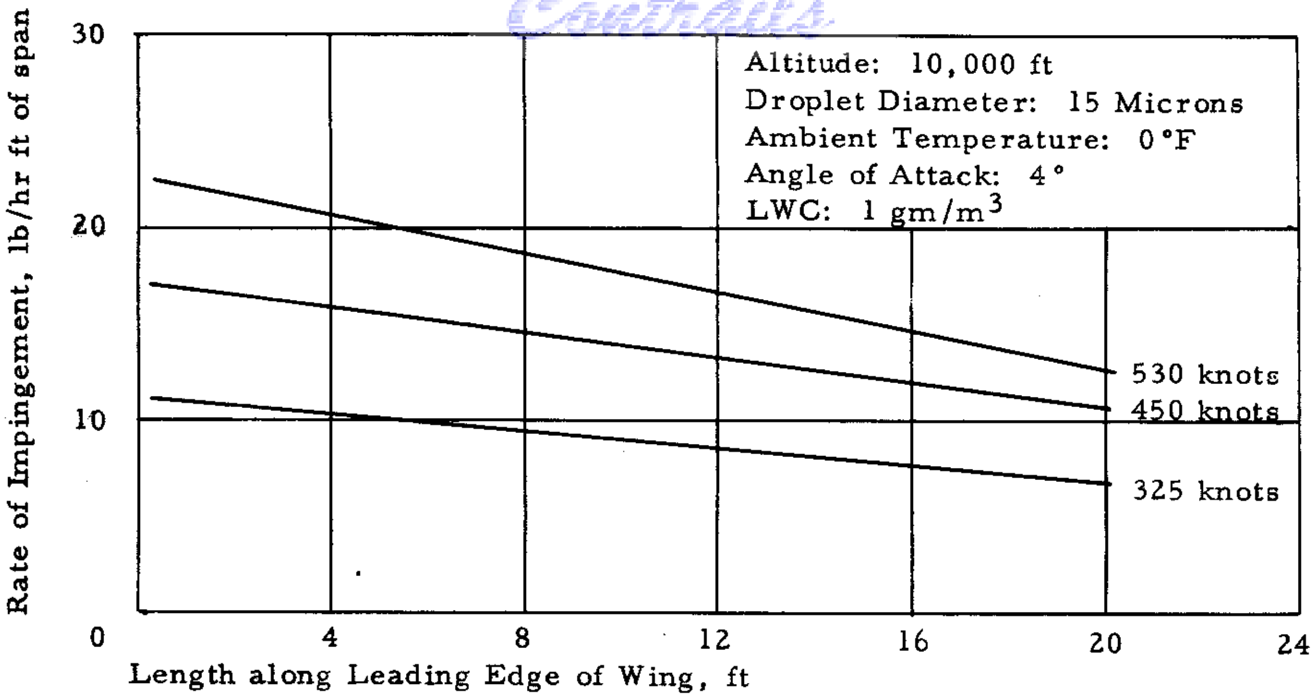
The performance of any ice removal or prevention system is partially determined by its ability to couple energy to the icing surface. Accordingly, the energy required to provide protection by the various actions previously listed is given below for the design meteorological conditions. Discussions are also presented on drag effects of ice accretion and aerodynamic heating since these significantly affect the overall energy requirements. In order to make the use of this section less cumbersome, the methods of calculation are presented in a series of appendices.

The rates and total amounts of water droplet impingement are calculated for both hypothetical aircraft at several meteorological conditions by the methods outlined in appendix I. Since the wings are swept, the actual impingement per unit span is less than for straight wings by the cosine of the angle of sweep (reference 4). The wings being tapered causes the impingement to vary along the span. Figure 6 illustrates this distribution along with the chordwise variation in local impingement rate at the midspan position with a 4° angle of attack. Total midspan accretion rates per foot of span for both aircraft are given in figure 7 as a function of velocity.

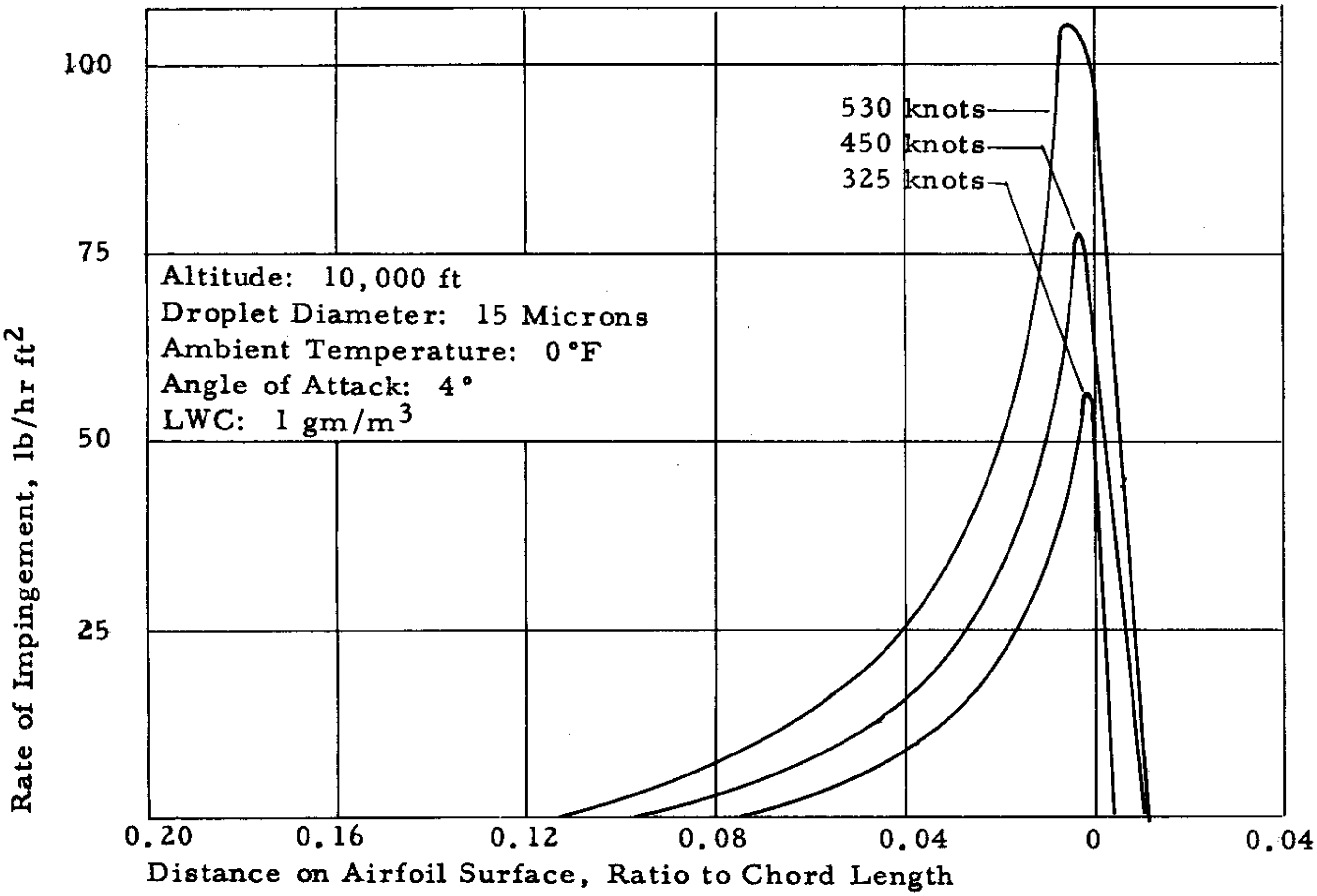
The heat required to maintain a dry evaporative impingement zone is calculated as described in appendix II for several meteorological conditions and airspeeds. In figures 8 and 9 it may be seen that the requirements rise rapidly with liquid water content and the rate of interception (airspeed). This is due primarily to the high heat absorption of the evaporative process. In the event that the icing cloud contains frozen particles, the heat requirements are much more severe since latent heat is used in melting the particles. No attempt is made to examine this subject here since it is a special case occurring infrequently. It is, however, treated in some detail in reference 5.

The heat required to maintain a running wet impingement zone is calculated by the same method for several conditions. It will be noted in figures 10 and 11 that these requirements tend to peak around 300 knots. Since much less total energy is required for this case, aerodynamic heating has a pronounced effect and tends to reduce the heat requirement above 300 knots even though more water is intercepted.

Fluid freeze-point depressant requirements are calculated by the method described in appendix III. Figures 12 and 13 show the amounts of ethylene glycol required to provide protection against formation of ice for a range of conditions. Glycol was chosen primarily because of its low vapor pressure and relatively high viscosity. The alcohols are generally more efficient depressants but their high evaporative characteristics tend to offset this advantage for most fixed-surface applications.



RATE OF WATER INTERCEPTION VERSUS SPAN



LOCAL RATE OF IMPINGEMENT AT MIDSPAN

FIGURE 6: IMPINGEMENT CHARACTERISTICS, SWEPT WING FIGHTER, NACA 65_1-208 AIRFOIL

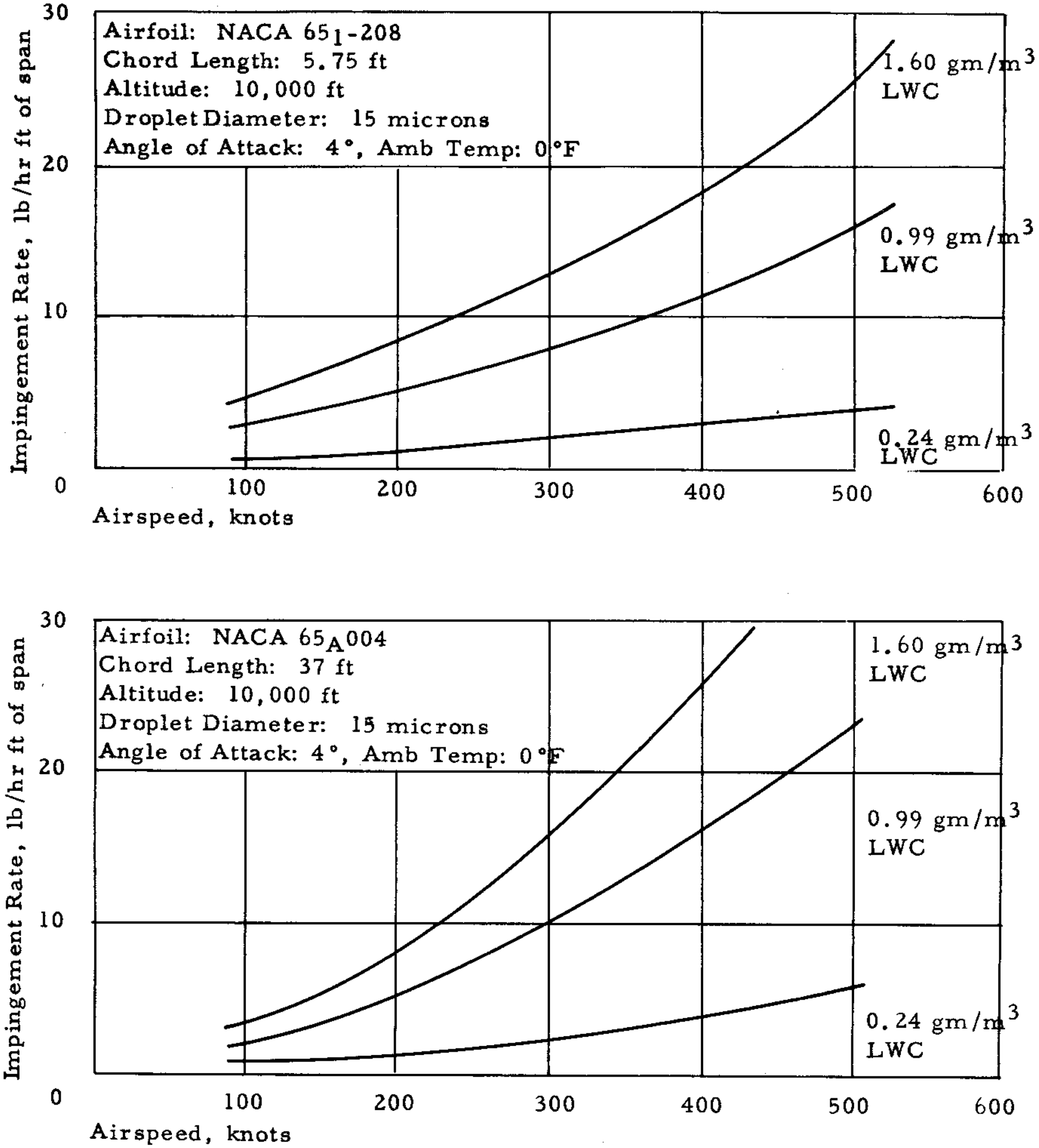


FIGURE 7: AIRFOIL IMPINGEMENT RATES AT MIDSPAN

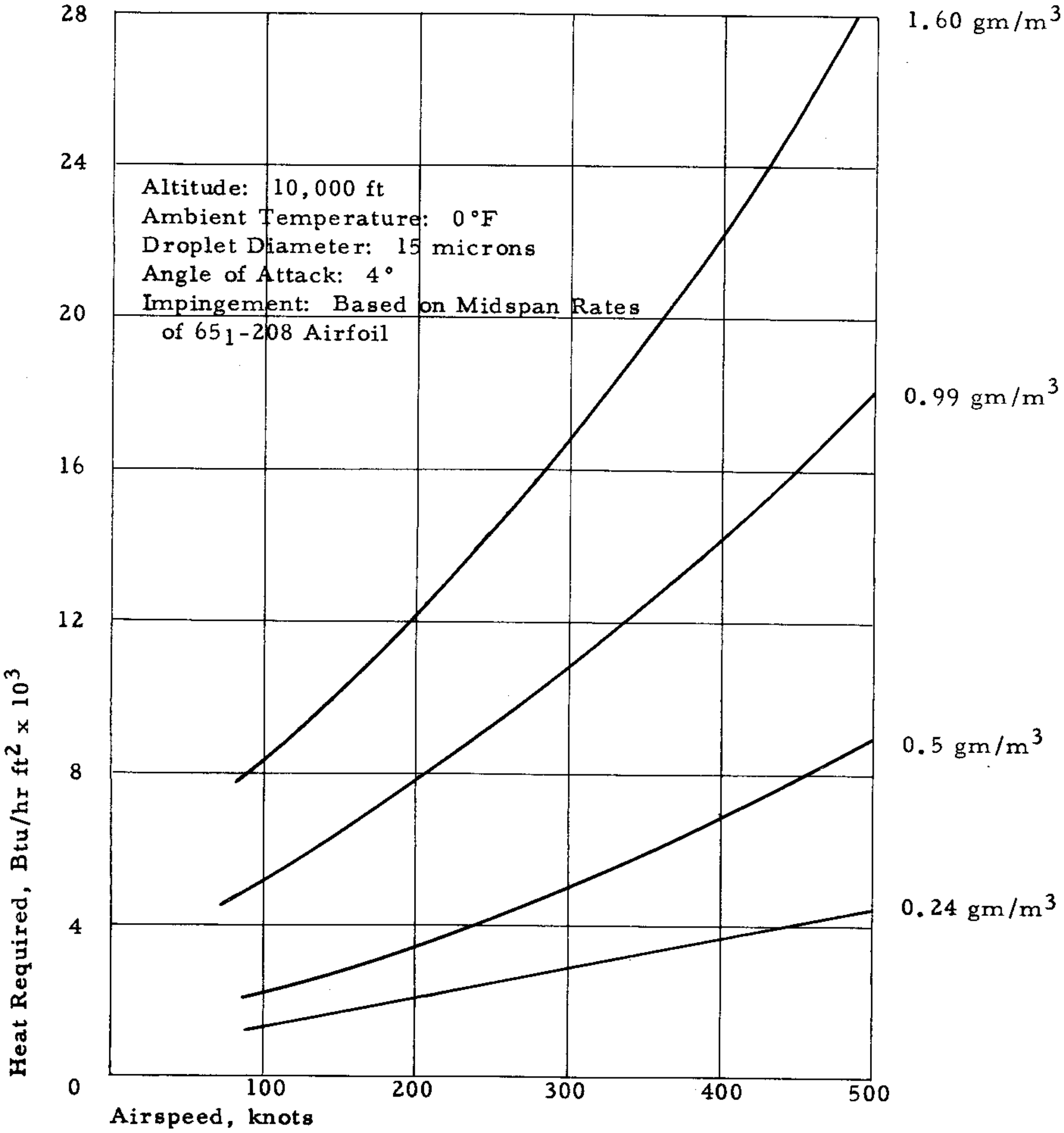


FIGURE 8: HEAT REQUIRED AT MIDSPAN TO MAINTAIN DRY SURFACE ON SWEPT WING FIGHTER

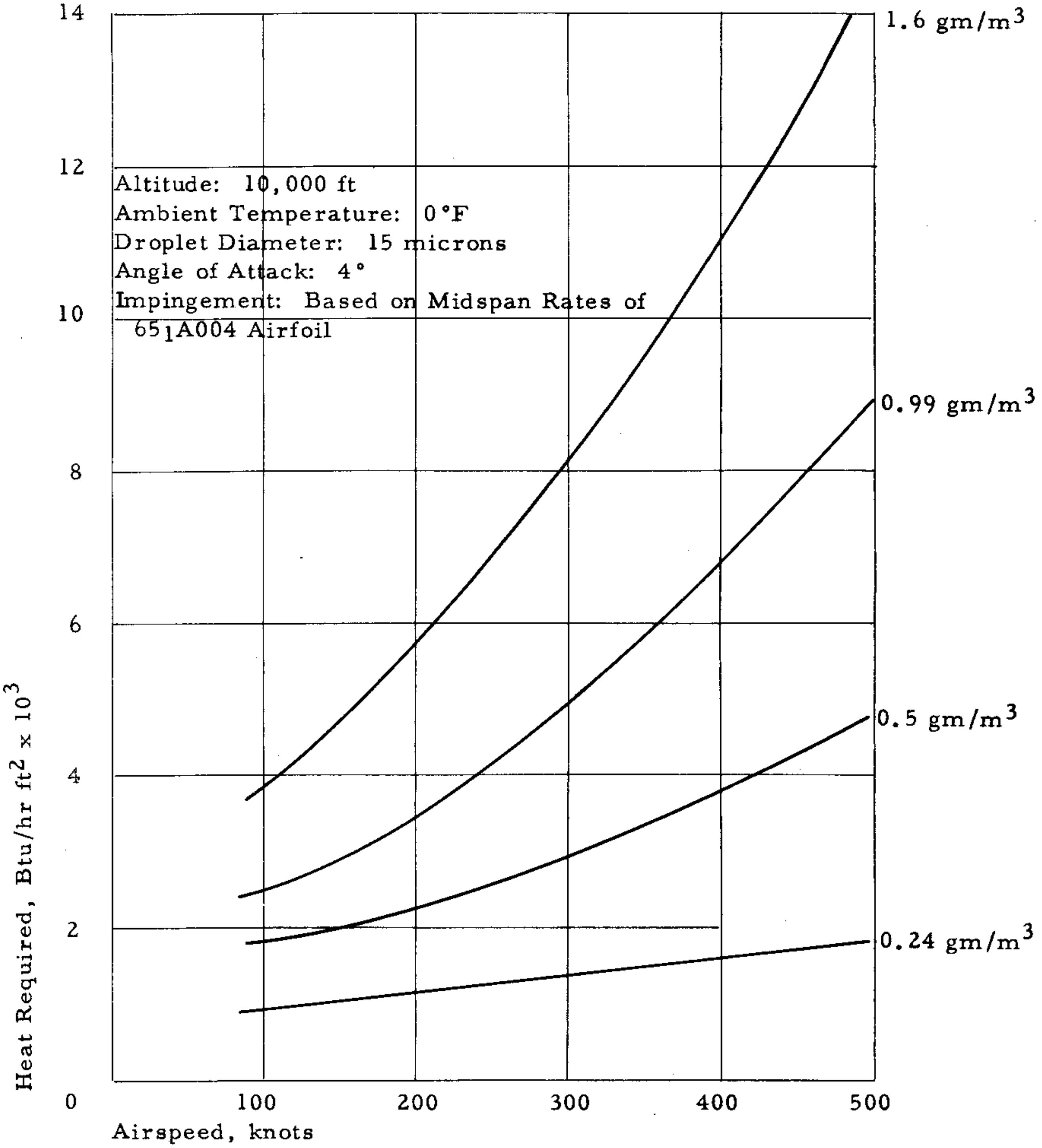


FIGURE 9: HEAT REQUIRED AT MIDSPAN TO MAINTAIN DRY SURFACE ON DELTA WING BOMBER

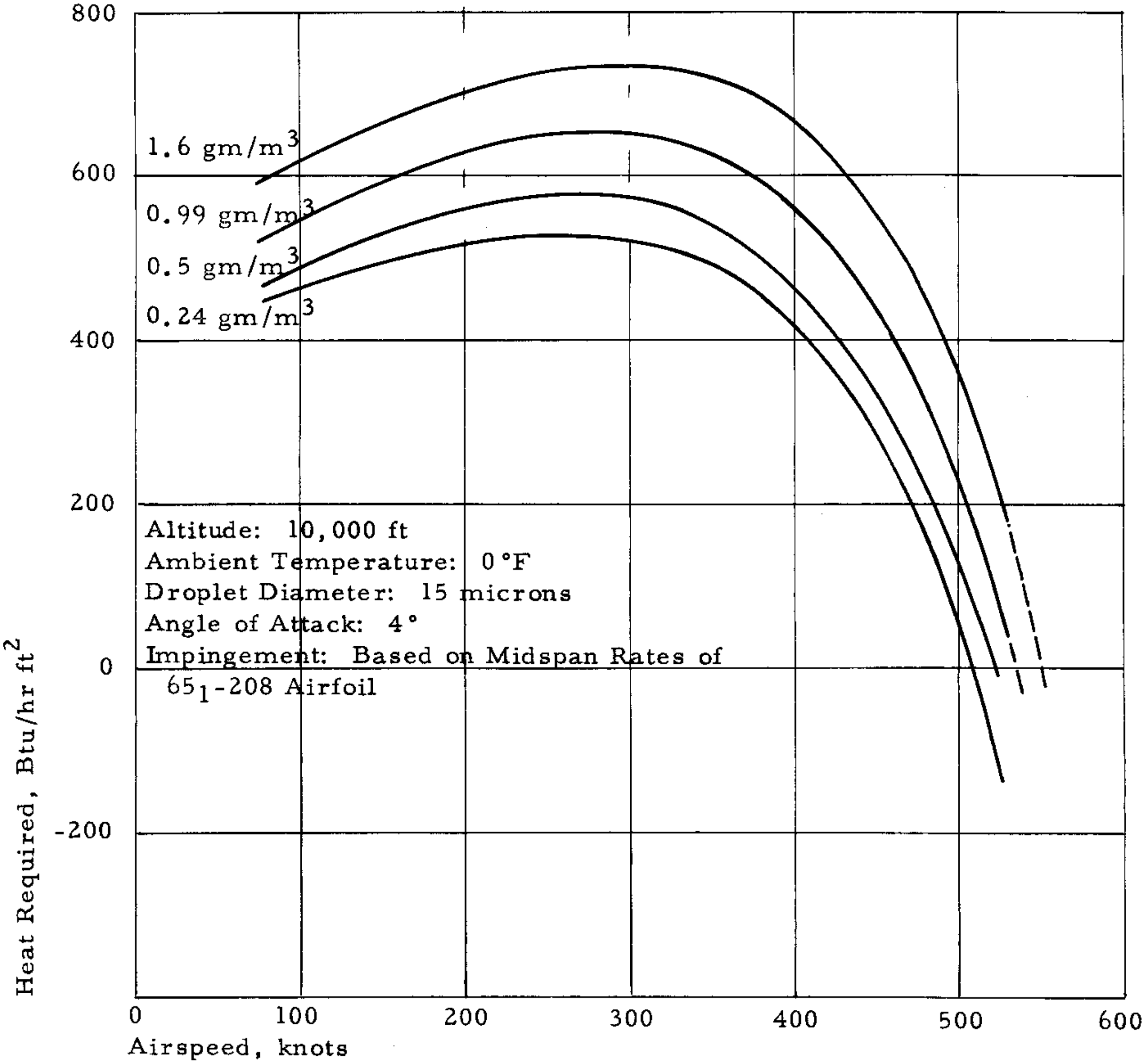


FIGURE 10: HEAT REQUIRED AT MIDSPAN TO MAINTAIN A RUNNING WET LEADING EDGE ON SWEPT WING FIGHTER

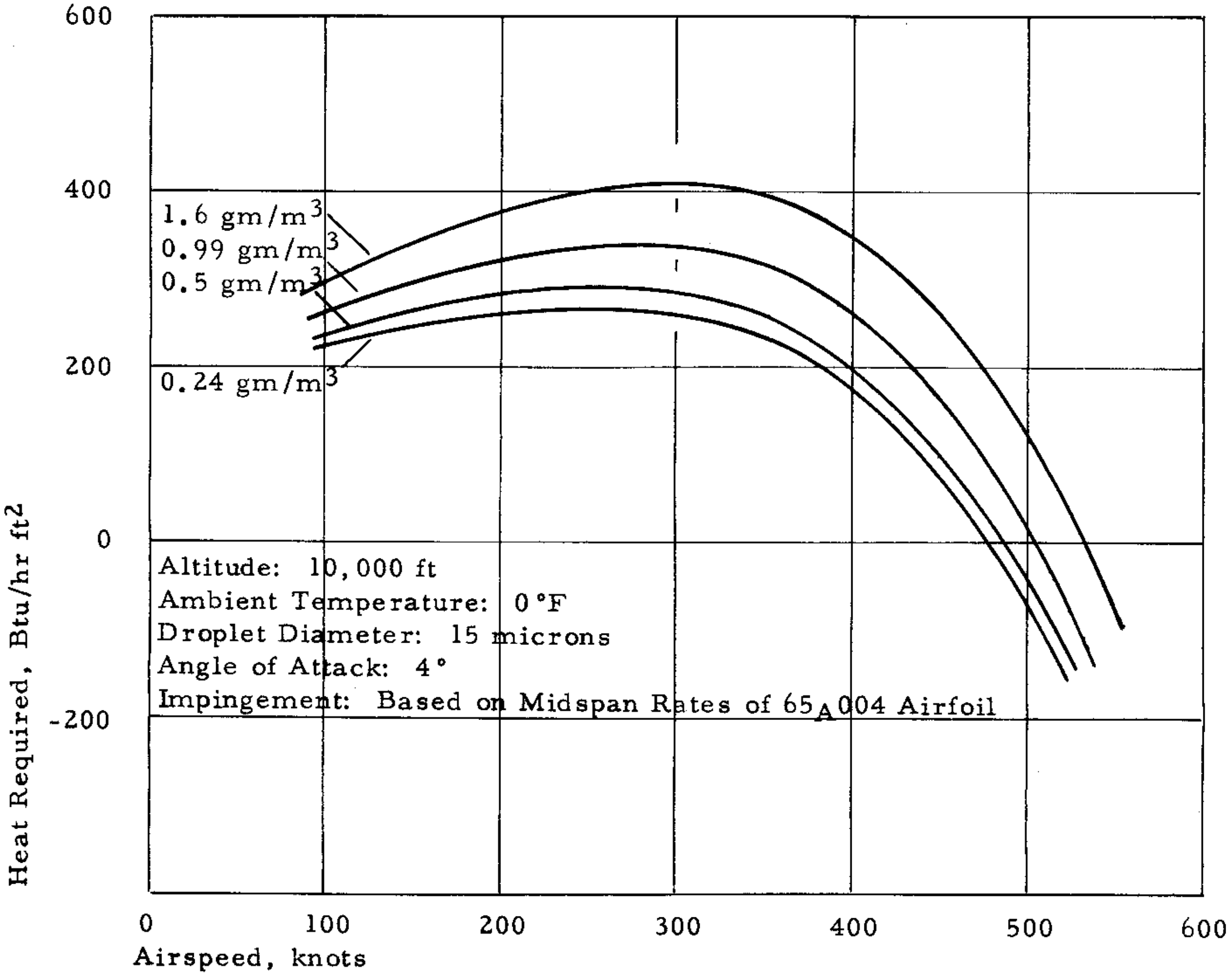


FIGURE 11: HEAT REQUIRED AT MIDSPAN TO MAINTAIN A RUNNING WET LEADING EDGE ON DELTA WING BOMBER

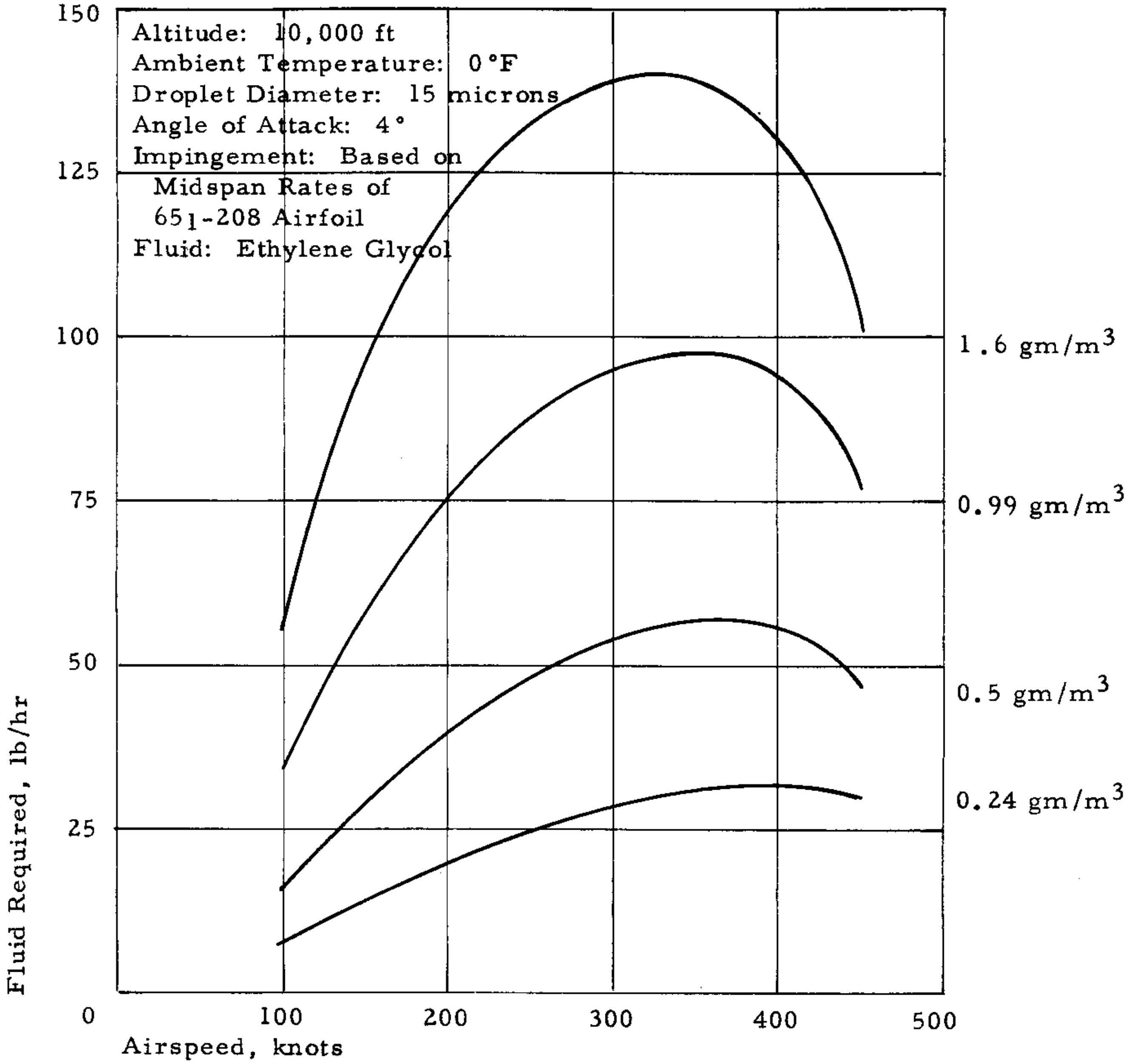


FIGURE 12: TOTAL FLUID REQUIRED TO MAINTAIN CLEAN AIRFOIL ON SWEPT WING FIGHTER

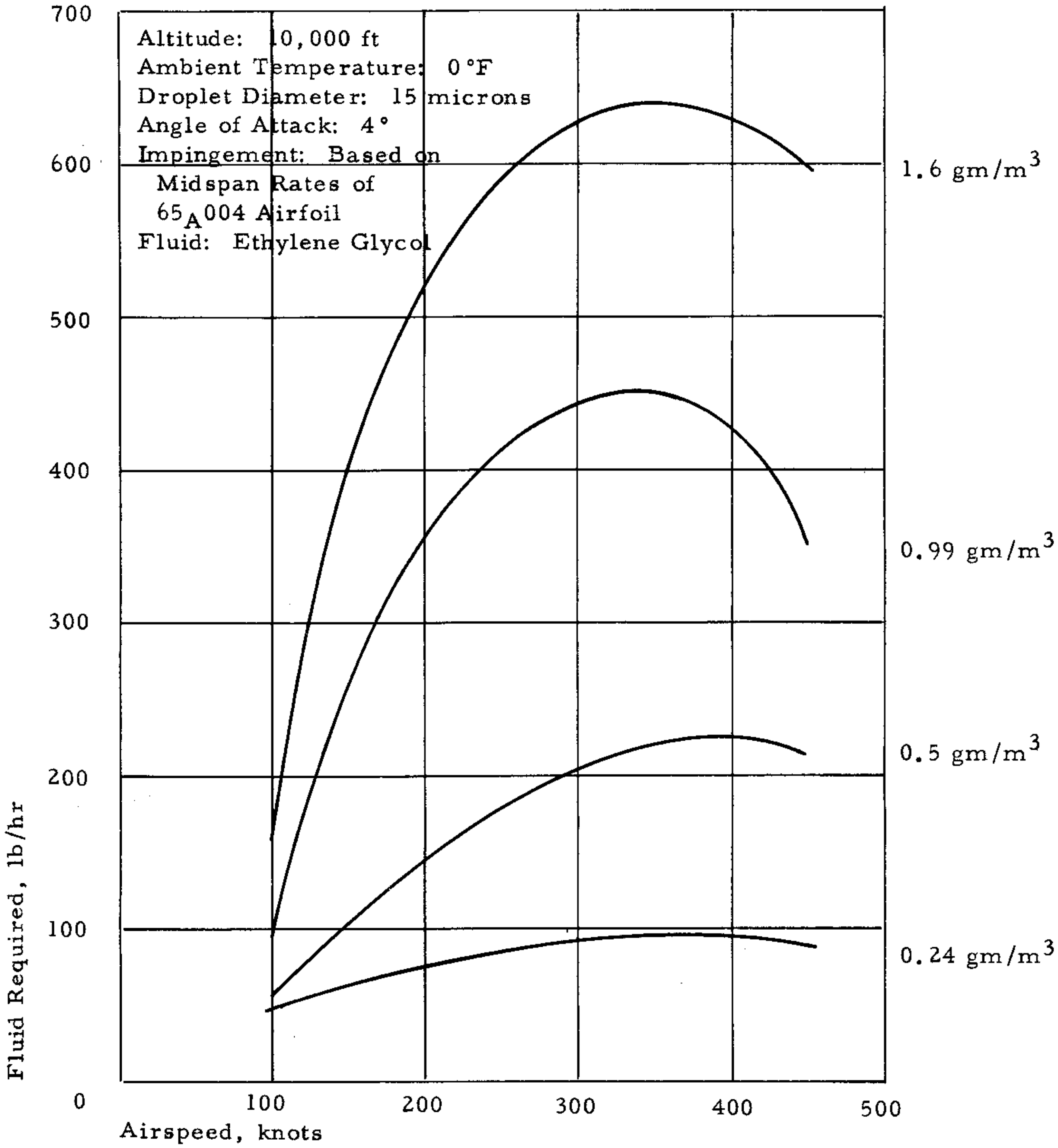


FIGURE 13: TOTAL FLUID REQUIRED TO MAINTAIN CLEAN AIRFOIL ON DELTA WING BOMBER

Aerodynamic heating has a pronounced effect in reducing protective requirements for present and projected aircraft. This is illustrated in the running wet heat requirements presented above. The speed at which a wetted, ice-free surface is maintained by aerodynamic heating has been determined in reference 6. Figure 14 illustrates this effect for several surface pressure ratios. For the conditions shown, a wetted surface would be maintained ice free at somewhat less than Mach 1 for temperatures above -20°F. Since icing is rarely encountered at this temperature, and almost never below -40°F, only a small area of vulnerability appears to exist at sonic speeds.

Sublimation processes will remove ice from aerodynamic surfaces whenever the vapor pressure at the surface exceeds the vapor pressure in the surrounding air. Generally, the rates of sublimation are only a small fraction of an inch of ice per hour even at very high velocities. If an aircraft achieves a speed sufficient to raise the temperature of its icing surfaces above the freezing point, the ice accretion will melt and run off at a much higher rate than that at which the water would evaporate from the surface, according to reference 7.

Drag penalties associated with accretion of ice may rightly be assumed to be a portion of the requirements and performance of an overall system. Unfortunately, there has been little done to date that may be applied directly to the thin airfoils of the hypothetical aircraft. The drag is known to vary with the shape and size of the ice formation, the basic wing profile, degree of sweepback, and the angle of attack. The shape of the ice accretion is determined in part by the droplet diameter and the ambient temperature at relatively low airspeeds (reference 8). These shapes are illustrated in figure 15. Little or nothing appears to be known about the configuration of accreted ice at high velocities where the total temperature of the airfoil approaches or exceeds 32°F. The size of the formation may best be determined from the data in figures 6 and 7. Generally, the thinner the airfoil, the more serious the effects of accretion on drag at lower angles of attack. The drag has also been found to increase with the degree of sweepback and the angle of attack (reference 8). Figure 16 illustrates the drag increases associated with an unprotected, 9 percent swept airfoil subjected to glaze icing. A method of estimating drag effects due to accretions of various sizes and locations on an airfoil is presented in a later section for the evaluation of partial protective systems.

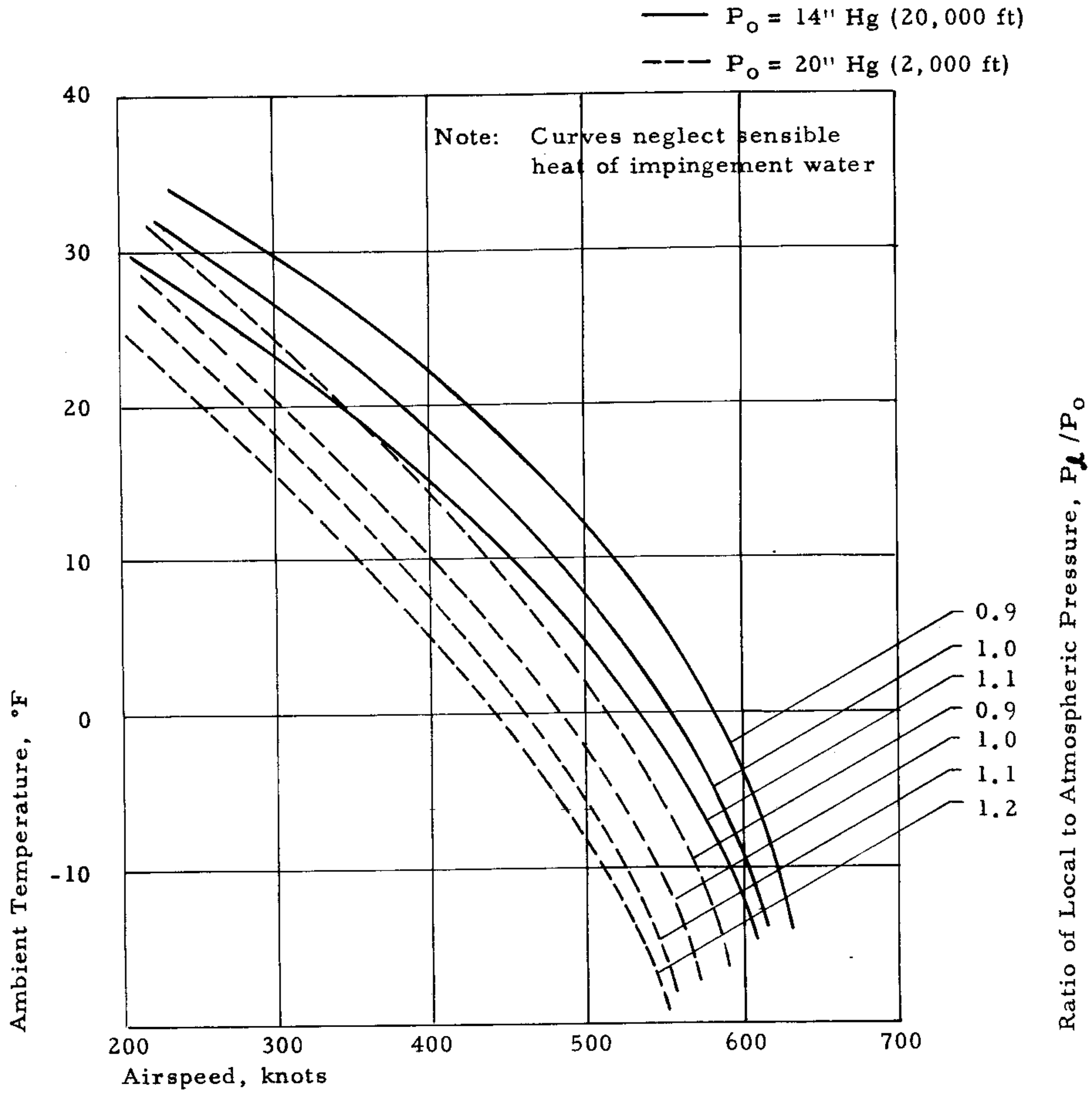


FIGURE 14: MINIMUM TEMPERATURE AT WHICH AERODYNAMIC HEATING WILL PRECLUDE ICE FORMATION

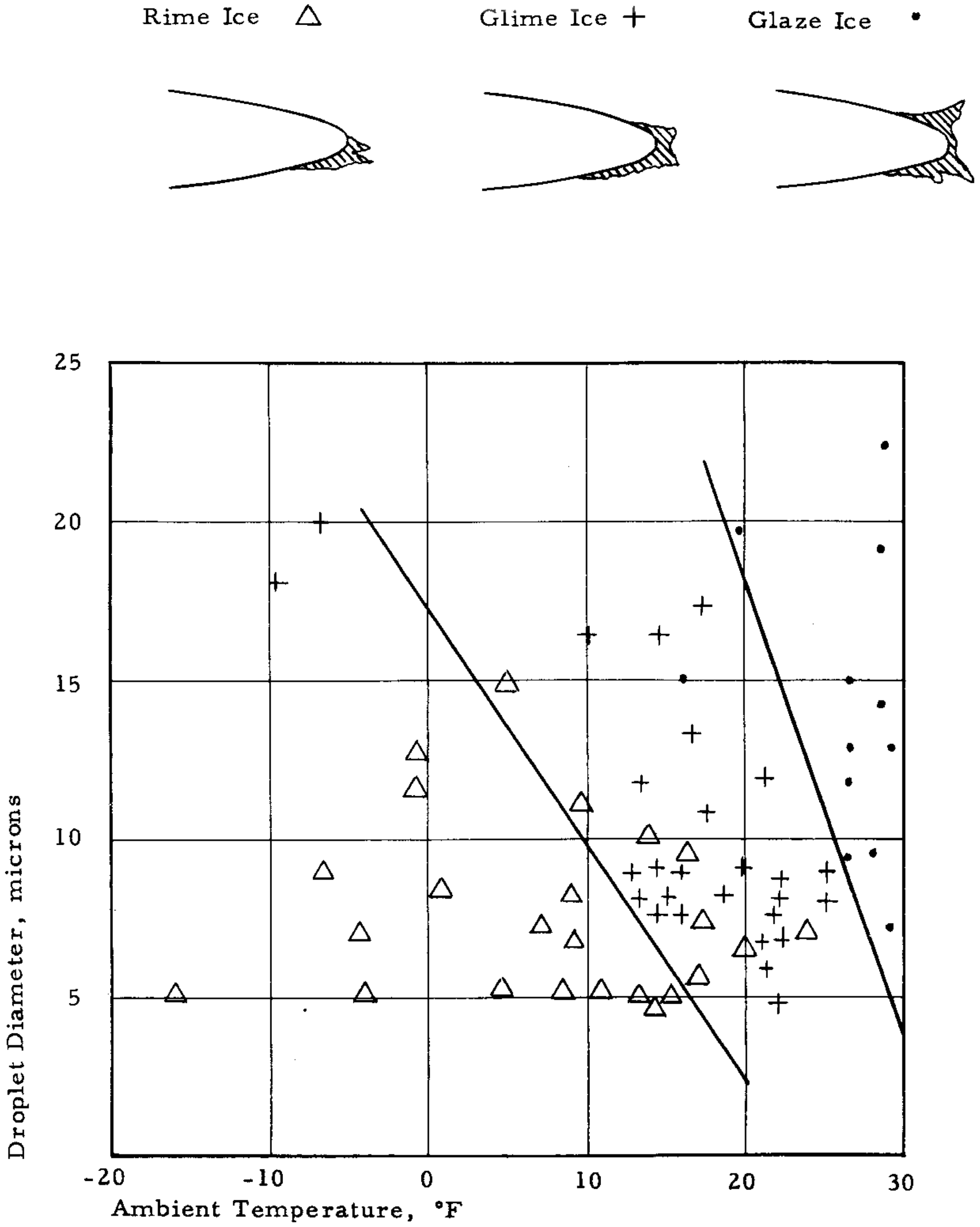


FIGURE 15: EFFECT OF DROPLET SIZE AND TEMPERATURE ON THE FORM OF ICE ACCRETION AT LOW VELOCITIES

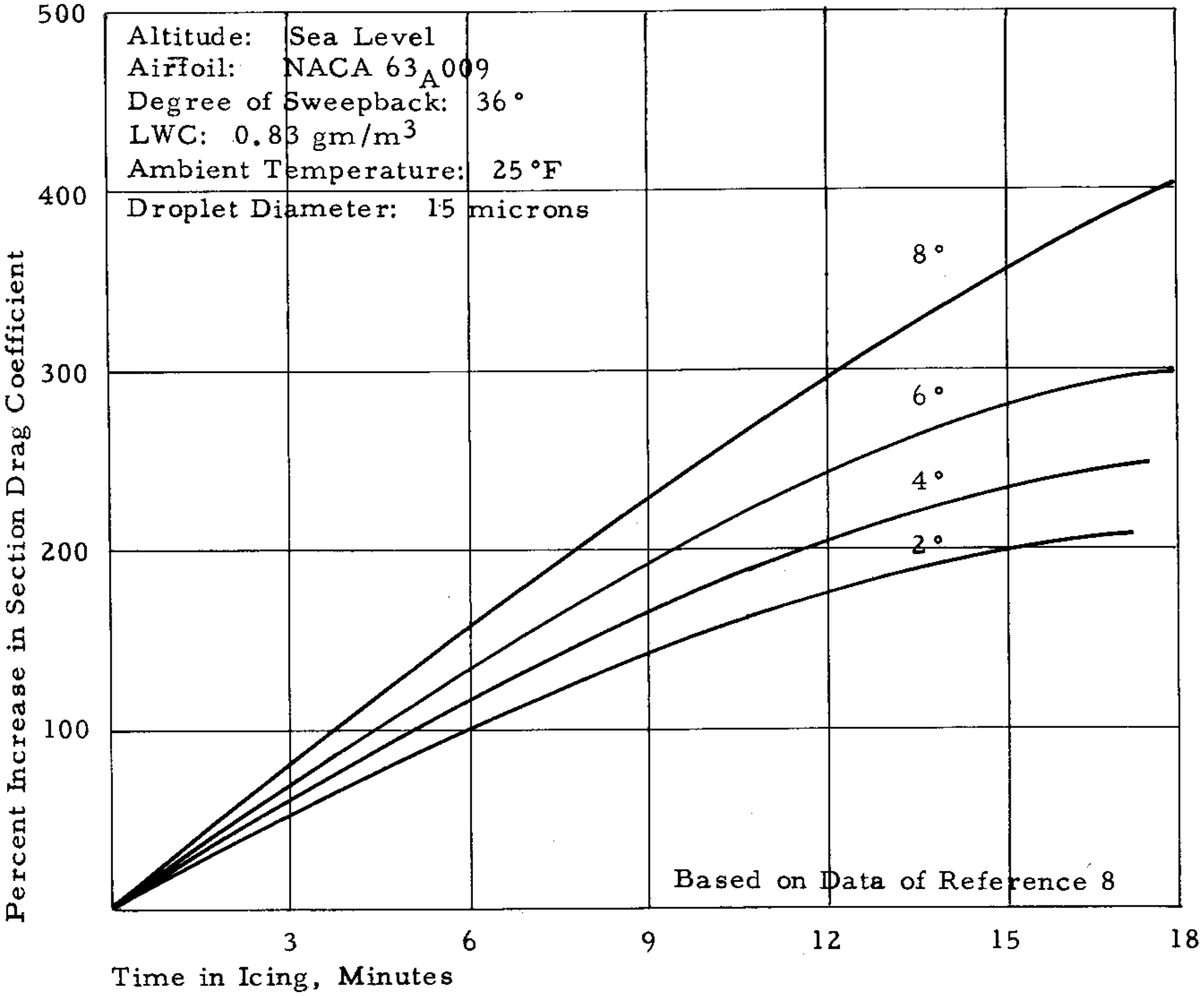


FIGURE 16: DRAG INCREASE DUE TO ICING EXPOSURE OF AN UNPROTECTED 9 PERCENT SWEPT AIRFOIL

SECTION II

SYSTEM COMPONENTS

In general, an icing protection system is composed of three basic elements: an energy source, an energy transfer medium, and an energy application means. Various components may be assembled into complete systems depending upon the characteristics of any particular installation problem and operational requirements. In order to assist in the selection of system components, descriptions of individual elements are presented below. Estimates of the installed weight, output energy requirements, etc., of each element are tabulated in table 1 for the summation of complete system performance.

A. Energy Sources

Combustion heaters are commercially available for aircraft hot air systems in capacities from 20,000 to 600,000 Btu/hr. They burn regular aircraft fuels and are usually supplied with ram air for combustion. An integral heat exchanger is used to isolate the heater exhaust. Such heaters are relatively compact and have a high Btu/lb weight ratio (references 9 and 10). While most useful on reciprocating engine aircraft where no ready source of high energy air is available, these may be considered wherever a localized source of hot air is required or wherever it is necessary to augment available hot gas supplies.

A high pressure heater has recently been developed to impart additional heat to compressor bleed air. This compact (4-inch diameter by 40-inch length) unit weighs 20 pounds and has an output of 200,000 Btu/hr.

Another model, described in reference 11, consists of a small diameter burner enclosed in a long conical jacket that extends the entire length of a wing leading edge. The jacket is perforated along the forward side to direct the augmented compressor bleed air against the region of greatest requirements.

Aircraft alternators are commercially available which deliver power from 15 KVA to 60 KVA at 208 volts, 400 cycles in single units. Larger sizes have a weight output ratio as low as 2 pounds per KVA. They may be driven directly from the engine accessory pad or by means of auxiliary turbine drive units.

Direct current generators are available in sizes up to 15 KW at 30 volts. The installed weight of low voltage d-c systems is usually higher than a-c systems for comparable power requirements. Starter generators are also in service which act as a starting motor for jet engines and then revert to a generator delivering 400 amperes at 30 volts (references 12 and 13). Combinations such as these can reduce the total weight chargeable to an icing system.

Air turbine auxiliary drive units are being developed (reference 14) to provide a power source isolated from the propulsive engine. They operate from turbojet compressor bleed air and may be used to drive electric generators for icing protective systems when there is no room on the engine accessory pad for additional power generation units. A high efficiency is claimed for these units although they require additional volume and add to the installed weight.

Batteries recently developed may serve as a practical source of energy for missile applications although they are quite expensive as yet. These batteries are much smaller and lighter than corresponding lead-acid types, have much lower internal resistance, and a higher capacity as described in reference 15. For instance, a block of cells of about 0.5 cubic foot volume and 64 pounds weight has a capacity of 100 ampere hours at 30 volts and will discharge as high as 1800 amperes for short periods of time.

Tail pipe heat exchangers can be used to heat ram air or increase the temperature of compressor bleed air for de-icing. Figure 17, obtained from reference 16, gives the performance and characteristics of a typical 6-foot, parallel-flow heat exchanger installed in a nonafterburning, 6000-pound thrust hypothetical jet engine tail pipe. The exchanger encircles the tail pipe for all or a portion of its length and also serves as a standoff heat shroud to protect the airframe from the intense radiation of the tail pipe.

Turbojet engines offer a variety of energy sources for icing systems; high pressure, high temperature bleed air is available from various stages of the engine compressor or from the combustion chamber. The exhaust may be used directly or in conjunction with a heat exchanger. Shaft power is also available to drive generators and other accessories.

The use of compressor bleed air is accompanied by a reduction in thrust and an increase in specific fuel consumption, depending upon the amount of air extracted and the point of extraction. This reduction varies with altitude, percent power, and airspeed. In general, sufficient heat appears to be available for evaporative anti-icing at most commonly

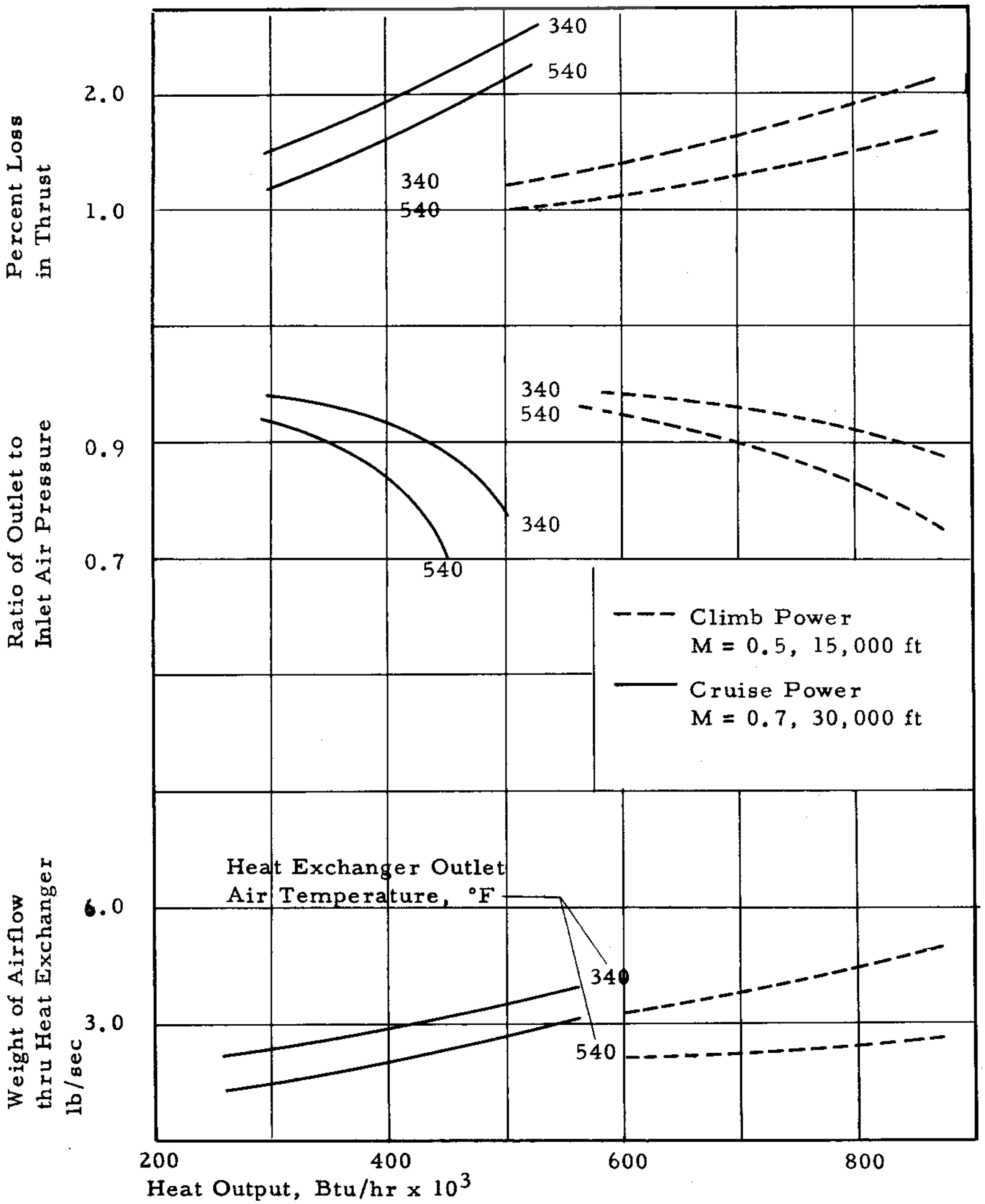


FIGURE 17: PERFORMANCE OF AN UNFINNED, PARALLEL FLOW, 6 FOOT TAIL PIPE HEAT EXCHANGER INSTALLED ON A HYPOTHETICAL JET ENGINE OF 6000 POUND THRUST (RATED GAS FLOW = 147 LB/SEC)

used power settings. Thrust losses vary from 1.5% at 80% rpm to 3.5% at 100% rpm. The maximum permissible air extraction for a typical jet engine (of approximately 6000 pounds static thrust) is superimposed upon the airflow required for anti-icing of the hypothetical fighter and bomber in figures 18 and 19 respectively. Engine characteristics are based on the data of reference 17. Air bled from the combustion chambers of turbojet engines has been proposed to augment compressor bleed air at low power settings (reference 14). This ultra-high temperature air may be used alone or in conjunction with compressor bleed air. Less thrust is lost by extraction of air at this point.

The high air-fuel ratio of turbojet engines makes the direct use of exhaust gases more feasible. The temperature and pressure of this gas vary from 1070°F, 26.5 psia at 325 knots and 100% power to 670°F, 16.3 psia at 130 knots and 80% power for a typical jet engine at sea level.

B. Energy Application Means

1. Double-Skin Heat Exchangers

Leading edge areas may be heated by passing hot gas between an inner skin and an outer skin which constitute a heat exchanger. Usually air is introduced from a distribution duct near the leading edge and flows rearwards between the inner and outer skins. Several novel exchangers are described in the following paragraphs.

An exterior duct formed by the application of a ribbed shroud over the leading edge to the 6% chord point is illustrated in figure 20. The total thickness of this shroud is only 0.030 inch thick. Air gaps 0.020 inch thick are formed integrally between the ribs. Initial tests indicated the following performance:

1) Heated air savings between 20 and 30%.
2) No appreciable runback ice formation.
3) Removal of pre-formed ice as far back as 40% of chord.

Information on this device has been published in WADC TR 55-148.

The high pressure, high temperature air obtained from a turbojet compressor bleed has been used in a recirculatory type of leading edge heat exchanger where the air leaving the double skin passages is mixed with incoming air in an aspirator arrangement as shown in figure 20. Higher efficiencies are possible because a greater portion of the bleed air heat content is utilized. This method is described in reference 18.

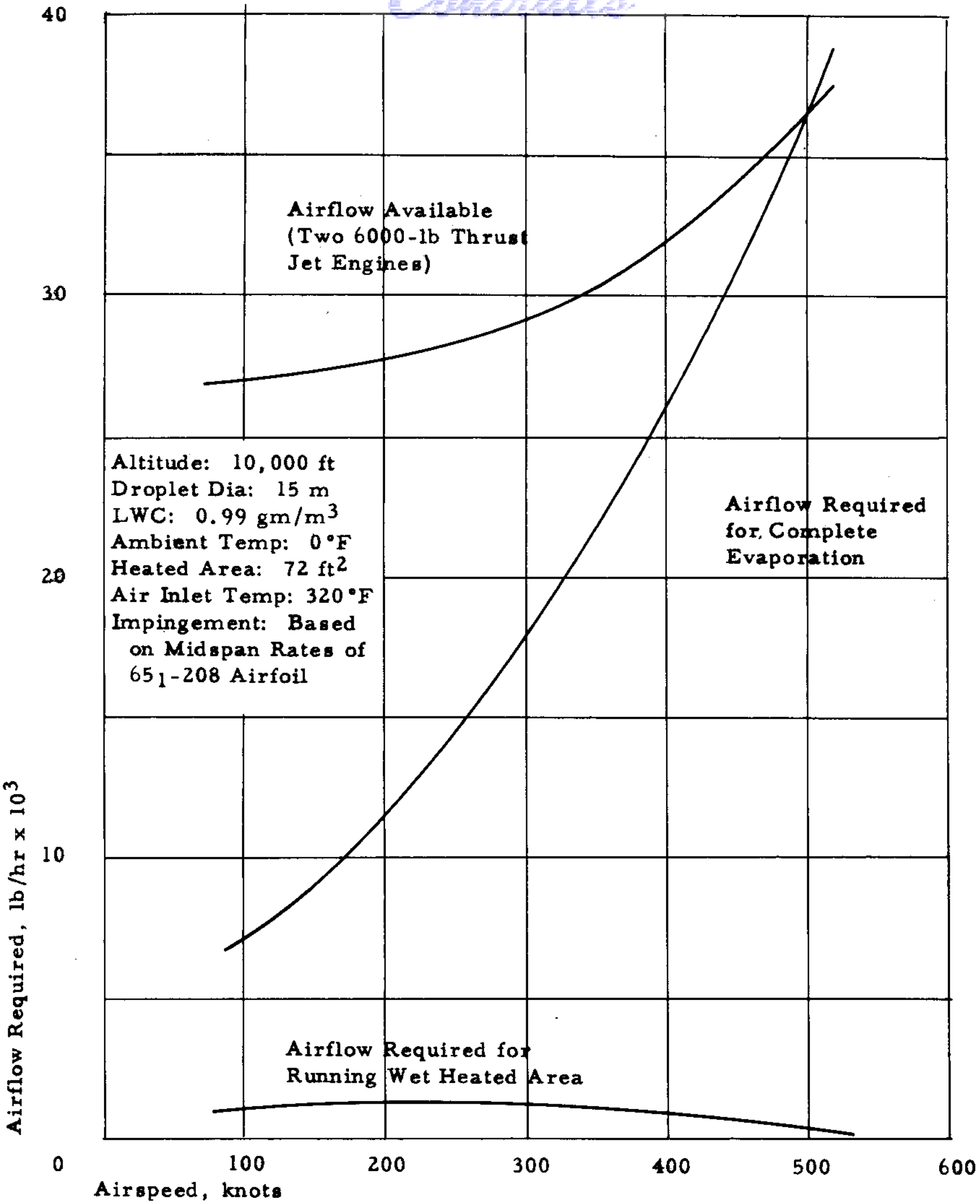


FIGURE 18: DOUBLE-SKIN HEATING SYSTEM AIRFLOW REQUIREMENTS, FIGHTER

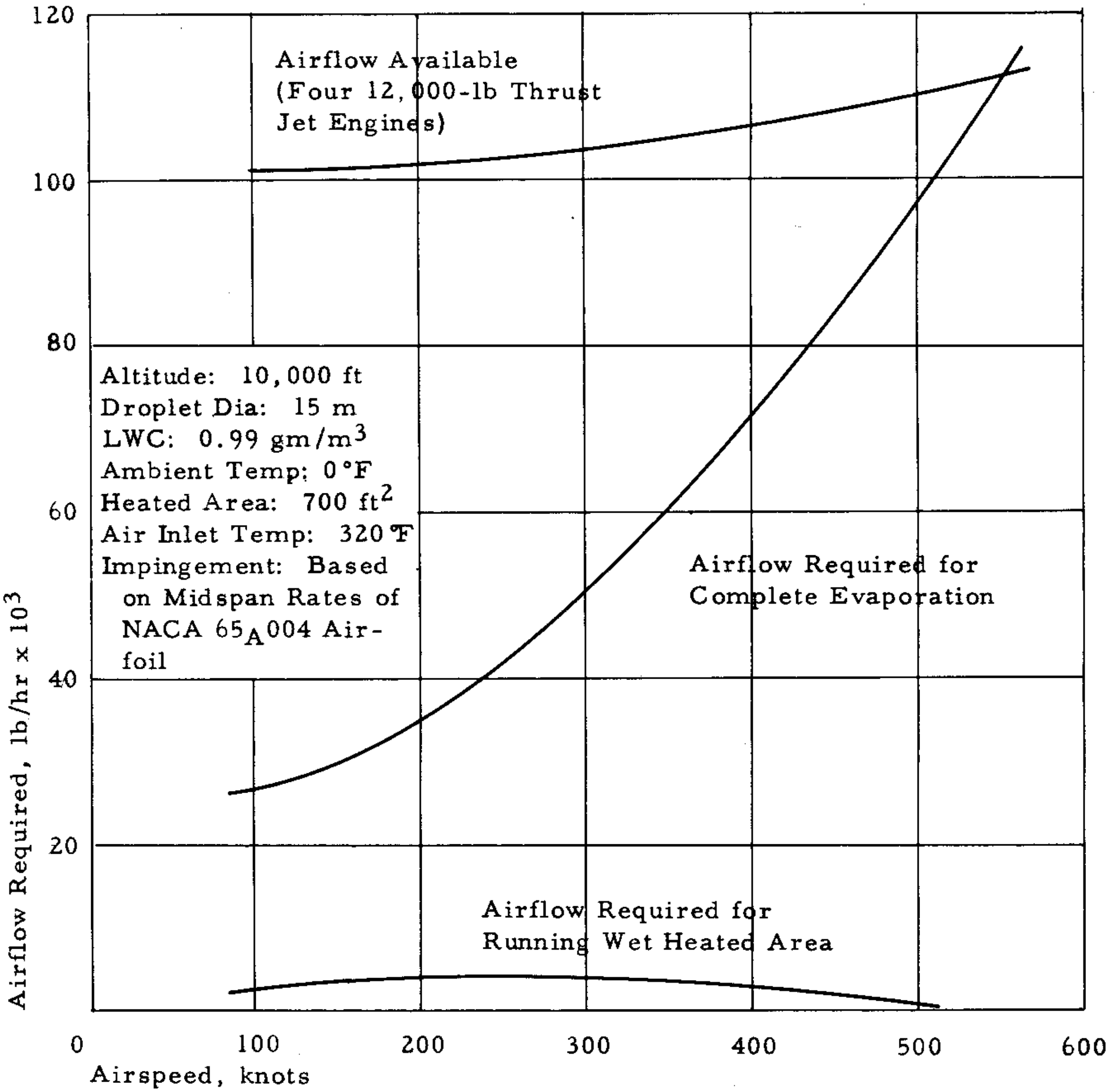


FIGURE 19: DOUBLE-SKIN HEATING SYSTEM AIRFLOW REQUIREMENTS, BOMBER

A perforated spanwise duct which would both distribute the hot air and form a double skin is shown in figure 20c. The perforations direct the hot gas directly against the skin. By varying the number and diameter of the perforations, the heat can be apportioned according to the requirements in any particular area. Weight would be minimized while maintaining an efficient heat transfer.

A leading edge fabricated from honeycomb material perforated for internal flow could serve as a heat exchanger and an efficient structural member as shown in figure 20d. Recent developments in honeycomb material include a perforated core which allows flow within itself (reference 19). Little is known on the flow characteristics of this material, but it is likely that pressure drops would be high. This material is also available with one porous metal surface. The increased heat transfer qualities of the porous surface might alleviate the pressure drop problem by reducing the airflow requirements.

2. Porous Leading Edges

Porous skins which can be used for the secretion of temperature depressant fluids or to pass hot gases are manufactured in varying thicknesses and permeabilities. These materials are manufactured from sintered powdered metal, sintered woven wire, metal mesh sandwiches, porous plastics, and Fiberglas compacts. Each type of material has its peculiar advantages and disadvantages so that an optimum choice for an application requires a careful consideration of individual properties. See references 20 and 21 for further data.

3. Electric Heating Elements

Electric heating elements are available for external surfaces in electrothermal ice protective systems. These film-like elements vary in thickness from 0.015 to 0.125 inch and in maximum power density from 8 to 40 watts per square inch.

Three basic types of elements exist: networks of fine heating wires laid between layers of neoprene or silicon rubber which are cemented directly to the surface; sprayed film-like elements consisting of a base insulation, a conducting film, and a protective cover; rubber elements which have a base layer, a conducting rubber film, and an outer protective coating. These are generally used for de-icing because of the high power requirements of thermal anti-icing and the ease of control associated with electrical circuits.

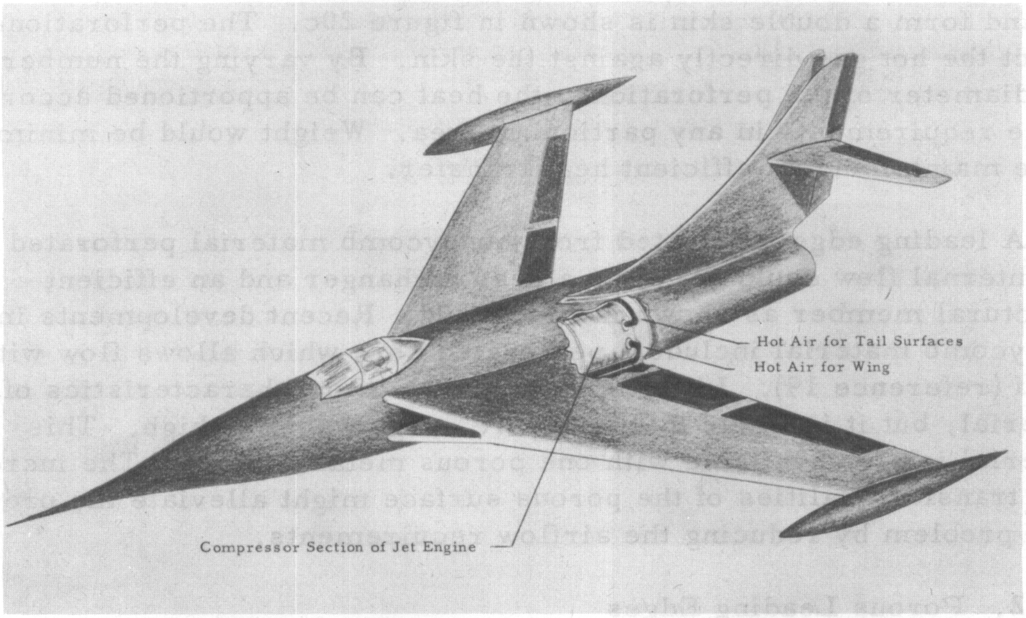


FIGURE 20 JET ENGINE COMPRESSOR BLEED AIR SYSTEM WITH VARIOUS DOUBLE SKIN CONFIGURATIONS

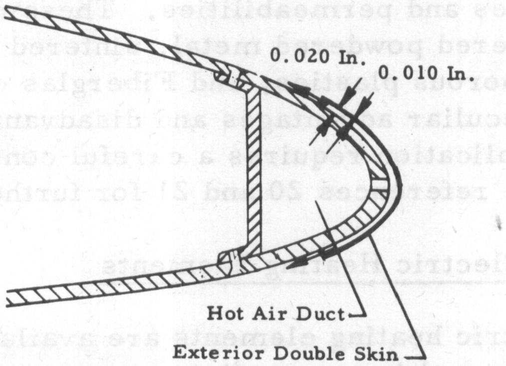


FIGURE 20a EXTERIOR DOUBLE SKIN

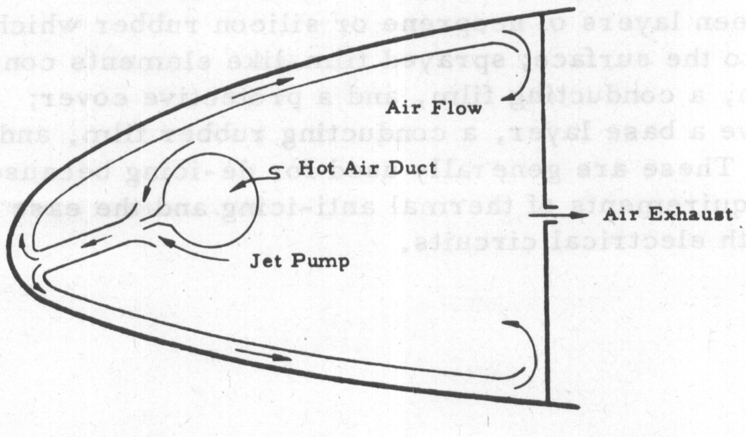


FIGURE 20b RECIRCULATORY SYSTEM

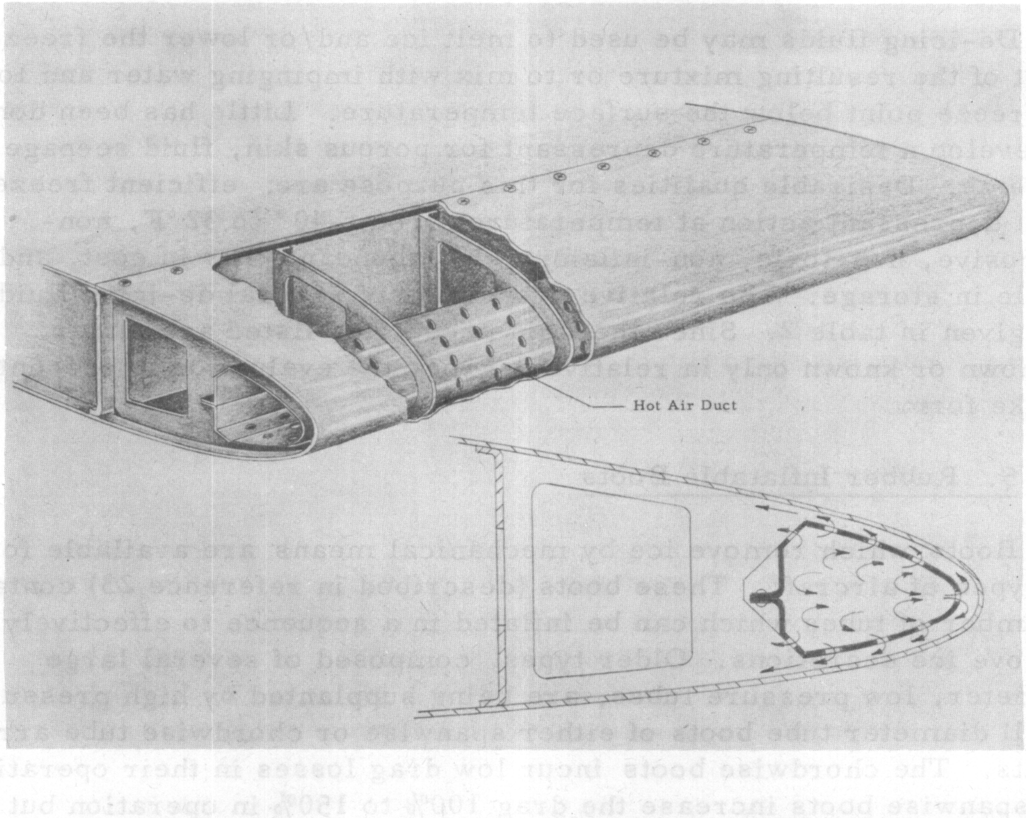


FIGURE 20c SIMPLIFIED HOT AIR DISTRIBUTION DUCT

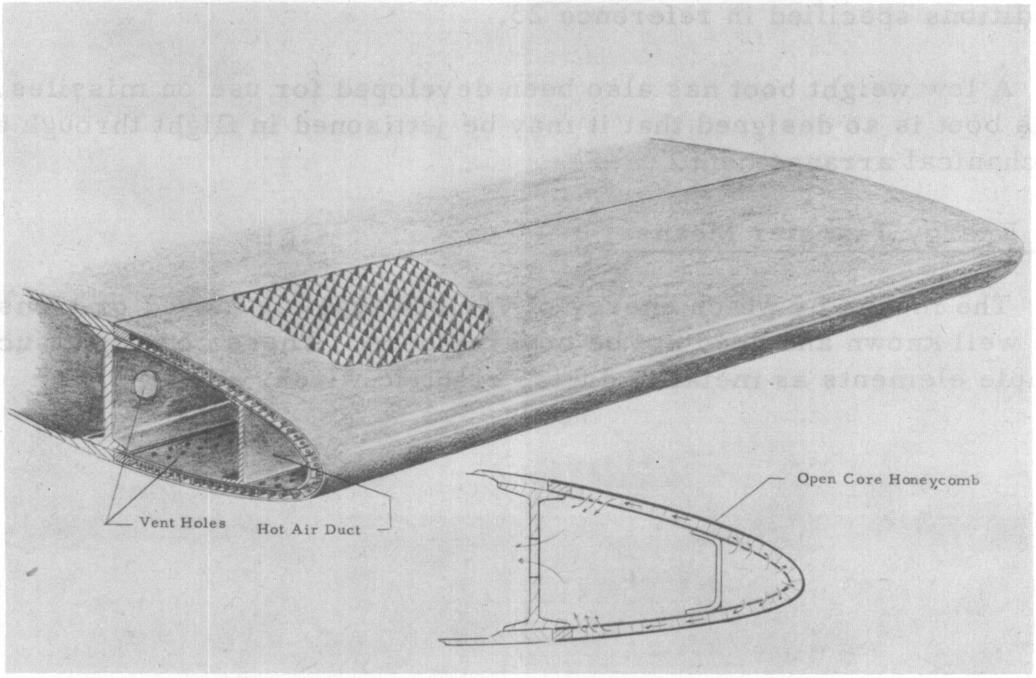


FIGURE 20d HONEYCOMB DOUBLE SKIN LEADING EDGE

4. Fluid Freeze-Point Depressants

De-icing fluids may be used to melt ice and/or lower the freeze point of the resulting mixture or to mix with impinging water and lower its freeze point below the surface temperature. Little has been done to develop a temperature depressant for porous skin, fluid seepage systems. Desirable qualities for this purpose are: efficient freeze-point depressant action at temperatures from -40° to 32°F, non-corrosive, non-toxic, non-inflammable, abundant, low in cost, and stable in storage. The relative properties of several de-icing fluids are given in table 2. Since the fluid properties listed are either unknown or known only in relative degree, the evaluation is presented in like form.

5. Rubber Inflatable Boots

Boots which remove ice by mechanical means are available for all types of aircraft. These boots (described in reference 23) contain a number of tubes which can be inflated in a sequence to effectively remove ice accretions. Older types, composed of several large diameter, low pressure tubes, are being supplanted by high pressure, small diameter tube boots of either spanwise or chordwise tube arrangements. The chordwise boots incur low drag losses in their operation; the spanwise boots increase the drag 100% to 150% in operation but are effective over wide ranges of angle of attack. Serviceability tests on the high pressure spanwise boots installed on a high performance fighter demonstrated satisfactory protection against the icing and flight conditions specified in reference 23.

A low weight boot has also been developed for use on missiles. This boot is so designed that it may be jettisoned in flight through a mechanical arrangement.

C. Energy Transfer Means

The means by which energy of various types is moved or transferred are well known and need not be covered here. These comprise such simple elements as metallic ducts, electric wires, etc.

TABLE I
CHARACTERISTICS OF SYSTEM COMPONENTS

Component		Description	Output	Weight (lbs)	Weight per Unit of Energy	Volume (ft^3)	Fuel Consumed (lb/hr)	Remarks
AC Alternator		Engine driven, 3-phase, alternating current	15 KW 120-208v, 320/480c 30 KW 120-208v, 320/480c 60 KW 120-208v, 320/480c	83 97 131	6.75 lbs/KW 3.90 lbs/KW 2.90 lbs/KW	.90 .95 1.05		
DC Generator		Engine driven, direct current	9KW, 30 v 12KW, 30 v 15KW, 30 v	60 69 78	8.4 lbs/KW 5.8 lbs/KW 5.2 lbs/KW	.36 .38 .35		
Battery		Lightweight jet engine starting battery	120 amp hr, 28 volt	46.3	48 watts-hr/lb	.40		Silver-zinc plates with electrolyte of KOH
Combustion Heaters	Low Pressure	Hot air heater burning aircraft fuel and ram air	20,000 Btu/hr 50,000 Btu/hr 200,000 Btu/hr 600,000 Btu/hr	20.0 24.5 30.0 95.0	1.00×10^{-3} lbs/Btu $.49 \times 10^{-3}$ lbs/Btu $.15 \times 10^{-3}$ lbs/Btu $.16 \times 10^{-3}$ lbs/Btu	.69 .88 1.00 7.50	1.5 4.8 16.2 48.0	
	High Pressure	Hot air wing heater	260,000 Btu/hr	30.0	1.15×10^{-4} Btu/lb	.62	21.5	Dimensions: 1-1/2 in. to 4 in. dia 15 ft long
		Hot air empennage heater	183,000 Btu/hr	26.0	1.42×10^{-4} Btu/lb	.52	19.5	4 in. dia 6 ft long
Pump		Electric driven 28v DC 3.2-5.8 amps draw	18-44 GPH (alcohol)	3.75				
Solenoid Valve		Liquid Air	29-180 GPH at 15-650 PSI 21 lbs/min	.70 5.5				
Filter		Fluid strainer		.3				

TABLE I

CHARACTERISTICS OF SYSTEM COMPONENTS

Component	Description	Output	Weight (lbs)	Weight per Unit of Energy	Volume (ft^3)	Fuel Consumed (lb/hr)	Remarks
Electric Elements	Sprayed conductive coating	Up to 40 watts/in^2	0.1 to 0.19 lbs/ft^2	Up to 3.0 x 10^{-5} lbs/watt	0.010 - 0.025 in. thick		
	Conductive rubber	1.04 watts/in^2	8-16 oz/ft^2	5 x 10^{-3} lbs/watt (approximately)	0.015 0.025 in.		
	Resistance wire or ribbon elements, rubber covered	Steady 0 - 15 watts/in^2 Intermittent 0 - 40 watts/in^2	0.5 lb/ft^2 silicone 0.4 lb/ft^2 neoprene rubber	Steady 2.3 x 10^{-4} lbs/watt Intermittent 0.62 x 10^{-4} lbs/watt	0.035 in. thick, up		
Turbine Drive	Auxiliary turbine drive units operated from compressor bleed air	3 hp	unknown	2.33 lbs/hp	0.18		Designed for emergency use to power 9kva alternator to power 300 GPM fuel transfer pump
		15 hp	35		1.80		
		40 hp	unknown		2.24		
De-Icer Boots	Regular boot		0.7 lb/ft^2				
	Short-life boot		0.5 lb/ft^2				

TABLE 2
RELATIVE PROPERTIES OF COMMON DE-ICING FLUIDS

Fluid	Ice-Melting Ability	Freeze Pt Depressing	Cor-rosivity	Vola-tility	Vis-cosity	Toxicity	Storage	Availa-bility	Remarks
Ethylene Glycol-Isopropyl Alcohol (4:1)	Average	Average	None	Low	High	Low	Stable	Good	Used by Air Force to de-ice parked aircraft
Ethylene Glycol-Water (3:1)	Average	Average	None	Low	Medium	Low	Stable	Good	Used by air lines to de-ice parked aircraft
Lithium Chloride	Good	Average	Slight	Low	Medium	None	Tendency for crystal growth	Limited	Being service-tested by Navy
Ethylene Glycol Potassium Acetate Sol	Good	Unknown	Slight	Low	Medium	Unknown	Unknown	Unknown	Recently developed by Snell, Incorporated
Kilfrost	Average	Unknown	Slight	Low	High	Low	Stable	Good	Used by British for de-icing
Isopropyl Alcohol	Poor	Good	None	High	Low	Low	Stable	Good	Used for propeller anti-icing
Ethyl Alcohol	Poor to Medium	Good	None	High	Low	Low	Stable	Good	
Methyl Alcohol	Poor to Medium	Very Good	None	Very High	Low	Very High	Stable	Good	Too toxic for general use

SECTION III

MAKEUP AND EVALUATION OF SYSTEMS

Many types of icing protective systems may be conceived varying in the mode of ice removal or prevention action, the time duration of the action, and the degree of surface protection afforded as described in section I. Some of these systems may be examined analytically by methods described in the references and by comparison with existing systems. A number of the systems do not lend themselves to such analyses but require experimental evaluation. The characteristics of these systems are estimated. In any case, the evaluations are limited by the information available and by the overall scope of the study program.

Systems are presented in groups below according to the time of actuation, duration of the action, and the degree of surface protection. The meteorological attributes and flight paths chosen as a basis for evaluation are designated in the first section.

A. Initial Systems

Initial systems are intended primarily for use on non-piloted aircraft which accelerate to speeds above the upper icing limit soon after take-off or rapidly penetrate the icing region and require no further protection. Ideally, the initial protective means should be capable of being applied externally to the critical surfaces, should be of low weight, and should not incur tangible aerodynamic losses in use. By its nature, an initial system has primarily an anti-icing action.

Only two basic types of initial systems are given below. These are both presented in the light of the above discussion.

1. Highly Viscous Freeze-Point Depressants

When applied prior to flight, these fluids fall within the category of initial systems. To function properly, these materials should remain on the surface in adequate quantities to prevent freezing until the icing layer has been penetrated or until a speed is reached where aerodynamic heating precludes icing. The quantity required depends upon the rate of water catch, the ambient temperature, and the nature of the material. Several possible compounds are described below:

1) The compound currently used by the Air Force for aircraft ground de-icing consists of ethylene glycol and dextrose (see MIL-D-8243). In its present form, it offers some initial protection during ground operation and take-off. Reference 24 describes the characteristics of this material thickened four times by additional dextrose.

2) A frost-removing composition is described in reference 25 as a non-corrosive, paste-like composition which prevents the adhesion of frost to chilled metal surfaces. It consists essentially of 60% to 80% ethylene glycol (by weight), 18% calcium chloride, and 0.5% to 1% sodium nitrate, the remainder being calcium soap of higher fatty acids for imparting a grease-like consistency to the composition. No data seem to be available regarding its performance.

3) A composite anti-icing surface that consists of two coatings which blend to form a layer firmly united to the aircraft surface is described in reference 26. The adhesive undercoating consists of a solution of glyceral phthalate in acetone and is easily applied by brush. The ice deterrent is a solution of glycol stearate in ethylene glycol worked into a cream and brushed onto the base coating. Prevention of ice accretion is claimed at temperatures as low as -83°F.

There are many efficient freeze-point depressants which have a corrosive nature. Since the life of a missile is so limited, it is possible that some of these chemicals would be of value for initial systems. Ammonia compounds and metallic salts are known to fall into this category. Unfortunately, little is known regarding their ice deterrent qualities because investigations in this field have been largely limited to non-corrosive agents.

2. Structural Heat Storage

An initial heat charge could possibly be imparted to a missile so that the skin temperature would remain above freezing until sufficient airspeed is gained to preclude icing. This heating might be achieved by the use of heating blankets, induction heating, or other means. Thick skin construction is essential in order to store greater amounts of heat.

An analysis of the time for the surface to cool to 32°F is possible with certain simplifying assumptions. Considering the skin to have the major heat capacity and neglecting the effect of skin conduction,

$$3600\ c_{p_m}\ \rho_m\ a\ (dT_s/dt) = q_s = h_a\ (T_s - T_o) \tag{1}$$

where c_{p_m} = specific heat of material, Btu/lb/°F
ρ_m = density of material, lb/ft^3
a = skin thickness, ft
T_s = skin temperature, °F
t = time, sec
q_s = surface heat flow, Btu/hrs/ft^2
h_a = heat transfer coefficient, Btu/hr/ft^2/°F
T_o = recovery temperature, °F

Although q_s is slightly dependent on time, mainly through h_a and T_o, it may be assumed to be essentially a function of the surface temperature T_s only. Therefore

$$3600 \quad t_2 - t_1 = \rho_m \, d \, c_p \int_{T_1}^{T_2} (d \, T_s/q) \tag{2}$$

where $t_2 - t_1$ = time interval under consideration
c_p = specific heat of air

Taking $T_1 = T_s$, the initial skin temperature, and $T_2 = 32$ °F, and $t_1 = 0$, the time for the leading edge to cool from temperature T_s to 32 °F may be expressed as

$$3600 \quad t = \rho_m \quad a \, c_p \int_{32}^{T_s} (d \, T_s/q) \tag{3}$$

The quantity q may be evaluated by the methods of reference 27.

For an NACA 65_1-208 airfoil at an average speed of 325 knots and being exposed to a liquid water content of 1 gm/m^3, the time for a 1/4-inch thick aluminum skin to cool from an initial skin temperature of 100° to 32 °F is found to be 14.4 seconds. Skin temperatures above 100 °F give diminishing returns due to evaporative effects.

It is doubtful, therefore, that protection could be achieved by this method for more than 30 seconds - an extremely limited time.

B. One-Shot Systems

A one-shot system is capable of removing ice once during any phase of the flight and thus offers a more flexible degree of protection than the initial system. For maximum utility, the system should be capable of being applied externally and should incur a minimum performance penalty before and after use. Such systems are essentially de-icers because the action involved is one of ice removal. They could be used either on non-piloted aircraft or on interceptor-type piloted aircraft to clear critical surfaces of accreted ice after the craft has passed through an icing atmosphere. The typical flight paths for which these systems are intended are illustrated by the dotted line in figure 1.

Several types of one-shot systems are described in the following paragraphs. Spanwise shedding devices were also considered. Since the high degree of sweepback present on many high speed aircraft would facilitate removal, there is some merit in it. For an action of this nature to be practical, however, the leading edges of the aircraft would have to be smooth and free of boundary layer fences, gun ports, tip tanks, etc. No system was conceived in the study which could overcome this basic difficulty.

1. Explosives

Crude experiments performed in the course of this study indicated the possibility of removing ice from fixed surfaces by subjecting it to an explosive shock. This shock could be generated from the detonation of some sort of miniaturized "prima cord" contained in a pressure-sensitive tape with an electrically operated detonator. Many variations on the above principle are possible. For instance, it is possible that the explosive could be impregnated in a lacquer-like coating or sandwiched between two thin plastic sheets. Greater reliability could be achieved by the use of redundant elements.

While this type of one-shot removal has considerable promise, it might have to be restricted to thick-skinned surfaces. It is expected that the explosive strip would require some development to obtain a safe, reliable element although there is a possibility that the state of the art is sufficient to easily solve a problem of this nature. Further testing would be necessary to establish this method of ice removal because of the large number of variables that must be examined and evaluated.

2. Inflatable Boot

A one-shot expendable rubber boot is shown in figure 21 affixed to an airfoil leading edge. In practice, it would only be attached at the trailing edges by a light adhesive. Upon inflation, the tube would pull loose in the manner shown and thus be removed along with any accreted ice by the slipstream.

Several means of inflating the tube are conceivable. For instance, an electrically initiated gas-generating chemical charge, a small air or carbon dioxide bottle, or a connection to the airframe pressure system.

Weight estimates of this system are given in table 3. Since this concept is an original one, actual tests would be necessary to establish its performance. Two points in particular should be investigated: the tendency of the boot to "lift" from the upper surface at the minimum surface pressure point and the time required for the boot to inflate and shed when actuated.

3. Sheddable Leading Edge Coatings

Several methods can be employed to shed leading edge coatings in addition to those mentioned above. The choice of a method is generally closely keyed to the sheddable material and so will be discussed in that light.

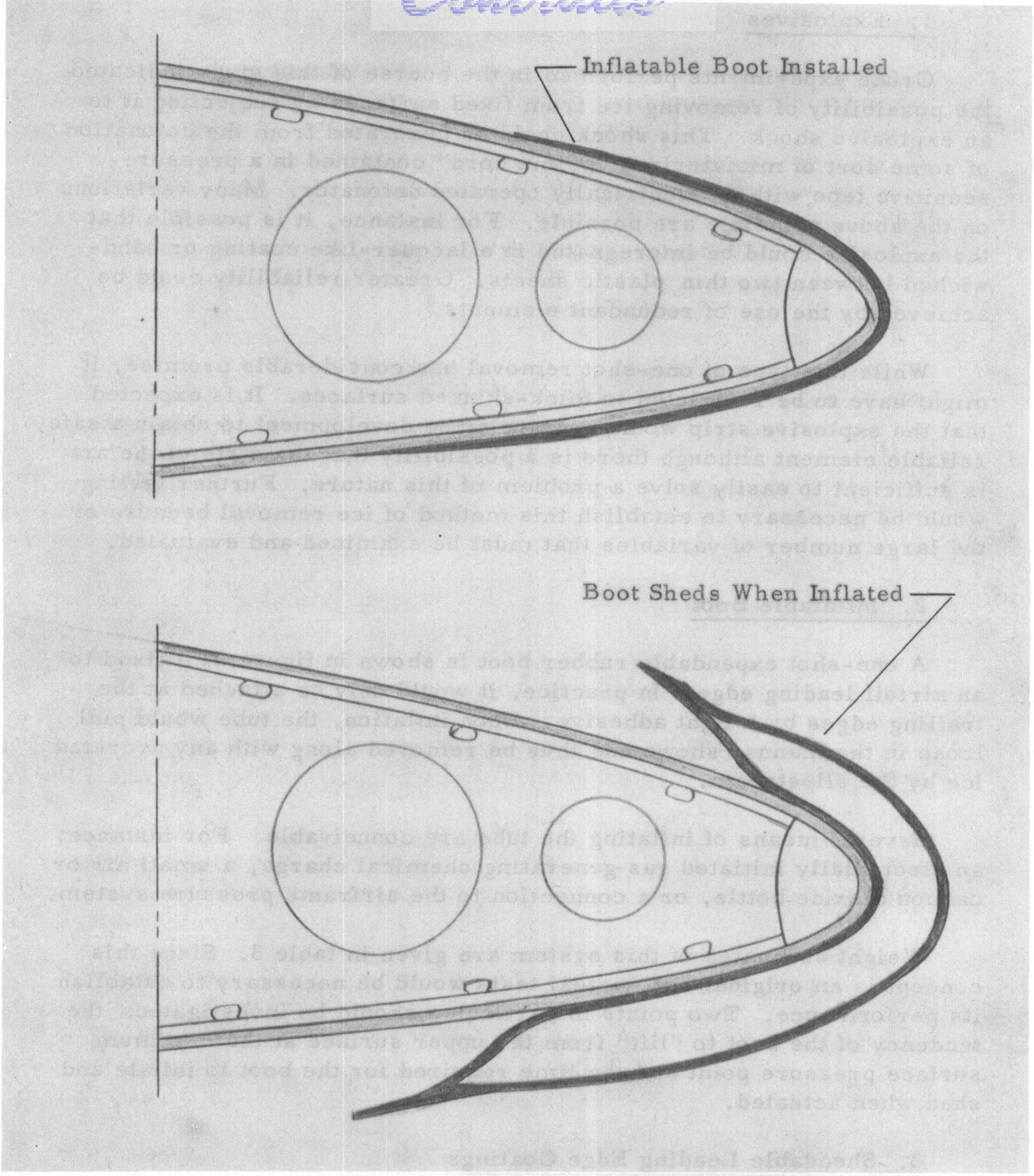


FIGURE 21: INFLATABLE BOOT

Frangible coatings which could be fractured and shed to remove accretions of ice could be utilized where the coating is either a thin sprayed film or a molded section shaped to fit the contour of the airfoil. They should be glass-like substances of low impact strength and low weight for this purpose. The polystyrene and polyester plastics have applicable properties which can be improved (in this sense) by the elimination of the plasticizer from the compounds. Fracture or "blow-off" of the coating could be accomplished mechanically or with light explosives. The latter offers the greatest simplicity and weight savings.

The primary disadvantage is the change in airfoil contour, particularly in the case of pre-shaped sections. Conceivably, this fault might be used to advantage by modifying the airfoil for better take-off and climb characteristics. Advantages include ease of adapting the system to a previously unprotected airframe, small initial weight and positive removal of ice. No attempt is made to evaluate the system further except to estimate its weight penalty. These values appear in table 3.

Sprayed strippable films, similar to those used commercially for surface protection, are particularly adaptable to the one-shot concept. These may be obtained in vinyl, rubber-based compounds, and even Teflon. They would be capable of being applied to complex surfaces without wrinkling and would constitute a minimum corruption of the aerodynamic profile. Generally speaking, the adherence of these materials is sufficiently low that they will strip off in a large sheet rather than tear.

A sprayed film could be shed either by the explosive or inflatable boot described previously and would serve to protect those elements before use while increasing the extent of protection when shed. It could also be shed by a wire in the manner shown in figure 22 which would break the ice cap in addition to severing the film or by a cutting tool pulled spanwise under the film by a wire.

Such coatings should be particularly useful in practice. It would, however, be necessary to verify their performance with suitable tests before reaching any final conclusions.

Adhesively applied films would function in the same manner as the strippable films and are available in a great variety of materials. For instance, vinyl, Polyethylene, Teflon, aluminum, rubber, and other materials would be suitable. Such films may be found coated with heat-, pressure-, and chemical-sensitive adhesives.

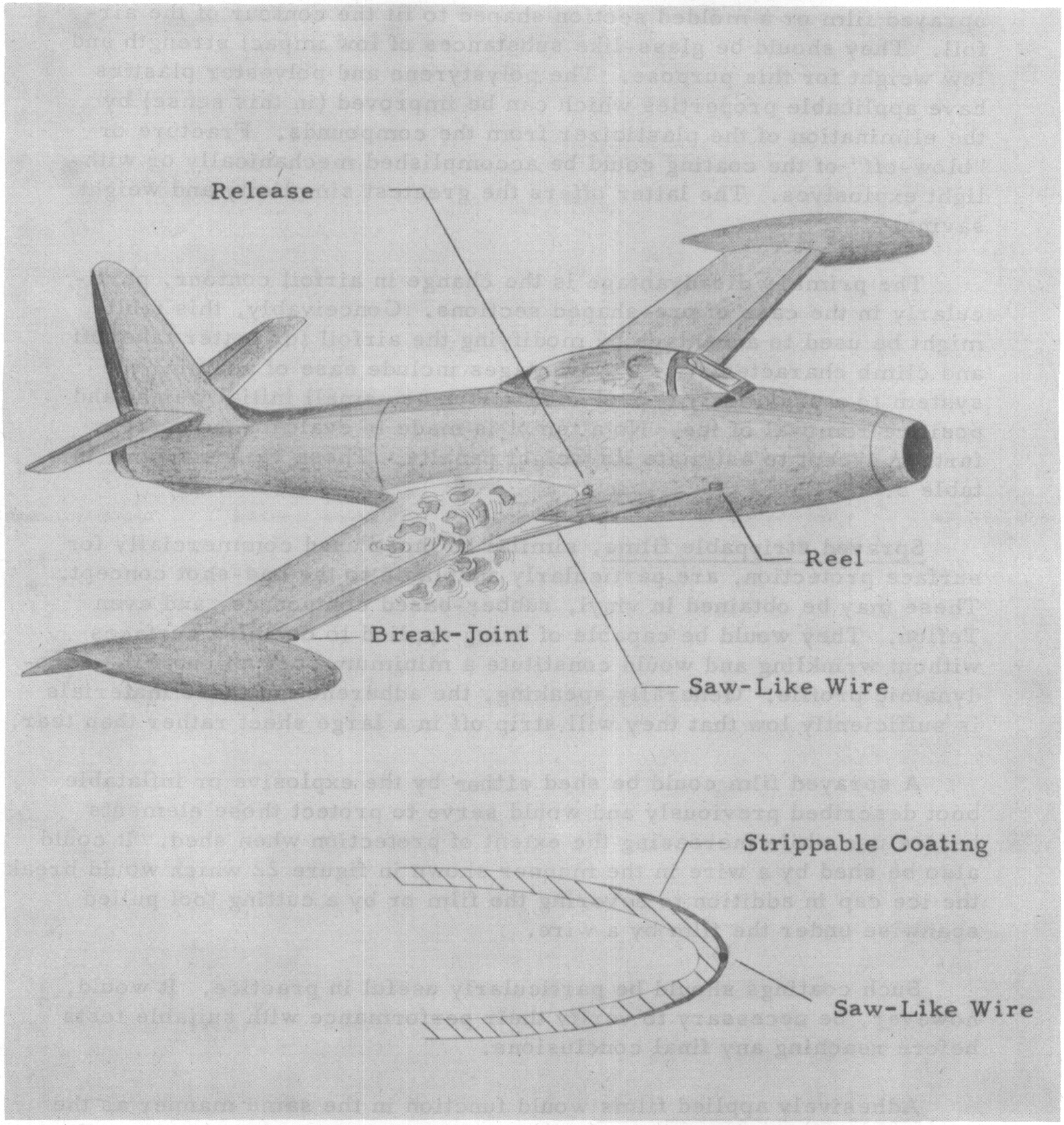


FIGURE 22 STRIPPABLE COATING ON LEADING EDGE

TABLE 3
ICING PROTECTION SYSTEM CHARACTERISTICS "ONE SHOT"

SYSTEM	Initial Installed Weight To Modify Airfoil (lbs/ ft of span)		Fixed Installed Weight Not Part Of Airfoil (lbs)		Expended Weight Of Materials (lbs/ft of span)		Net Weight (lbs)				REMARKS
							Fighter		Bomber		
	Fighter	Bomber	Fighter	Bomber	Fighter	Bomber	Initial	Final	Initial	Final	
Frangible Leading Edge	0	0	3.0	5.0	1.57	4.7	69.2	3.0	653.3	5.0	Frangible Material 0.10 thick 94 lb/ft³
Strippable Coating	0	0	7.0	10.0	0.8	2.4	36.5	7.0	324.0	10.0	Saw-Like Wire For Removal
Ballon Type Expendable Boot	0	0	15.0	40.0	0.97	2.91	50.0	15.0	420.0	40.0	
False Leading Edge Shed By Expanding Boot	0	0	15.0	40.0	2.05	5.18	89.0	15.0	713.0	40.0	Alum Foil LE, Wt 0.1132 lb/ft²
De-Icing With Explosives	0	0	3.0	5.0	0.16	0.49	5.87	3.0	63.7	5.0	
Expendable Leading Edge Shed By Explosives	0	0	3.0	5.0	0.24	0.72	11.7	3.0	99.5	5.0	Alum Foil LE, Wt 0.1132 lb/ft²
Leading Edge Covering Shed By Burn-Off Element	0	0	5.0	10.0	0.23	0.27	13.6	12.92	46.0	38.6	Generator Weight Not Charged To System

The same shedding means are advocated here as above. It must be noted, however, that a careful study would have to be made of the adhesive strength since this has a close relation to the ease of shedding. The usual effort is to manufacture as strong an adhesive as possible. In this case, an adhesive of limited strength would be required which would be relatively unaffected by temperature, humidity, etc.

C. Limited-Duration Systems

Limited-duration systems increase the degree of protection over one-shot systems by allowing more than one ice removal. They are generally intended for piloted aircraft which may operate in icing conditions for a limited length of time or be exposed to icing atmospheres more than once in a single flight. Protection may be achieved by either a de-icing or an anti-icing action as defined in section I. Systems of this type may be expected to be characterized by various types of expendable energy sources and mechanical ice shedding devices which function a limited number of times. Several such systems are described below.

1. Mechanical Systems

Simplified expandable boots (see section II) may be inflated from a compressed air bottle or a chemical gas generator to attain limited-duration icing protection. This system is attractive for missiles where a convenient energy source is not available or for high performance aircraft where simplified piping and control might result in weight savings. For boots to be useful in an application of this nature, they should not add appreciably to the drag during non-operating periods. (It appears that the drag increase would be low at subsonic speeds.) An estimate of weight penalties using a compressed air bottle for four applications is given in table 4.

One-shot systems employing strippable films might be converted to a limited-duration system by using several layers. Shedding one film at a time would be the most difficult problem. The saw-like parting wire shown in figure 22 might be employed where a separate wire is used for each layer, although this would tend to defeat the inherent simplicity of the system. A better arrangement would consist of separate layers, each of which is shed by a separate explosive strip. Undoubtedly, it would be necessary to carefully regulate the detonating force to where it would shed the outermost layer without damaging those underneath. The release devices presented herein are not ideal. It is believed that a design program would provide several practical methods of shedding multi-layer films.

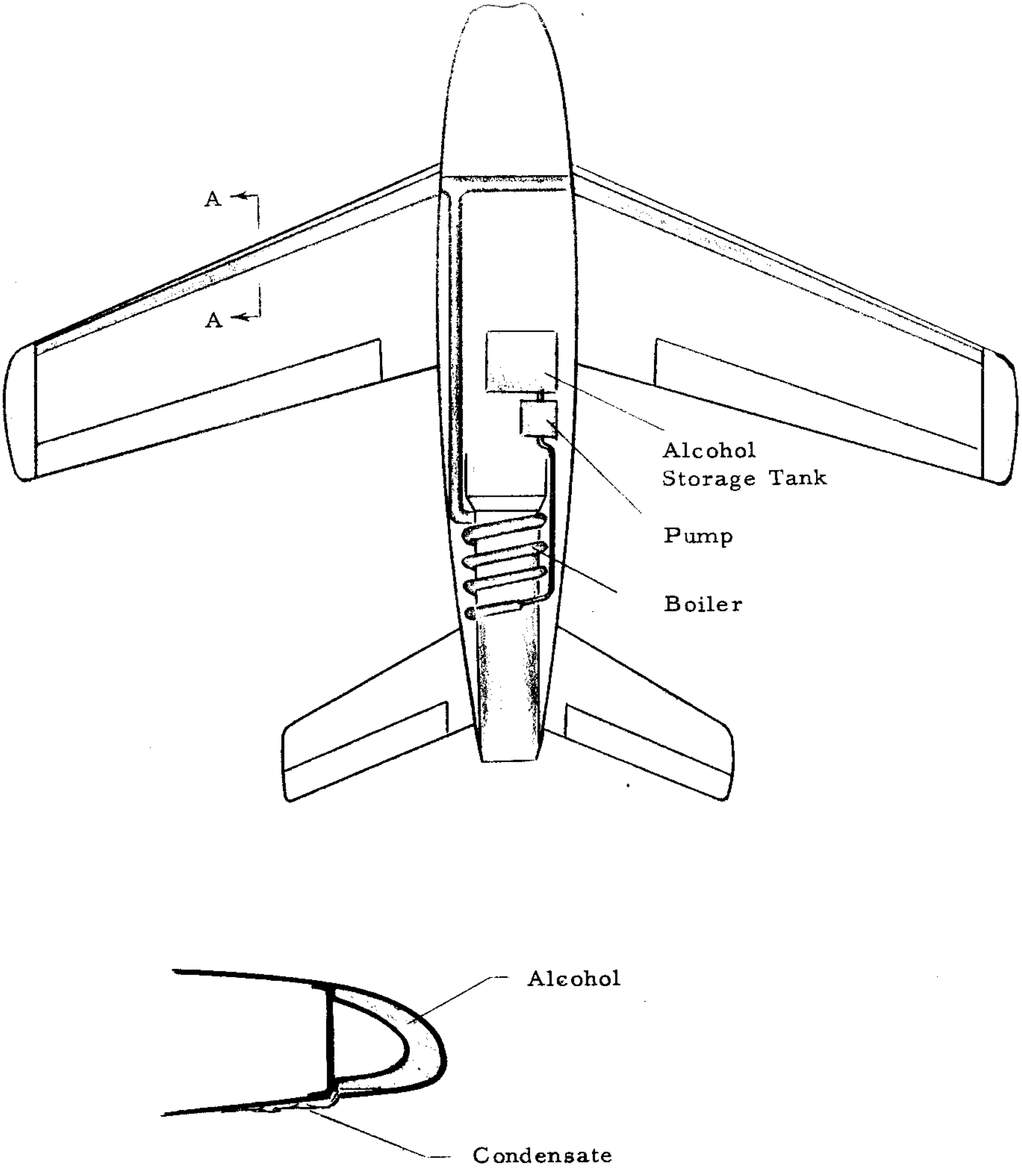
2. Electrical Systems

The use of limited-duration electrical power sources, such as batteries or JATO-actuated generators which could be jettisoned also appears possible. The surface could be heated by sprayed-on electrical elements to present a minimum fixed weight once the heavy exhausted power source was dropped. This system might be practical on missiles for short-term protection where no ready source of electrical power is available. JATO-actuated electrical generators are not known to be available as yet. However, high capacity, low-weight batteries, as described in section II, do exist. A cyclic system would be the best action with its minimum runback, although some complexity exists in the cycling controls. The weight of a cyclic system employing a battery power source is given in table 4 for three minutes' protection, based upon the specifications given in reference 15. For purposes of calculation, the heating area was divided into one-foot cyclic segments covering the impingement zone, separated by one-inch parting strips. A density of 30 watts/inch^2 with a heat-on time of 10 seconds (90 seconds off) was used for cycled zones. Parting strips were operated continuously at 13 watts/inch^2.

3. Vapor Heating Systems

Limited-duration vapor heating systems may be considered using ethyl alcohol as a heat transfer medium. As shown in figure 23, the system consists of a storage tank from which the alcohol is pumped to a boiler located around the exhaust pipe. From the boiler, the alcohol vapor is piped to the icing surfaces, condensed to release its latent heat, and exhausted to the exterior of the surface. This method has been studied previously in references 28 and 29.

Two cases are investigated: a dry evaporative impingement zone and a running wet impingement zone. The heat requirements used are based on an altitude of 10,000 feet, a velocity of 325 knots, a liquid water content of 0.99 gm/m^3 and an exposure time of 10 minutes. The case of dry surface anti-icing proves to be prohibitive. The weight of alcohol carried alone is 397 pounds for the fighter and 1690 pounds for the bomber. The case for wet surface anti-icing is more promising. The weight of alcohol for the fighter is about 100 pounds and for the bomber, about 500 pounds. The weight of the heat exchanger is approximated from equivalent standard units to be about 30 pounds for the fighter and 100 pounds for the bomber. It is possible that the condensed alcohol could be exhausted in such a manner as to provide some freeze-point depressant protection for the after surfaces.



Section A-A

FIGURE 23 VAPOR HEATING SYSTEM

The total installed and operating weights are given in table 4. While it was originally felt that vapor systems showed some promise, in practice several disadvantages are apparent, such as the high installed weight, system complexity, and the potential fire hazard.

4. Fluid Freeze-Point Depressant Systems

Fluid freeze-point depressant protective systems are essentially of limited duration depending upon the quantity of fluid carried. One method of distributing this fluid is to exude it through a porous or perforated leading edge so that the depressant mixes with impinging water and lowers the freezing point of the resulting mixture below the surface temperature as described in section I. The porous panel need not extend over the entire impingement area since the mixture will run back to the after surfaces and neutralize the after impingement (see reference 30). A distributor of this type may either be fit into the leading edge at manufacture as shown in figures 24a and 24b or it may be mounted externally as shown in figure 24c. The external distributor, while possessing some advantage, must necessarily balance the fluid passage requirements against the allowable drag caused by the distributor protuberance. It is likely that a distributor similar to that shown in figure 24c could not service a long span unless several fluid feeder points were established along its length which would, more or less, defeat its purpose. Such distributors could incorporate any of the porous materials described in section II or they could be constructed of materials perforated with small holes.

The amount of fluid required for a particular encounter depends upon the rate of water catch, surface temperature, altitude, and characteristics of the fluid. Figures 12 and 13 indicate the amount of fluid required for the hypothetical fighter and bomber. The method used in calculating the fluid requirements is given in appendix IV.

The fixed weight and performance penalty compared with other systems is shown in table 4. While very low installed weights and no performance penalties appear to characterize this system, there are several operational problems associated with it. For instance, the amount of fluid actually required to protect a surface may be more than twice the theoretical requirements because of poor mixing at the icing surface and because the fluid film tends to break into rivulets at some minimum film thickness (reference 31). Thus, the amount of fluid required to protect the after surfaces is based somewhat on mechanical considerations. There is usually some clogging of porous leading edges both from impurities in the fluid system and from atmospheric contamination. Insufficient data are available at this time to predict the severity of this problem. In spite of the above considerations, simplified fluid systems appear to have promise because of their low penalties and because aerodynamic heating effects tend to minimize the fluid requirements.

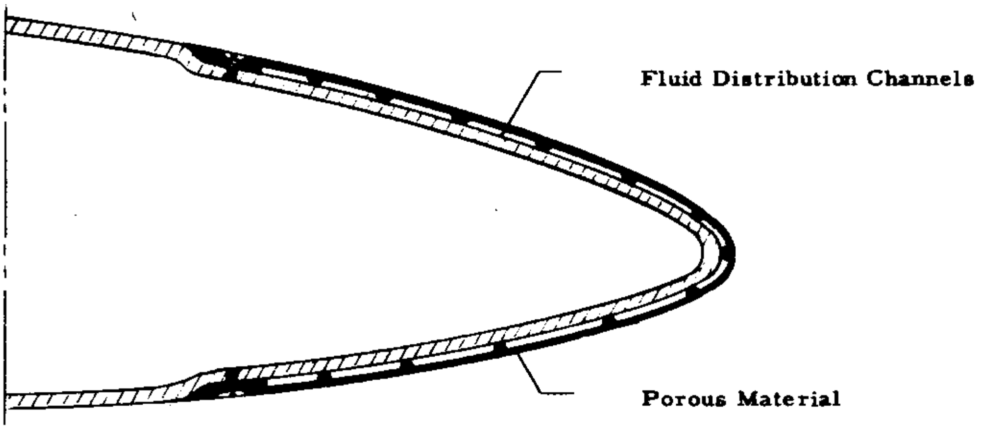


FIGURE 24a: FLUSH PLASTIC DISTRIBUTOR

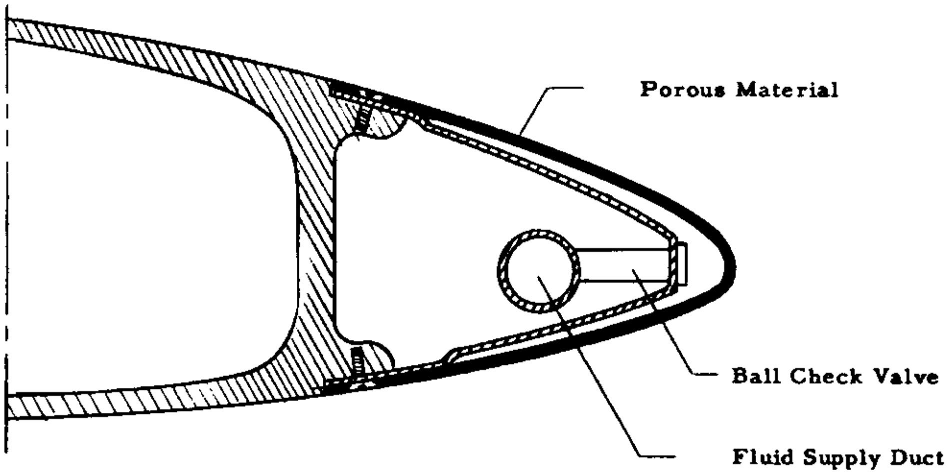


FIGURE 24b: PRESSURE-REGULATED DISTRIBUTOR

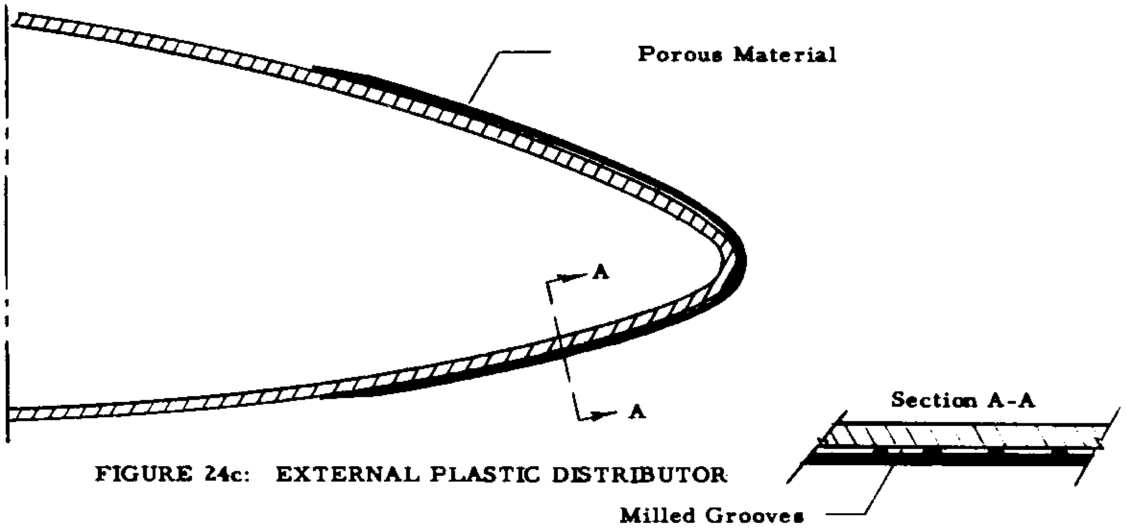


FIGURE 24c: EXTERNAL PLASTIC DISTRIBUTOR

FIGURE 24 FREEZE-POINT DEPRESSANT DISTRIBUTORS

TABLE 4
ICING PROTECTION SYSTEM CHARACTERISTICS "LIMITED DURATION"

SYSTEM	Duration of Protection or Number of Applications at 0°F LWC = 0.99 gm/m³				Fixed Installed Weight to Modify Airfoil (lbs/ft of span)		Fixed Installed Weight Added to Fuselage (lbs)		Expendable Weight of Materials at 0°F LWC = 0.99 gm/m³ (lbs)				Maximum Net Weight (including expendable materials) (lbs)		Reduction in Thrust at 0°F LWC = 0.99 gm/m³		REMARKS
	Fighter		Bomber		Fighter	Bomber	Fighter	Bomber	Fighter		Bomber		Fighter	Bomber	Fighter	Bomber	
	325 k	130 k	200 k	130 k					325 k	130 k	200 k	130 k					
Boot Inflated From Compressed Air Bottle	4 App	4 App			1.0		5.0		153	153			194		0	0	Air stored at 2200 psig
Several Layers of Strippable Films	4 App	4 App	4 App	4 App	0	0	15.0	50.0	1.6	1.6	4.8	4.8	63.0	673	0	0	Using Saw-Like Parting Wire
Electrical De-Icing Using Limited Power Sources	3 Min	3 Min	3 Min	3 Min	0.38	1.14	105.5	916	298	298	1685	1685	416.8	2749	0	0	"Sivercell JSB" Battery Power
Vapor Heating System	10 Min	10 Min	10 Min	10 Min	4.48	3.08	100	500	397	202	1690	1270	657.0	2590	Neg	Neg	Evaporative Anti-Icing
Fluid Freeze Point Depressant System	30 Min	60 Min	30 Min	68 Min	0.381	0.773	17.4	34.8	0.045 lb/min per ft	0.023 lb/min per ft	0.058 lb/min per ft	0.026 lb/min per ft	79.8	361.8	0	0	Ethylene Glycol De-Icing Fluid
Ammonia Gas De-Icer					2.0	5.95									0	0	Qty Req & Wt of Storage Unknown

5. Gaseous Freeze-Point Depressant Systems

Reference 32 describes a windshield de-icing system tested by the Germans during World War II which used ammonia gas to melt ice. The system was based on the observation that ice melts rapidly on contact with ammonia gas and that the freezing point of water completely saturated with ammonia is -145 °F. In this system the gas was stored under pressure in the liquid state and applied to the windshield by a light metal tubing with small holes drilled along its length to serve as discharge nozzles. A 5-second discharge was stated to be sufficient to clear the windshield completely.

No data are available as to the amount of gas that would be required for a large surface and it is felt that an estimate might be misleading. Disadvantages are inherent in the relative corrosiveness and toxicity of the gas.

D. Continuous Systems

Continuous systems are capable of ice removal or prevention protection throughout an entire mission. Almost all of the systems in use today are of this type. Since these are well known as a whole, they will only be described briefly below. In addition to the common systems, a number of unusual approaches gleaned from the literature are presented and discussed. The weight and performance penalties of these systems are evaluated in the section devoted to partial systems.

1. Mechanical Systems

Conventional inflatable boots, described in section II, remove ice by deformation of the ice adhesion surface. A simple pneumatic system supplies air to these boots in a cyclic fashion. References 22 and 23 describe these systems in detail. Reference 33 describes a boot that may also be used to modify the aerodynamic surface.

The primary disadvantage of pneumatic boots is incomplete removal of residual ice. The overall system is reliable and of low weight. In addition, the leading edges of the airframe are protected against abrasion, etc.

The "shoe shine" de-icer discussed in reference 34 consists of a very thin (0.005 in.) stainless steel sheet covering over the leading edge of a structure. It sheds ice by reciprocating chordwise around the leading edge as shown in figure 25. The high heat conductivity of the thin metal shell is said to allow rapid freezing which results in a less tenacious ice formation. Aside from mechanical difficulties (which are considerable), this system appeared promising although no flight tests are known to have been made by the agency that developed it.

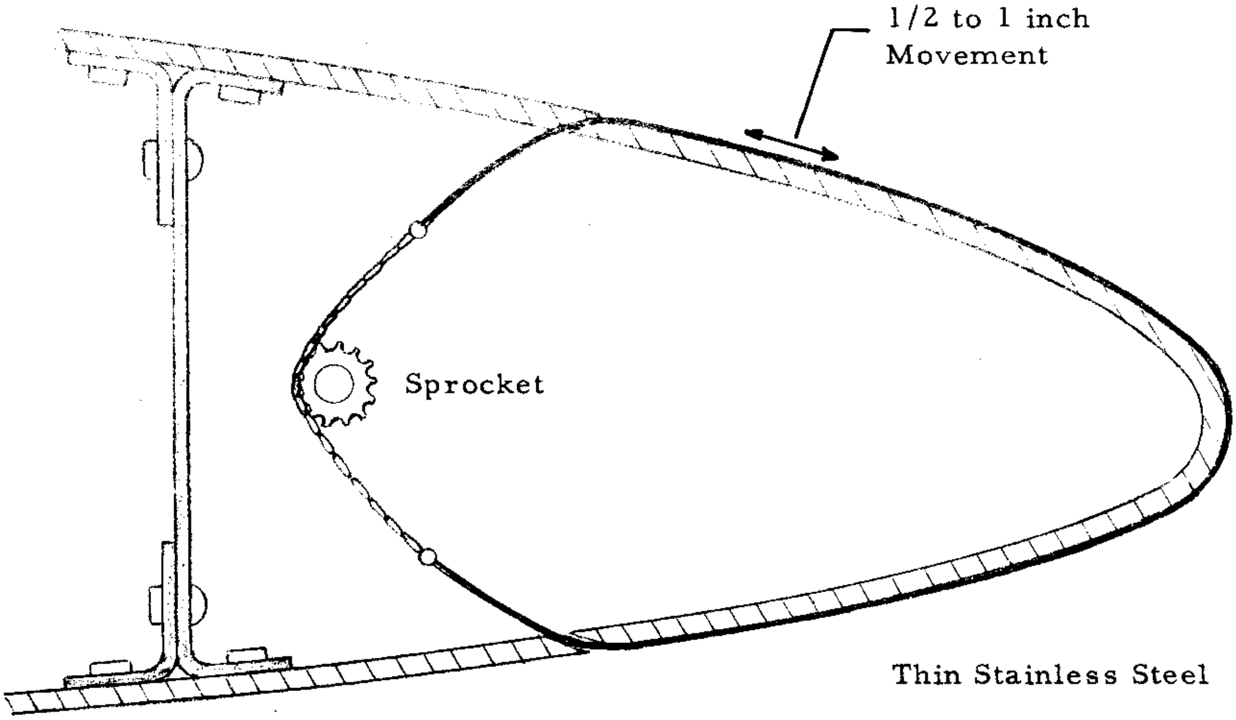


FIGURE 25 "SHOE-SHINE" DE-ICER

Miscellaneous mechanical ice breakers are described in the literature (references 35, 36, and 37 are typical examples) in considerable number. The mechanical difficulties involved in all the known systems of this sort appear to be almost insurmountable for present-day aircraft.

2. Electrothermal Systems

Icing protection may be achieved by electrothermal means utilizing electrical resistive heaters bonded to the exterior of the icing surface and powered from the aircraft electrical system. Several heating pads are described in section II. High temperature radiant heating elements are also available but must be considered impractical for most installations because of the fire hazard and the inefficient distribution of energy. Any of the ice removal or prevention actions described in section I may be achieved by electric heaters although the power requirements for evaporative anti-icing are so severe that it has never been attempted for a large surface. Although running wet protection of the impingement area is practical with electrical heaters, cyclic de-icing protection is usually associated with electrothermal systems.

Generally, electrical systems are characterized by fairly large generator installations which greatly increase the specific fuel consumption when used, although the net reduction in thrust is nil for typical turbojet engines (see section II). Some fire hazard exists and the relative system complexity is high.

3. Conventional Heated Air Systems

Systems employing continuous heated gas flow through surface heat exchangers are well established. Hot air is normally used. It may be obtained from combustion heaters, jet engine compressor bleed, or exhaust gas heat exchangers as enumerated in section II. In use, the heated air imparts its energy to a heat exchanger built into the impingement region of the icing surface (several exchangers are described in section II) and is exhausted eventually into the atmosphere. The rate of heating is dependent upon the airflow, the temperature of the air and skin, and the exchanger configuration. The heat requirements of the hypothetical fighter and bomber for running wet and evaporative impingement areas are given in figures 8 through 11. Matching airflow requirements for an intermediate condition appear in figures 18 and 19.

These systems have the advantages of being light weight, reliable, and requiring a minimum of maintenance. Further, they are established by long use.

Because of the limited space available in modern high performance aircraft, a serious disadvantage in air systems lies in the size of the supply ducts required. Severe icing requirements or low energy air supplies intensify the problem. Numerous solutions have been proposed, such as augmentation by tail pipe heat exchangers, compressor bleed combustion heaters, electric elements, and, more recently, combustion chamber bleed air. These are covered in other sections.

Cyclic hot air systems have been tried experimentally to reduce gas flow requirements. Reference 38 describes these tests but recommends simpler controls to reduce weight and complexity. Generally, the installed weight is higher with air cyclic systems although thrust penalties are somewhat reduced.

A porous bleed system utilizing hot gas flow through the surface has been tested by an airframe manufacturer as a means of increasing the effective heat transfer to the icing surface. A relatively high efficiency was claimed for the system. One of the primary problems with the system consisted of properly regulating the flow through the skin over the leading edge area since the external skin pressure has a tangible effect on the flow through it.

4. Novel Heated Air Systems

Running wet systems may be considered on a continuous basis if some means of dealing with the runback is available. One method of removing runback is to incorporate suction slots in the wing aft of the primary impingement zone (figure 26) that would collect this water and discharge it at some convenient point. The slots and collection channels would, of course, require heating. A tail pipe eductor or individual eductors at surface extremities might be used to supply the necessary suction. Surface heating could be achieved by any of the appropriate methods discussed elsewhere in the report.

Preliminary calculations indicate that approximately 3.5 horsepower would be required to maintain a one-pound pressure differential (not including pipe friction losses) across a 1/16-inch slot spanning the wing of the hypothetical fighter. Porous metal specifications show that a skin of 40-micron permeability covering a channel 0.3-inch wide would require the same power. The greater area of the porous insert would be more efficient in removing runback and also act to filter out objects which might otherwise obstruct an open slot.

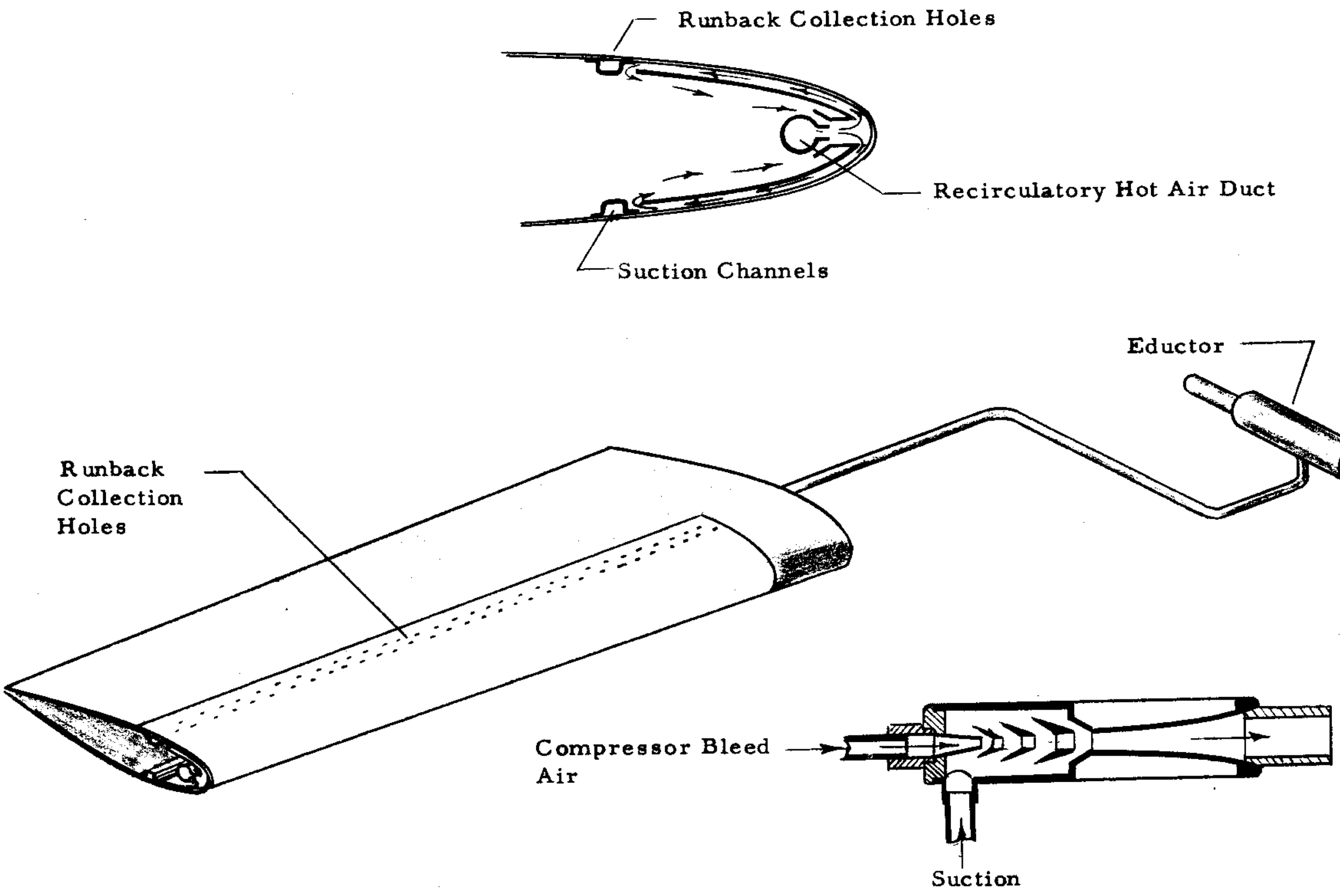


FIGURE 26: RUNNING WET SYSTEM EMPLOYING RUNBACK COLLECTION

One of the difficulties inherent in a compressor bleed type of anti-icing system is that a reduction in thrust is experienced during the icing penetration resulting in a much reduced rate of climb. The system illustrated in figure 27 could help to alleviate this condition. An electrically heated parting strip is used to prevent a difficult-to-shed ice cap from forming over the leading edge during the climb. Once operating altitude is achieved, the surfaces would be de-iced by a pulse of compressor bleed air. Any simplified form of surface heat exchanger would suffice for this purpose.

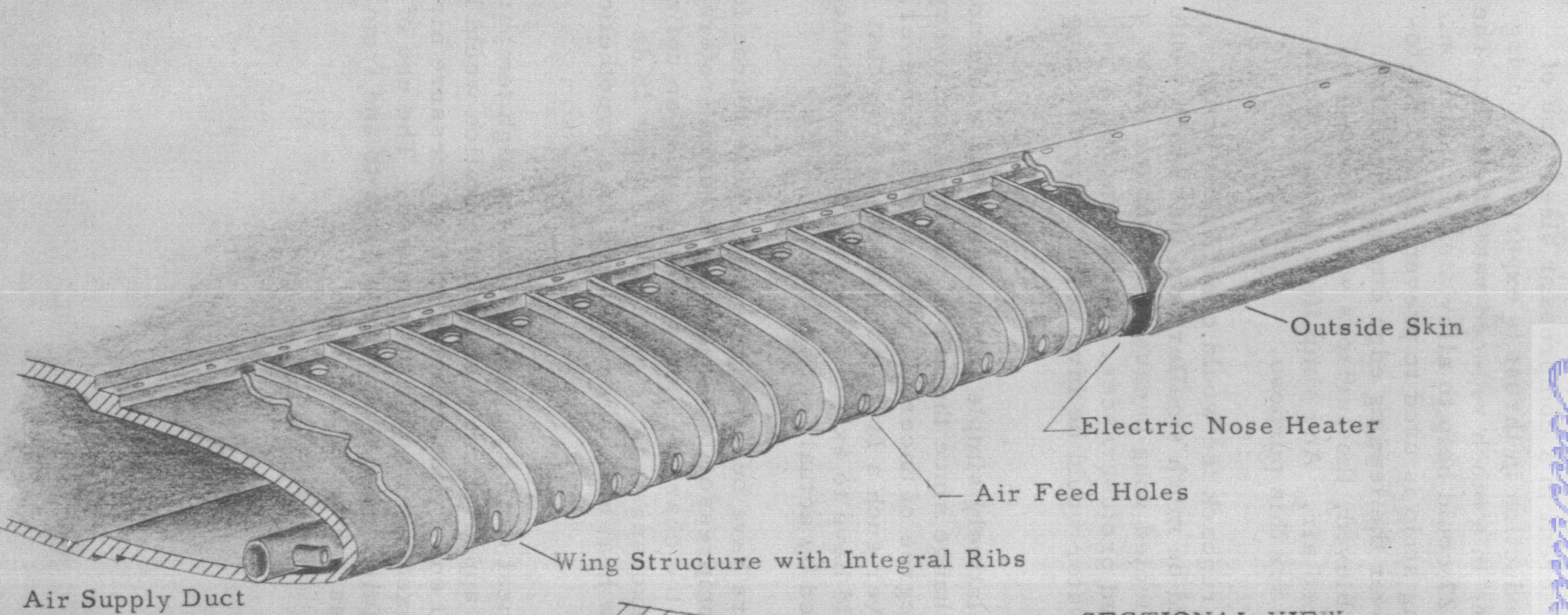
While it is true that the runback ice would constitute a drag increase, this increase would be much smaller than that which would be associated with the unprotected wing because the runback tends to freeze in the form of faired protuberances. Furthermore, a relatively small amount of water would be involved in a typical icing penetration (see figure 1).

The system would be relatively simple to construct and would not require an efficient heat exchange since the air is required for a very limited period of time. A degree of uncertainty is present, however, in that the runback might cover such a large portion of the wing that the air de-icing system would have to extend aft a prohibitive distance. This could best be determined by actual testing.

Tail pipe heat exchangers have been proposed as a heat source for de-icing using ram air or compressor bleed air as a medium (reference 18). Reference 39 presents the characteristics and output of an unfinned parallel-flow tail pipe heat exchanger using ram air. Figure 28 depicts a six-foot parallel-flow heat exchanger installed on a hypothetical jet engine.

Undoubtedly additional heat can be obtained from the high temperature potential of the tail pipe. It appears that such a configuration would be most useful where additional energy is imparted to high pressure air even though a heavier heat exchanger would be required. The use of ram air, for instance, would require excessively large ducts to and from the exchanger. Weight estimates are given in table 5.

PERSPECTIVE VIEW



SECTIONAL VIEW

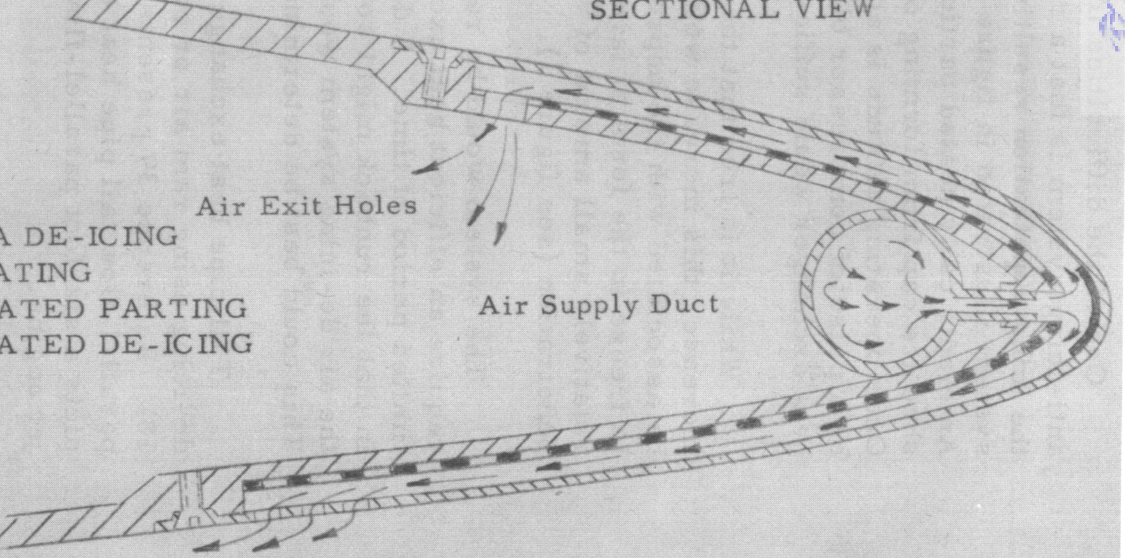


FIGURE 27 ILLUSTRATION OF A DE-ICING SYSTEM INCORPORATING ELECTRICALLY HEATED PARTING STRIP WITH AIR HEATED DE-ICING SURFACES

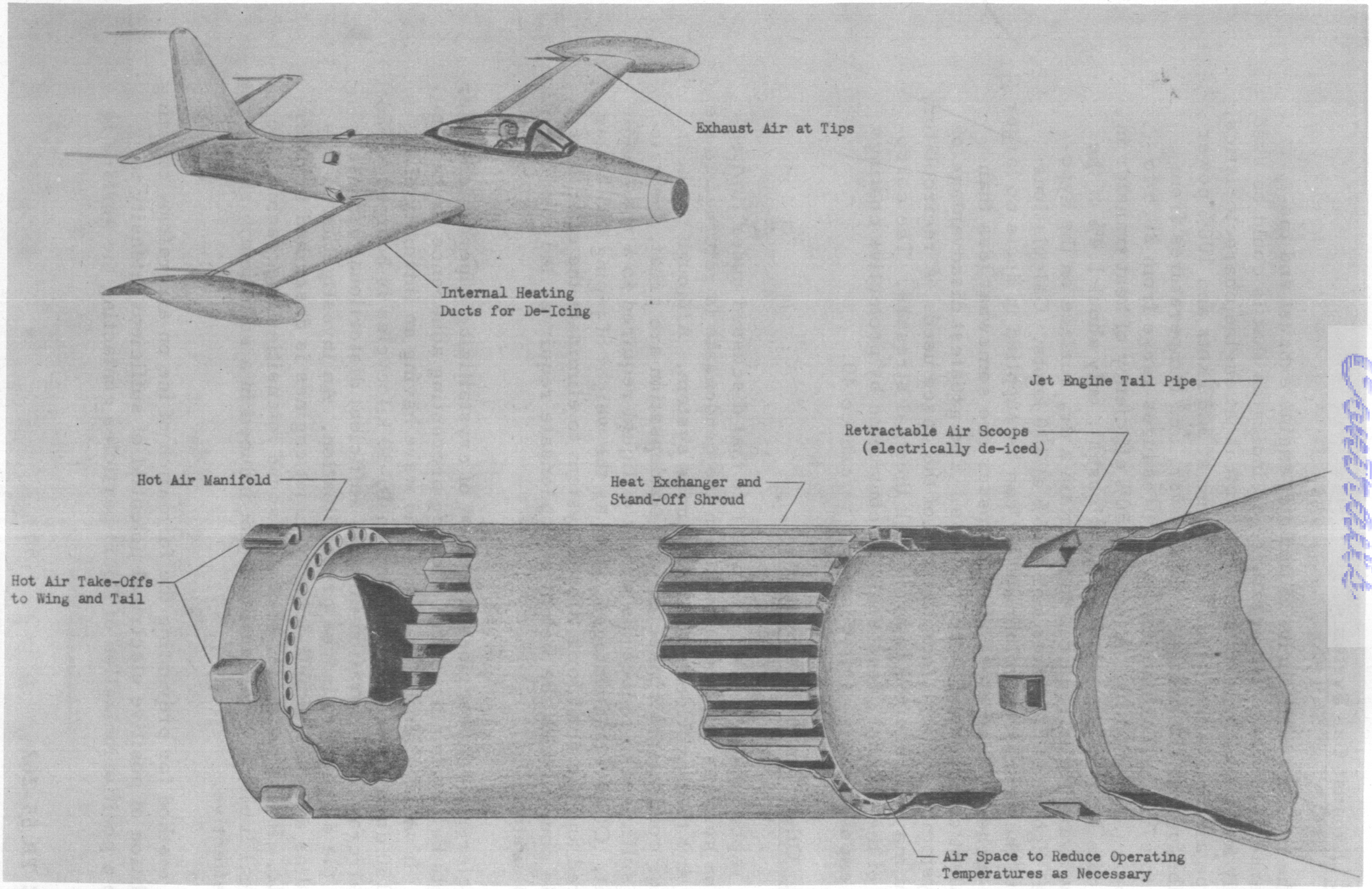


FIGURE 28 CONTINUOUS TYPE DE-ICING SYSTEM EMPLOYING JET ENGINE TAIL PIPE HEAT EXCHANGER

5. Exhaust Gas Systems

The relative high purity of turbojet engine exhaust and the abundance of this high temperature gas indicates that is could be used directly for anti-icing. Based upon typical jet engine characteristics, tail pipe airflow varies from 73 lbs/sec at 325 knots and 100% power to 53 lbs/sec at 130 knots and 80% power, and temperatures from 1070° to 670°F. Turbine discharge pressures range from 26.5 to 16.3 psia (at 15,000 ft). Assuming 50% efficiency of heat transfer in the double skin (neglecting pressure losses), only about 1.4% of the airflow available is required to maintain a dry surface on the hypothetical fighter at 325 knots and 1.55% at 130 knots. Calculations indicate the necessary volume of air can be supplied in ducts no larger than 6 inches in diameter. Thrust losses are somewhat less than equivalent compressor bleed systems. The greatest disadvantage of this system is the high temperature of the gases used. A recirculatory system may be required to avoid high thermal stresses. The corrosivity of the exhaust gases could be controlled by protective coatings on all exposed parts as discussed in reference 40.

6. Other Continuous Systems

A vapor heating system, similar to that discussed under limited-duration systems is possible wherein the condensate is returned to the boiler and thus provides for a continuous system. Although the heat transfer coefficients connected with condensation are great, the rate is not sufficient to reduce the weight of liquid required to a reasonable amount. Other disadvantages, such as the weight of piping and boiler required and the need for a closed system to eliminate the effects of altitude coupled with the weight of condensate required, led to elimination of this system.

Reference 41 describes a method of crystallizing supercooled water droplets before impingement, thereby preventing adherence to the aircraft. It was claimed that, if a sound wave having an intensity of at least 150 db and a frequency between 15-30 kilocycles is beamed ahead of an aircraft, the vibration imparts sufficient distortional stresses within the droplets to induce crystallization. An investigation of this method as a means of anti-icing turbojet engines is described in reference 42. It was concluded that with sound intensities approaching the practical limit, crystallization is not induced in a sufficiently short time to be effective.

A method for preventing the formation of ice on aircraft by creating a condition of positive electrical potential of sufficient intensity to induce a positive ionization of liquid particles contacting the surface is described in reference 43. It is claimed that the water will not freeze on this ionized surface. This also has been disproved through experiments conducted in reference 44.

5. Partial Protection Systems

Partial systems as defined in section I afford less than total protection for icing surfaces while still maintaining adequate protection for safe operation of the aircraft. Since only critical areas are considered under this philosophy, whole icing surfaces may be unprotected as well as the non-critical portions of other surfaces. Critical areas may be defined for the purposes of this report as those areas upon which ice accretion will cause large increases in drag, decreases in lift, or will greatly magnify the problems of stability and/or control.

Since partial protection may be achieved by any type of action or system, any of the systems covered previously may be considered. Table 5 presents tabulations of continuous protection penalties and requirements for the entire impingement area of the icing surface. For purposes of rough estimation, the weight and thrust penalties of these partial systems may be obtained by taking a simple proportion of the energy requirements and penalties for the fully protected surface.

Some data have been made available in reference 45 on the drag increases caused by icing of various portions of a straight winged aircraft (B-25 bomber). Figure 29 shows that the largest single drag increase may be attributed to the outboard wing panels. Since stall characteristics are most affected by these areas, it would appear that these are most critical. The empennage is presented as a total drag. It may be reasoned that the horizontal stabilizers are next most critical; the vertical stabilizer is operating at zero angle of attack and does not affect the longitudinal trim of the aircraft. The inboard wing sections do not appear critical for this aircraft. The drag percentage due to miscellaneous components must be reduced for modern aircraft because they are aerodynamically cleaner than those of World War II.

Partial area protection may be expected to affect ice accretion in the manner illustrated in figure 30. The drag increases associated with such protection may probably be estimated within an order of magnitude accuracy by a method presented in reference 46. A composite figure illustrating the effect of a straight-edged protuberance on the section drag coefficient of an airfoil is plotted in figure 31 from data presented in the above reference. Since the data are presented for a 12% unswept airfoil and the hypothetical interceptor has an 8% swept wing, a

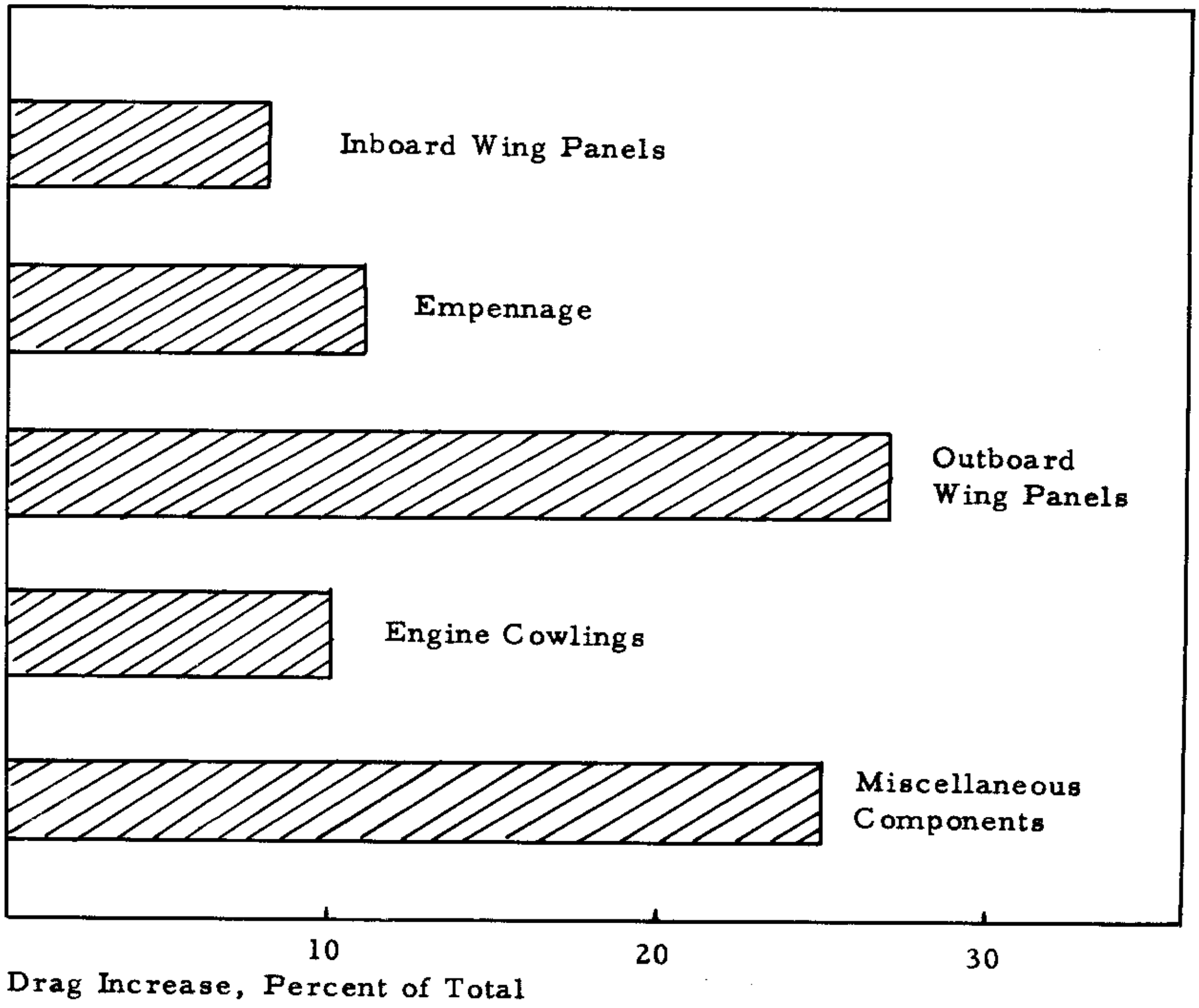
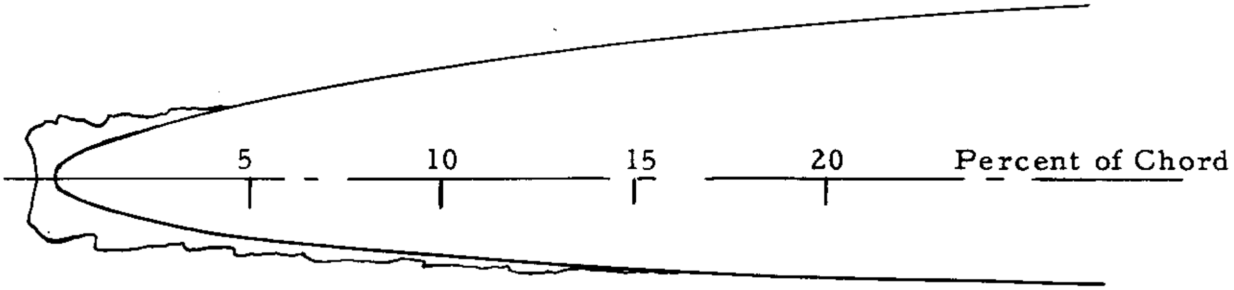
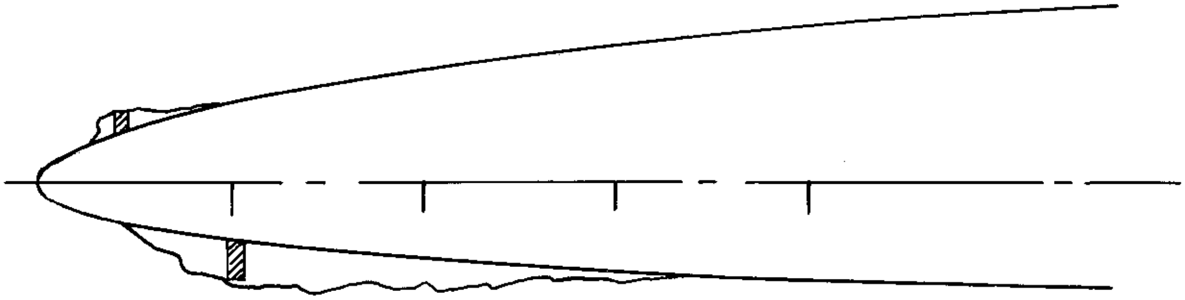


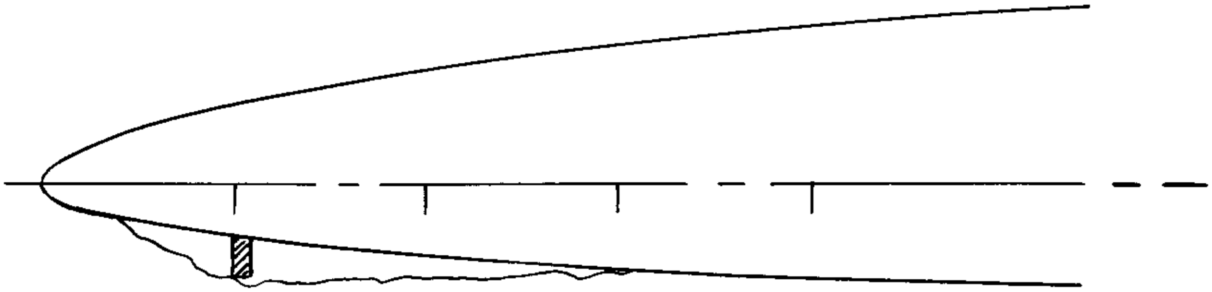
FIGURE 29 DRAG INCREASE DUE TO ICING OF INDIVIDUAL COMPONENTS OF A B-25 AIRCRAFT



(a) No Protection



(b) Leading Edge Protection Only



(c) Leading Edge and Upper Surface Protection Only

FIGURE 30 TYPICAL ACCRETION PATTERNS FOR A PARTIALLY PROTECTED 8 PERCENT AIRFOIL

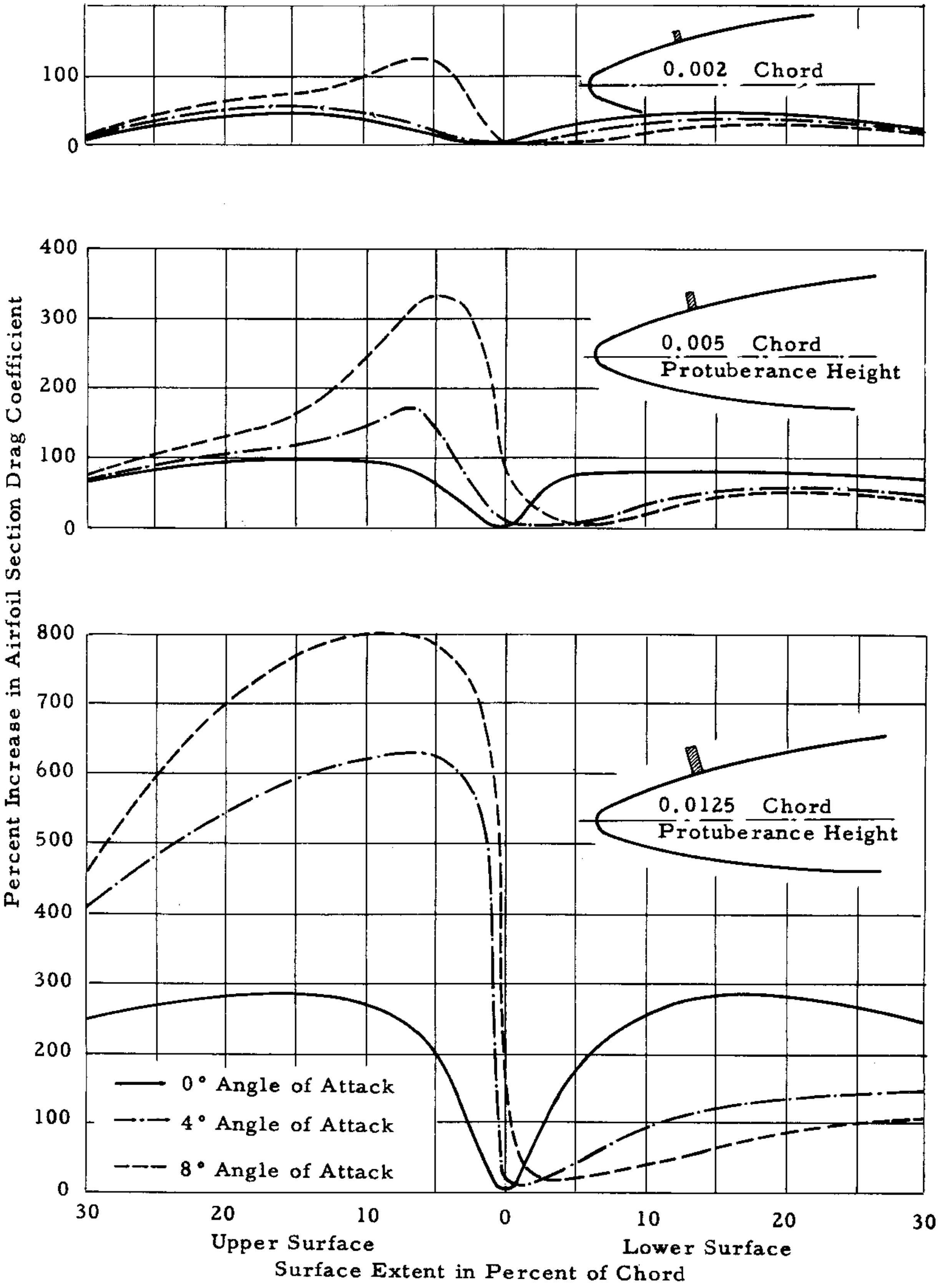


FIGURE 31 DRAG INCREASE DUE TO A STRAIGHT PROTUBERANCE MOUNTED SPANWISE ON AN OTHERWISE CLEAR 12 PERCENT AIRFOIL

multiplying factor of approximately 3 should be used to apply the values in the figure to the hypothetical interceptor (obtained by comparing data in references 47 and 48). It is interesting to note that the drag coefficients are highest in all cases for accretion on upper portions of the leading edge.

In addition to the above data, references 48 and 48 showed that the drag increase due to chordwise streaks of runback is negligible. If the formation assumes the shape of a faired protuberance, the drag increase is also small.

The above estimates are based upon such sparse data that it is difficult to accept the results as conclusive although the trends exhibited should be of use in establishing the performance penalties associated with partial protection of aerodynamic surfaces for subsonic speeds.

TABLE 5
ICING PROTECTION SYSTEM CHARACTERISTICS "PARTIAL"

SYSTEM		Fixed Installed Weight to Modify Airfoil (lbs/ft sp)		Fixed Installed Weight Added to Fuselage (lbs)		Expendable Weight of Materials at 0°F, LWC = .99/gm/m3 (lbs/ft sp, min)				Maximum Net Weight (not inc fuel)(lbs)		Percent Reduction in Thrust at 0°F, LWC = .99 gm/m^3				REMARKS
		Fighter	Bomber	Fighter	Bomber	Fighter		Bomber		Fighter	Bomber	Fighter		Bomber		
						325 k	130 k	200 k	130 k			325 k	130 k	200 k	130 k	
Conventional Pneumatic Boots		1.4	4.2	26.6	260	0	0	0	0	77.0	770	Neg	Neg	Neg	Neg	High Pressure (22 psi) Chordwise Tube Boot
Electrical Systems	Wet	0.2	0.6	117.5	399	.028	.0185	.03	.016	114.7	417	-.3*	-.2	-.3	-.4	
	Dry		1.14		3278			.23	.115		3426			-2.5	-2.5	High Watt Density Sprayed Element
	Cyclic	0.38	1.14	257.6	1412.2	.036	.022	.08	.041	270.9	1560	-.4	-.3	-.8	-1.0	
Compressor Bleed Hot Air Systems	Wet	1.6	4.8	41.0	145	.004	.002	.004	.004	98.5	769	.2	.2	.1	.1	
	Dry	1.6	4.8	55.0	175	.036	.037	.021	.029	112.5	799	3.2	1.4	1.6	1.2	
	Cyclic	1.6	4.8	75.0	215	.009	.009	.008	.006	132.5	839	.8	.35	.3	.3	
Combustion Heater Hot Air Systems	Wet	1.6	4.8	71.0	240	.0081		.007		126.5	864	0	0	0	0	
	Dry	1.6	4.8	350.0	1345	.072		.054		407.5	1969	0	0	0	0	
	Cyclic	1.6	4.8	170.0	400	.024		.013		227.5	1024	0	0	0	0	
Hot Air with Runback Collection		2.0	5.0	16.0	161	.004	.002	.004	.004	118.0	811	.2	.2	.1	.1	Compressor Bleed Hot Air
Tail Pipe Heat Augmentation		1.6	4.8	105.0	375	.036	.037	.021	.029	172.5	849	3.2	1.4	1.6	1.2	Evaporative Anti-Icing
Combustion Heated Augmentation		1.6	4.8	85.0	295	.044	.045	.021	.029	142.5	919	3.2	1.4	1.0	.8	Evaporative Anti-Icing
Combined Hot Air and Electric Parting Strip		1.65	4.88	155.0	365	.076	.067	.023	.032	212.5	989	3.7	1.8	1.4	1.0	Evaporative Anti-Icing
De-Icing Combined with Positive Ice Removal		0.88	2.14	85.0	245	.036	.022	.08	.041	114.7	523.2	-.4	-.3	-.8	-1.0	
Hot Gas Anti-Icing Using Engine Exhaust		1.6	4.8	124.0	309	.016	.04	.03	.071	181.5	645	1.4	1.55	2.95	3.0	Evaporative Anti-Icing

* Increased Power Due To Large Increase In Fuel Flow

SECTION IV

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SECTION V

LIST OF SYMBOLS

a	skin thickness, ft
c_p	specific heat of air at constant pressure, 0.24 Btu/lb °F
c_w	specific heat of liquid water, 1.0 Btu/lb °F
e	partial pressure of vapor, inches of Hg
E	anti-icing fluid distribution efficiency factor
h_a	average external heat transfer coefficient, Btu/hr ft^2 °F
h_e	effective internal heat transfer coefficient, Btu/hr ft^2 °F
h_i	internal heat transfer coefficient, Btu/hr ft^2 °F
J	mechanical equivalent of heat, 778 Btu/ft lb
K	surface wetness fraction
K_{ev}	coefficient of evaporation
ℓ	distance on airfoil from stagnation point, ft
L	latent heat of vaporization of water, Btu/lb
LWC	liquid water content of free air, gm/m^3
M	molecular weight
p	absolute static pressure, inches of Hg
q	rate of heat transfer, Btu/hr ft^2
Q	ratio of anti-icing fluid to water to prevent freezing
r	leading edge radius, ft
S	heated length of surface, ft
t	time, hours (unless otherwise noted)

T	temperature, °F
V	relative velocity between surface and stream, ft/sec
W	weight rate of flow, lb/hr ft^2
μ	droplet diameter, microns
ρ	density, lb/ft^3
η_r	fin effectiveness
ω	specific humidity

Subscripts

a	air
d	datum
e	effective
ev	evaporation
f	fluid
l	local
m	metal
o	ambient
s	surface
w	water

APPENDIX I

METHODS USED IN THE CALCULATION OF WATER DROPLET IMPINGEMENT

Most impingement data are presented for unswept wings of low taper ratio. In order to establish the impingement for the aerodynamic surfaces of the hypothetical aircraft (shown in figures 2 and 3), special methods were used.

Reference 4 suggests that the impingement characteristics of swept wings be determined using the velocity, airfoil section, and chord lengths normal to the wing leading edge. To simplify calculations, the airfoils of the hypothetical aircraft are specified to be NACA 65_1-208 and NACA 65_A-004 in the normal plane since impingement data were available for these shapes in references 48 and 49 at 4° angle of attack. Initial impingement calculations are carried out on a step-by-step basis along the span in accordance with reference 4 to minimize the effect of taper.

The actual rates of water interception in pounds per hour per foot of span and the local impingement rates in pounds per hour per square foot are determined from data plotted in references 48 and 49. It may be seen in figure 6 that the characteristics at midspan are sufficiently representative of the average impingement along the span to serve as a basis for calculation. The impingement data are therefore presented in terms of the midspan accretion in figure 7. Figure 6 also illustrates the local impingement rates in a chordwise direction at midspan as obtained from the references.

APPENDIX II

CALCULATION OF HEAT REQUIREMENTS TO MAINTAIN A DRY EVAPORATIVE AND A RUNNING WET IMPINGEMENT AREA

The heat requirements at midspan to maintain a dry evaporative and a running wet impingement area are determined from the methods and charts of reference 50.

The total heat transfer from a wing consists of three quantities: sensible heat loss to the water, heat loss by evaporation, and the net rate of heat transfer by convection. These may be denoted on a unit basis as q_1, q_2, and q_3, respectively. (The third accounts for aerodynamic heating.) The kinetic gain from impinging droplets is neglected since it is relatively small. The rate of heat transfer per unit area may therefore be expressed as:

$$q = q_1 + q_2 + q_3 \tag{4}$$

where q = total heat transferred from surface, Btu/hr ft^2

q_1 = sensible heat transfer to the impinging water, Btu/hr ft^2, given as

$$q_1 = W_w C_w (T_s - T_o) \tag{5}$$

where W_w = weight rate of water impingement, lb/hr ft^2

C_w = specific heat of water, 1 Btu/lb °F

T_s = surface temperature, °F

T_o = ambient temperature, °F

q_2 = heat loss by evaporation, Btu/hr ft^2, given as

$$q_2 = W_w L (\beta / \alpha) \tag{6}$$

where W_w = weight rate of water impingement, lb/hr ft^2

L = latent heat of evaporation, Btu/lb

(β / α) = a constant $\cong 1$

q_3 = convective heat transfer, Btu/hr ft^2, given as

$$q_3 = h_a (T_s - T_o - \eta_r V^2/2g J c_p) \tag{7}$$

where h_a = average heat transfer coefficient, Btu/hr °F ft^2
T_s = surface temperature, °F
T_o = ambient temperature, °F
η_r = fin effectiveness factor, dimensionless
V = velocity, ft/sec
g = gravity acceleration, 32.2 ft/sec^2
J = mechanical equivalent of heat, 778 ft lb/Btu
c_p = specific heat of air, 0.24 Btu/lb °F
assuming no change in temperature in the boundary layer.

The heat requirements for a running wet surface are calculated according to equation (4) by assuming a surface temperature of 32°F. The evaporative term, q_2, is neglected for this case since it is negligible. The external heat transfer coefficient, h_a, is obtained from the data of reference 50.

For a dry surface condition, where all impinging moisture is evaporated in the heated area, it is necessary to determine the surface temperature, T_s. An approximation to this value is the average surface temperature required to evaporate all the impingement in the heated area. Assuming a surface pressure to ambient pressure ratio (P_s/P_o) of 1.0, the specific humidity for the wetted surface is given as:

$$\omega_s = W_w\, c_p / I\, h_a + \omega_o \qquad (8)$$

where ω_s = specific humidity at surface
W_w = weight rate of water impingement, lb/hr ft^2
c_p = specific heat of air, 0.24 Btu/lb °F
I = a constant given in reference 50 as 1.12
h_a = average heat transfer coefficient, Btu/hr °F ft^2
ω_o = ambient specific humidity

The surface temperature is obtained from curves in reference 50 which are presented in terms of ω_s. The total heat transfer, q, is then calculated according to equation (4).

For a high degree of accuracy, local requirements at several points on the heated area may be integrated to determine a total value. To obtain an overall idea of the heat requirements, however, a mean value over the heated area will generally suffice. The requirements for the hypothetical aircraft are calculated in this manner, assuming a heated length 1.0 foot aft on upper and lower surfaces of the fighter and 3.0 feet on the bomber.

The results are plotted in figures 8 and 9 for a dry evaporative surface and in figures 10 and 11 for a running wet surface.

APPENDIX III

METHODS USED IN THE CALCULATION OF AIRFLOW REQUIREMENTS FOR MAINTAINING RUNNING WET AND DRY EVAPORATIVE IMPINGEMENT AREAS

The airflow required to maintain a running wet and dry evaporative impingement area is calculated for a representative meteorological condition in order to determine the compressor extraction rate required for the case of a compressor bleed system. A conventional double-skin configuration is assumed for the heated area. Several assumptions are made to simplify the calculations, namely: no heat is assumed lost to structural members, the surface temperature is assumed uniform, and the inlet temperature of the heated air is assumed to be 320°F. The airflow requirements are then determined from the methods and charts of reference 50 as given below.

The airflow requirements are expressed in the following relationship based upon the assumptions given above:

$$W_a = q/c_p\,(T_a - T_s)\,(1 - e^{-z}) \qquad (9)$$

where W_a = weight rate of airflow, lb/hr ft^2
q = total heat transferred from surface, Btu/hr ft^2
c_p = specific heat of air, 0.24 Btu/lb °F
T_a = temperature of air at inlet, °F
T_s = surface temperature, °F
$z = h_e\, S/W_a\, c_p$

where S = heated length of surface, ft
h_e = effective internal heat transfer coefficient, Btu/hr °F ft^2 (given in reference 50 as $1.5\ h_i$)

Equation (9) is solved by trial-and-error methods and plotted in figures 18 and 19 for the two hypothetical aircraft. The maximum allowable air extraction rate is superimposed upon the requirement curves to show the feasibility of a running wet or dry system at various airspeeds.

APPENDIX IV

METHOD USED IN THE CALCULATION OF FLOW REQUIREMENTS FOR FLUID FREEZE-POINT DEPRESSANT SYSTEMS

The amount of fluid required to anti-ice an aerodynamic surface may be expressed as

$$W_f = E\, W_w\, Q + (M_f/M_a)(K_{ev}\, \rho_a\, V_o)\frac{(e_{df} - e_{\ell f})}{P_\ell} \qquad (10)$$

where W_f = weight of fluid, lb/hr ft^2
E = anti-icing fluid distribution efficiency factor
W_w = weight rate of impingement, lb/hr ft^2
Q = ratio of anti-icing fluid to water to prevent freezing at surface temperature, T_s
M_f = molecular weight of fluid
M_a = molecular weight of air
ρ_a = air density, lb/ft^3
K_{ev} = coefficient of evaporation
e_{df} = datum partial pressure of fluid, inches of Hg
$e_{\ell f}$ = local partial pressure of fluid, inches of Hg
P_ℓ = local absolute pressure, inches of Hg

The first term represents the amount of fluid necessary to neutralize the impinging water (neglecting water evaporated) and the second term represents the fluid lost by evaporation. This expression is derived from an analysis presented in reference 51.

Calculations for this report are based upon the use of an ethylene glycol-water mixture for which the amount lost to evaporation can be neglected. Solution of the first term requires that the surface temperature be known. This is determined from equation (4), appendix II, for a running wet surface. The heat input q in the case of a fluid system is zero, hence the equation must be solved for an equilibrium surface temperature. Once the surface temperature is established, the amount of fluid necessary to neutralize the impinging water may be determined from figure 33 (obtained from reference 31).

The fluid distribution factor, E, may vary from 1 to 3 depending upon the distributor used, the wetting action of the fluid, etc. In these calculations E is assumed equal to 1 since this produces results similar to those obtained experimentally for a porous distributor. The fluid requirements for the hypothetical aircraft are presented in figures 12 and 13.

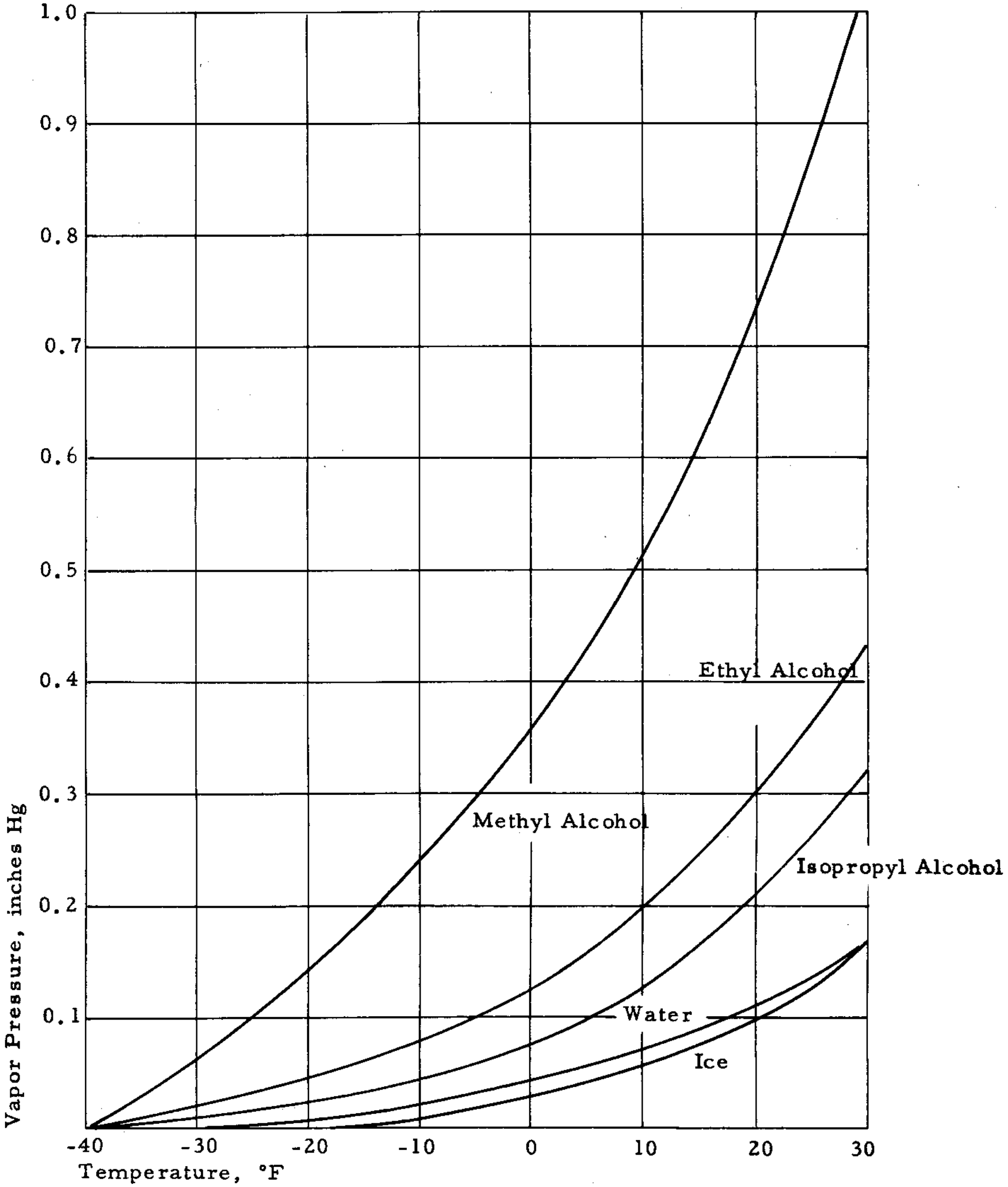

FIGURE 32 PLOTS OF VAPOR PRESSURE VERSUS TEMPERATURE FOR SEVERAL COMMON FLUIDS

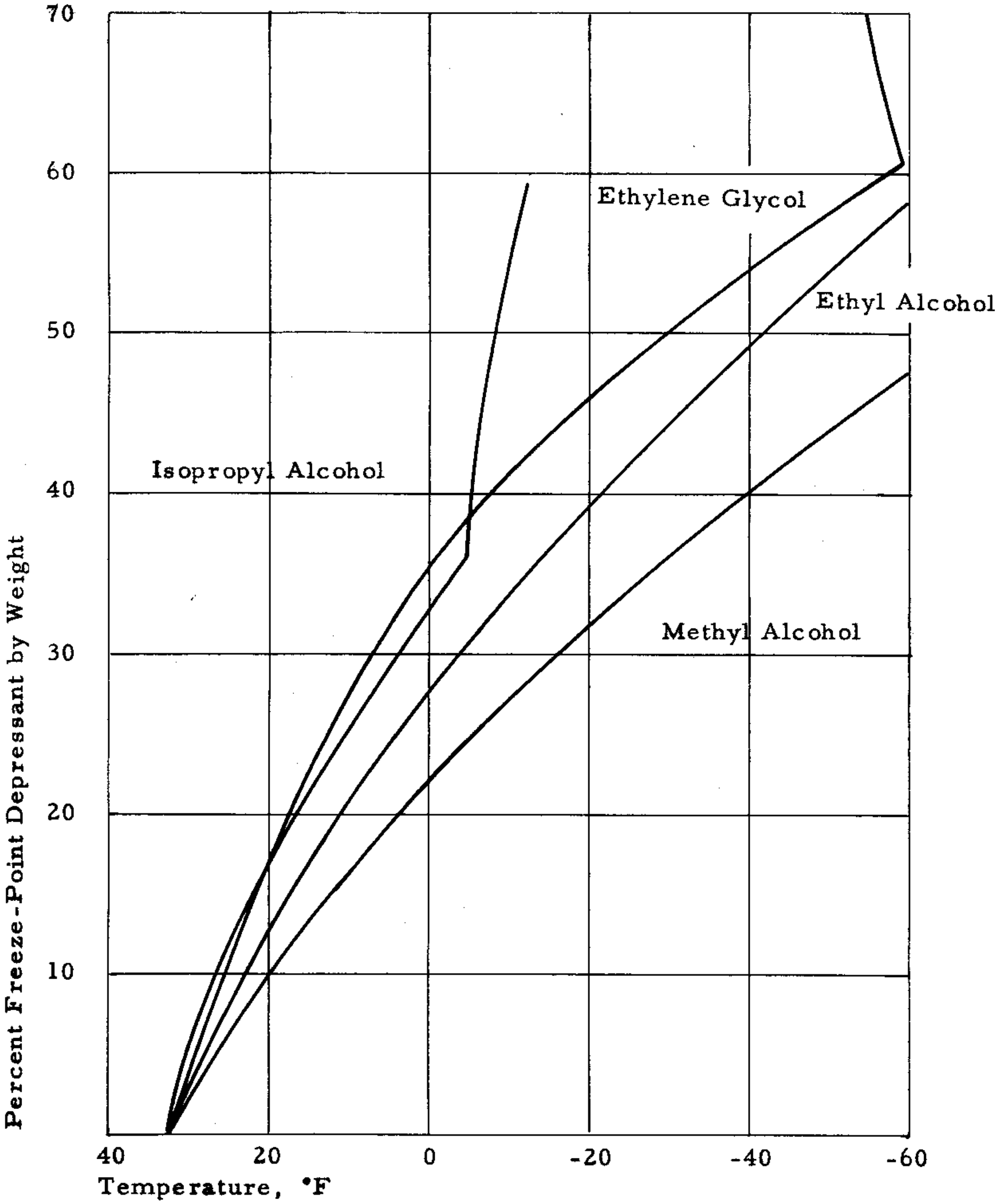

FIGURE 33 FREEZE POINT PLOTS FOR AQUEOUS SOLUTIONS OF SEVERAL FREEZE-POINT DEPRESSANT FLUIDS