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ICING PROTECTION FOR A TURBOJET TRANSPORT AIRPLANE: HEATING REQUIREMENTS, METHODS OF PROTECTION, AND PERFORMANCE PENALTIES

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Page 47, figure 6: The explanation of the dash-dot line should read "Surface temperature constant."

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SUMMARY

The problems associated with providing icing protection for the critical components of a typical turbojet transport airplane operating over a range of probable icing conditions are analyzed and discussed. Heating requirements for several thermal methods of protection are evaluated and the airplane performance penalties associated with providing this protection from various energy sources are assessed.

The continuous heating requirements for icing protection and the associated airplane performance penalties for the turbojet transport are considerably increased over those associated with lower-speed aircraft. Experimental results show that the heating requirements can be substantially reduced by the development of a satisfactory cyclic de-icing system. The problem of providing protection can be minimized by employing a proper energy source since the airplane performance penalties vary considerably with the source of energy employed.

The optimum icing protection system for the turbojet transport or for any other particular aircraft cannot be generally specified; the choice of the optimum system is dependent upon the specific characteristics of the airplane and engine, the flight plan, the probable icing conditions, and the performance requirements of the aircraft.

INTRODUCTION

The introduction of the high-speed, high-altitude, turbine-powered airplane for all-weather operation makes necessary a new appraisal of the icing protection requirements. The unique design features and mode of operation of the turbojet airplane may result in requirements for adequate icing protection that are considerably different from conventional aircraft. In addition to operating at speed and altitude conditions differing greatly from current conventional aircraft, the turbojet airplane has a high rate of fuel consumption and a restricted flight plan. Thus, any penalties imposed upon the airplane performance by the provision and operation of the icing protection system assume great importance. These factors, together with the demand for all-weather operation, require that careful consideration be given to the problems associated with providing icing protection for the turbojet airplane. The major problems that must be considered are: (1) the conditions of icing and the degree of protection required, (2) the method of protection and the associated protection requirements, and (3) the penalties imposed by the protection system on the airplane performance. The purpose of this report is to analyze and evaluate the icing protection problem for a high-performance turbojet transport airplane in terms of these three considerations.

Although various schemes of mechanical and chemical icing protection have been and continue to be employed, the successful operation of the thermal method of protection in current aircraft has proved it to be practical and desirable. This report will, therefore, consider only the thermal method, although some of the information contained herein is of interest in other types of icing protection systems.

The material in this report is presented in several phases. Consideration is first given to the severity of icing to be encountered at the various operating and meteorological conditions. A study is included of the combination of operating and meteorological conditions that will result in an ice-free surface without the application of heat. Secondly, an analysis is made of the heat dissipated from a heated surface of an airplane component exposed to icing for a wide range of icing and flight conditions in order to reveal those factors in the heat-transfer process associated with high-speed, high-altitude flight that are responsible for any marked changes in the heating requirements for icing protection over those for conventional aircraft. This analysis is followed by a determination of the heating requirements of the several airplane components vulnerable to icing for specific methods and systems of icing protection. Finally, the total airplane heating requirements and associated performance penalties are evaluated to illustrate their relation to the protection methods and systems as well as to the operating and meteorological conditions. The results, which are based on theoretical studies augmented by limited experimental data, are presented in terms of a specific airplane configuration, flight plan, and icing atmosphere in order to indicate their practical and quantitative significance. The investigation was conducted at the NACA Lewis laboratory.

CONDITIONS OF ICING

In order to determine the severity of icing, the need for protection, and the magnitude of the protection requirement, it is necessary to relate the meteorological conditions to the airplane operating conditions and design characteristics. For this reason a hypothetical airplane, a typical flight plan, and probable meteorological conditions are taken for this analysis.

Aircraft and flight plan. - The airplane assumed for this analysis is a turbojet transport (fig. 1) with the following specifications: gross weight, 125,000 pounds; wing span, 158 feet; mean chord, 15.8 feet with a 4 to 1 taper ratio; and airfoil section, NACA 65_1-212. Propulsion is obtained from four axial-flow turbojet engines, each engine having a compressor pressure ratio of 5 and a rated thrust of 6000 pounds. The airplane is assumed to climb to its cruising altitude of 30,000 feet at maximum thrust and at a flight speed (350 mph) which gives the maximum rate of climb. The descent is also made at a speed of 350 miles per hour for all altitudes. The cruising speed of the aircraft is 500 miles per hour with a cruising range of 3000 miles. For convenience in the analysis the flight plan has been divided into four categories (see table I) consisting of three 10,000-foot altitude ranges in the climb and descent conditions and a 30,000-foot cruising condition.

Meteorological conditions. - An icing protection system for a turbojet-powered aircraft depends, in large part, on the selection of the meteorological factors on which to base heating requirements. The selection of the meteorological factors is modified, however, by the probability of encountering such a design meteorological condition. It may be necessary to design some icing protection equipment for icing conditions less severe than the maximum expected in order to obtain acceptable heating requirements. This procedure may be particularly necessary if the probability of encountering the most severe icing condition is very low and the heat required for protection at this condition is several times that required for the most probable icing condition. Statistical analyses of limited flight data in references 1 and 2 provide a means of making reasonable engineering assumptions as to the particular combinations of the important meteorological variables. In particular, the method presented in reference 1 for the selection of the meteorological factors for which the system is designed to protect is used in this analysis.

The meteorological variables necessary to determine the requirements for icing protection are: air temperature and pressure, cloud liquid-water content, water droplet size and size distribution, extent or duration of icing conditions, and frequency of occurrence. The rate and location of ice or water collection, which are sensed by a body, determine the protection requirement and hence the seriousness of a particular icing condition. The selection of design variables consists in determining that combination of the meteorological variables which for a specific body geometry and flight speed results in the maximum rate of collection for a specified frequency of occurrence. Consideration must also be given to the extent or duration of the icing condition. For a complete evaluation of the probability of encountering an icing condition of given severity, all these variables should be considered simultaneously. Because of the complexity and incompleteness of the meteorological data, such an analysis is not made at the present time.

Sufficient accuracy in determining protection requirements and reasonable values of the meteorological variables are obtained by considering only the major components of the airplane and applying the values so obtained to the remaining components. From this procedure and the method and data of reference 1, design values of the meteorological conditions for each of the four altitude ranges were selected and are also given in table I. For selected meteorological and airplane operating conditions, the amount and location of water droplet impingement on the various aircraft components subject to icing can be estimated.

Water droplet impingement. - In order to evaluate the rate of water interception by a component, the collection efficiency of the component must be determined. The collection efficiency of a body E_M, defined as the ratio of the water intercepted by the component to the total mass of water in the volume swept out by the moving body, is a complex function of the physical dimensions and attitude of the body and the airspeed, as well as the meteorological variables: droplet size, air temperature, and air pressure.

By the method of reference 1 a rate of water collection can be selected as the design criterion for icing protection for a particular component. Because the collection efficiency depends on the physical dimensions of a component, the collection rates for all components will not necessarily be the same for a given meteorological condition. Each component should therefore be analyzed independently if the total heat requirement for efficient and adequate icing protection is to be held to a minimum.

Droplet trajectories and the corresponding rate and area of water impingement have been calculated for a limited number of aerodynamic shapes and airfoils (references 3 to 5). The impingement patterns for the NACA 65_1-212 airfoil assumed for the turbojet transport were estimated from the results of references 3 and 5. These estimated local impingement values for the mean chord of the NACA 65_1-212 airfoil at the four flight conditions of table I are presented in figure 2 together with the respective collection efficiencies. The minimum extent of impingement occurs at the lowest altitude (condition 1), extending between 0.6 percent of chord on the upper surface and 1.2 percent of chord on the lower surface. As the flight altitude and angle of attack increase during the climb (conditions 1 to 3), the area of interception on the lower surface is increased because of the greater surface area exposed at the larger angles of attack and also because the reduced drag forces on the droplets at altitude deflect the droplets less from the path of the advancing airfoil. The greatest value of the total water intercepted, however, is obtained at condition 2 (approximately 8.0 lb/hr/ft of span). The amount of water caught at the cruise condition 4, where the greatest percentage of the airplane flight time occurs, is only one third of this maximum value.

Because the local impingement rate varies with the body size, the impingement along the span of the wing and on the tail surfaces differs from that for the wing mean chord. The magnitude of this variation of impingement is given in figure 2(b), where the impingement on the root, mean, and tip airfoil sections of the wing is shown. These results are presented for condition 4. The amount of water caught is greatest for the mean chord station. The variation in total amount of water caught varies only slightly despite an almost four-fold increase in collection efficiency from root to tip. Although there is a large variation in extent of impingement in terms of percent of chord, the difference in actual distance is rather small, varying from 0.58 to 0.63 feet.

For the remaining components of the airplane the impingement was determined from interpolation of the calculated values for cylinders, spheres, and airfoils, and from experimental determinations of the icing characteristics of specific bodies.

Conditions resulting in aircraft icing. - It is apparent that those airplane surfaces which experience a temperature rise, due to aerodynamic heating and other effects, sufficient to maintain a surface temperature above 32° F will not require icing protection. The temperature t_s' (symbols defined in appendix A) of an unheated surface in an air stream containing liquid water is obtained from a solution of the heat balance for an insulated surface after consideration of heat gains from frictional heating, kinetic energy of the impinging water, and release of heat of fusion as opposed to the heat losses from convective, evaporative, and sensible heat losses. Details of the analysis for the determination of this equilibrium surface temperature for an ice-free surface are given in appendix B.

The minimum flight speeds required to maintain the stagnation point of a body ice free at 32° F are presented in figure 3 for both dry-air conditions and cloud or wet-air conditions. These results are given as a function of the assumed altitude-temperature relation (table I). All conditions of altitude, temperature, and speed that fall below and to the right of the curves have a stagnation equilibrium temperature above the freezing point. The numbers on figure 3 correspond to the assumed flight and altitude conditions of table I. For convenience, a line for a free-stream Mach number of 1.0 is included, indicating the possibility of icing well above this speed at low air temperatures. A marked increase in speed is required to obtain a stagnation temperature above 32° F in a cloud as compared with that in dry air. This difference increases with altitude because of the increased rate of evaporation at the lower pressures and subsequent greater cooling effect. At condition 1, the assumed flight speed is very close to the calculated value (355 mph) required to maintain a surface temperature above 32° F in a cloud. At the other three assumed flight conditions the requisite speed is not obtained. In fact, for these three conditions the speed corresponding to the critical Mach number of the NACA 65_1-212 airfoil is insufficient to maintain a stagnation temperature above 32° F in a cloud. Thus, on the basis of the stagnation temperature of the unheated surface, icing protection will be required for all the assumed flight conditions given in table I.

The results presented in figure 3 are for the airfoil stagnation point only. At other positions on a body where the local velocities and rates of impingement are different from those at stagnation, varying values of the temperature of the unheated surface will be obtained. In figure 4 the temperature distribution around the leading edge of the NACA 65_1-212 airfoil is shown for the lowest altitude, condition 1, at a flight speed just sufficient to maintain all the airfoil above freezing. This minimum flight speed is 365 miles per hour and the coldest point on the airfoil is at 0.75 percent chord on the lower surface. As shown in appendix B, the unheated equilibrium surface temperature is dependent upon the specific meteorological and operating conditions and body geometry. The results of figures 3 and 4 are applicable only to the assumed conditions of this analysis. Although the surface-temperature rise obtained for the turbine-powered transport airplane is not sufficient to preclude provision of an icing protection system, the rise is appreciable and of importance in reducing the amount of heat that must be drawn from a heat source on the airplane for adequate icing protection.

METHODS OF PROTECTION AND HEATING REQUIREMENTS

General Considerations

After the selection of the operating and meteorological conditions for the turbojet transport airplane, the determination of conditions resulting in icing, and the determination of the degree of protection required for each airplane component have been made, the heat required for icing protection may be determined. The determination of these heating requirements presents a complex problem in heat transfer from the heat source to the air stream. The heating requirements are not only dependent upon the meteorological and airplane operating variables and the geometry and design characteristics of the various airplane components, but also are a function of the method of protection, the protection system, and the heat source itself. This discussion will consider and evaluate both the heat transfer to the air stream from the exposed airplane surface heated to protect against icing and the total heat demand on the heat source for various thermal icing protection methods and systems as applied to the turbojet transport airplane.

Vulnerability of Airplane Components to Icing

Although all forward-facing surfaces of any aircraft are subject to icing, experience, economy, and the mission or purpose of a specific airplane will dictate the components for which icing protection must be provided. The major components essential to the operation of an aircraft are the engines, wings, and tail surfaces. Aircraft designed for all-weather operation must provide adequate protection for at least these components. The windshield and other vital transparencies must be kept clear to permit the control and navigation of the aircraft. Additional components such as small air scoops, vents, external stores, and so forth may demand special consideration. The determination of the protection requirements for such components is at present based on empirical methods. In addition, the requirements for these components are usually small compared with the total airplane icing protection requirement. This discussion will, therefore, be concerned only with the protection of the wing and tail surfaces, the engines, and the windshield.

The evaluation of the protection needed by each component and the proper type of protection to employ is extremely difficult. The critical components are readily identified, but their susceptibility to icing and the impairment of the component operation and airplane performance vary not only with each component but also with the icing and operating conditions. Performance, economy, and safety limitations must be considered in the determination of the amount and type of protection necessary. In this report a somewhat arbitrary selection of the criterion for protection has been made based primarily on the function of the various components. The criterion for the wing and tail surfaces is that they must be kept free of ice except for the small amounts that form when a cyclic de-icing system is used. The windshield is to be kept ice free at all times, although it is not necessary to evaporate all the impinging water. This latter criterion is applied also to the vulnerable engine components.

Methods and Systems

The protection of high-speed, high-altitude, turbojet-powered aircraft by local heating of the areas subject to icing may be accomplished by either continuous heating or cyclical de-icing. In continuous heating, the surfaces subject to icing are either raised to a temperature just sufficient to maintain the impinging water in a liquid state or are supplied sufficient heat to evaporate all the impinging water within a specified distance from the leading edge. In cyclical de-icing some ice is permitted to form on the surfaces and then is removed periodically during short, intense applications of heat. A water film between the surfaces and the ice is produced by the heat application and permits ice removal by aerodynamic forces. Because the heating is intermittent, heat is supplied successively to relatively small surface areas and a constant heat load is thus maintained on a heat source. The total heat input for cyclical de-icing can be greatly reduced, therefore, from that required for continuous heating.

Because ice formations normally extend over the leading edge and onto some of the remaining surface area of a component, removal by aerodynamic forces may be slow and erratic. The desirability of a continuously heated parting strip near the leading edge of such a component as an airfoil is indicated in references 6 and 7. When such an ice-free strip is maintained, the ice formation is divided into two parts and ice removal by aerodynamic forces is facilitated.

Icing protection systems comprise the heat source and the various means by which the heat is distributed and utilized at the vulnerable airplane component. Various combinations of systems are available for the generation, distribution, and utilization of heat for the different protection methods. For the case of anti-icing or continuous heating, the most generally used systems are those using hot gas or local surface heating by electric heaters. The ordinary hot-gas system consists essentially of a single-pass heat exchanger with the airplane surface acting as one side of the heat exchanger. Another type of hot-gas system utilizes a porous surface through which the hot gas is bled; both the surface and the boundary-layer air are thus heated directly. Sufficient information on this system, however, is not available at present to permit determination of the heating requirements. Cyclical de-icing systems may employ electric heaters or hot gas as the heating medium. Possible heat sources for all the icing protection systems include use of heat exchangers, combustion heaters, hot gas bled from the turbojet engine, auxiliary power units, and electric generators driven by the engines or separate power units.

The variation in the heat requirement with the meteorological and operating conditions will be different for each method and system. For example, in a system designed to evaporate all the impinging water, changes in the amount of water caught will obviously change the heat required to vaporize this water load. In contrast, a system which merely maintains all the water above freezing will not be sensitive to changes in the amount of water caught because the wetting of the surface, not the depth of the water film normal to the surface, is pertinent. The heat requirements for this latter system will be primarily dependent on changes in free-stream static air temperature and flight speed and their effect on the equilibrium surface temperature. Similar considerations apply for each of the operating and meteorological variables as well as the system characteristics in their effect on the heat requirements for a particular method and system. Because of the numerous possible combinations of methods and systems of icing protection and the complex nature of the heat-transfer relations, it is not possible to discuss in detail the effects of all the variables on the heat requirements. The continuous hot-gas double-skin anti-icing system designed to evaporate all the impinging water has been chosen to illustrate some of the effects of the system and envionmental variables on the heat requirements. This system is currently in wide-spread use and is subject to a fairly complete theoretical analysis illustrating most of the important thermal effects of interest.

Continuous Heating of Airfoils

The use of continuous electrically heated protection systems for relatively large areas as exemplified by the leading edges of wing or tail surfaces does not appear feasible at this time because of the enormous power required and the associated installed weights of adequate power-generating equipment. Continuous electric heating for relatively small airplane elements such as engine components or windshields does appear reasonable, but will be evaluated in the report when icing protection of these airplane components is considered.

A typical thermal icing protection system for wing and tail surfaces which is being used successfully in several current aircraft is the chordwise-flow, hot-gas system illustrated in figure 5. The system consists of a spanwise D-shaped supply duct insulated from a double skin which forms a number of small chordwise-flow corrugations. Representative of some current designs, the dimensions for the chordwise channels or passages are: depth, 1/8 inch; width, 1 inch; and spacing, $1\frac{3}{4}$-inch intervals. Hot air or gas is introduced to the chordwise passages from the D-shaped supply duct at the airfoil leading edge and flows rearward through the shallow heating channels. After leaving the channels, the gas passes through lightening holes in the front spar and is subsequently dispersed to the air stream, carrying with it the heat not transferred to the airfoil surface.

In order to simplify the presentation of the heat-transfer relations from the heat source to the air stream and to illustrate some of the important relations involved, consideration is first given to the heat dissipated from the surface to the air stream with a wing continuously heated. A detailed analysis of the heat transfer from the hot gas supplied by a D-duct to the wing surface and thence to the air stream is presented in appendix E.

External heat transfer with continuous heating. - The heat transfer to the air stream from a surface exposed to icing consists of the following terms: (1) sensible heating of the impinging water, (2) heat required for the evaporation of the impinging water, (3) convective heat transfer, and (4) radiation from the heated surface. The magnitude of the radiation effects is of minor importance in this analysis and is neglected. The equation for the heat transferred from an exposed heated surface in a cloud given in reference 8 may be written in the following manner:

$$q = h_c \left\{ (t_s - t_0) \left[\left(\frac{M_a}{h_c} \right) + 1 \right] - \frac{V^2}{2gJc_p} \left[1 - \left(\frac{U}{V} \right)^2 (1 - N_{Pr}{}^{n}) + \left(\frac{M_a}{h_c} \right) c_p \right] + \frac{0.622LK}{c_p} \left[\left(\frac{e_s}{p_1} \right) - \left(\frac{e_0}{p_0} \right) \right] \right\} \tag{1}$$

The evaporation and convective heat-transfer terms of equation (1) are discussed in detail in appendixes C and D, respectively. All the terms in equation (1) with the exception of the heated surface temperature t_s are known or can be determined independently of the icing protection system. In order to determine this heated surface temperature and the corresponding total heat requirement for a particular protection system, equation (1) must be solved simultaneously with other relations describing the heat-transfer processes between the heat source and the exposed surface.

In order to illustrate some of the relations described by equation (1) before consideration of a specific icing protection system, arbitrary temperatures of the heated surface were assumed for the mean wing chord (15.8 feet) of the NACA 65_1-212 airfoil. The wing was assumed to be heated so as to produce a uniform surface temperature for a distance sufficient to evaporate all the impinging water. The effects of a variation in this uniform surface temperature on the heat transferred from the wing and the corresponding heated chordwise distance required to evaporate all the impinging water are shown by the solid curves of figure 6 for the meteorological condition associated with condition 4 and for two flight speeds. Advantages of the smaller heated areas and smaller quantities of heat required are obtained by use of the higher surface temperatures (dot-dash curves). The minimum value of chordwise distance heated (limit of impingement) and heat required occurs when all the water is evaporated as it strikes within the impingement area. Decreasing the surface temperature level requires an increased chordwise distance heated, allowing the unevaporated water from the impingement area to run back in rivulets producing a partly wetted surface. This partial wetness is represented by the factor K in equation (1). (Discussion of the wetness factor K and its use are presented in appendix C.) As the heated distance is increased and the surface temperature level is decreased, a point is finally reached at which all of the water is just evaporated; the surface temperature level at this point will be 32° F. This situation represents the maximum distance and amount of heat transferred from the surface to the air stream. The maximum required heat is 3.9 and 2.7 times the minimum value obtained for total evaporation in the impingement area for the 350- and 500-mile per-hour conditions, respectively. The requirements for the case in which the surface is heated only to a level of 32° F for various chordwise distances are also indicated in figure 6 (dashed curves). In this case only partial evaporation of the impinging water will take place for all chordwise distances less than the maximum. This will result in the formation of run-back ice beyond the heated areas. As the distance heated is increased, the difference in heat transferred from the surface for the two means of providing protection by continuous heating (complete evaporation versus surface at 32° F) becomes less with a common value finally being reached. The results of figure 6 indicate the importance of the surface temperature and the extent of surface heated in determining the quantity of heat required at the surface for the case of complete evaporation. Flight speed is also shown to have a larger effect on the required heat for complete evaporation as compared with heating all the surface to 32° F. Although the results of figure 6 are for an ideal case (uniform surface temperature), the relations between the requirements at the airfoil surface for the two means of providing continuous heating are similar for a system in which the chordwise surface temperatures are nonuniform.

Total heat requirements with continuous heating. - The quantities of heat discussed thus far are dissipated at the airfoil surface and, because no consideration has been given to the internal heat transfer, do not represent the total demand on the heat source. It is necessary, therefore, to investigate the over-all heat-transfer processes from the heat source to the air stream for a continuously heated system with hot gas as the heating agent.

Not only does the total heat demand on the source depend on the external heat transfer, but, equally important, the total heat required for icing protection depends on the mode of continuous heat application and on the structural geometry of the anti-icing system.

Because of interest in the high-speed, high-altitude icing problem, condition 4 was chosen to serve as a basis for evaluating and comparing the effects of these variables on the total heating requirements.

An inlet gas temperature of 350° F at the inlet to the double skin was arbitrarily selected in order not to exceed a temperature limitation of 200° F for an aluminum leading edge and spar structure.

The results of a typical set of performance calculations for a chordwise-flow icing protection system in which all the impinging water is evaporated are shown in figure 7. These curves are for the upper surface, the mean chord of the wing of the airplane assumed herein operating at condition 4, and the heating channel dimensions as previously stated. Both the total heat requirement and the heat dissipated at the airfoil surface for several air speeds in addition to the nominal airspeed of 500 miles per hour for condition 4 are presented. The values of the heat required at the surface are similar to those of figure 6, the differences arise from the nonuniform chordwise surface-temperature distribution obtained by using a conventional hot-gas double-skin system. The total heat requirement decreases with increasing heated surface distance. This effect is caused by a more efficient utilization of the double-skin system as a heat exchanger and becomes more pronounced as the flight speed is increased; however, the increase in the total heat requirement becomes less as the flight speed is increased. Each curve for both the external and total heat requirements increases until a heated chordwise distance is reached at which all the water is just evaporated and the surface temperature at this point is 32° F. Envelope curves have been drawn through these points. A comparison of these envelope curves indicates that the efficiency of the double-skin heating system, defined as the ratio of external heat transfer to the total heat load on the source, decreases with increasing air speed to a minimum value of about 60 percent at approximately 350 miles per hour, after which the system efficiency increases. The results shown in figure 7 indicate the importance of considering the total heat requirement rather than the heat required at the surface and thus the importance of the protection system in the determination of protection requirements. In addition, figure 7 indicates that the savings in total heat requirement obtained by increasing the heated distance are greatest at the higher flight speeds, the normal cruise condition of a turbojet transport. An extremely large increase in the total heat demand from a low-speed condition (200 mph) to the high speeds characteristic of a turbojet transport is also indicated. Similar results were obtained at the other combinations of operating and meteorological conditions presented in table I.

The requirements presented in figures 6 and 7 are given in terms of heat quantities in Btu per hour per foot span. For a hot-gas system it is usually more significant to know the quantity of hot gas required. The required weight flows of hot gas with an inlet gas temperature to the double-skin system of 350° F are presented in figure 8 as a function of the heated distance for two conditions of table I. The results in general are similar to those of figure 7; namely, the weight flow or total heating requirements are reduced as the chordwise heated area is increased. For the cruise condition (fig. 8(a)) the minimum weight flow of hot gas for complete evaporation is 9.2 pounds per hour per passage as compared with 23.5 pounds per hour per passage at condition 2 (fig. 8(b)). The required heated length at condition 4 (4.9 percent chord, fig. 8(a)) is approximately one fourth of that required at condition 2. If the hot-gas weight flow is reduced below the minimum values required for complete evaporation, the skin temperature will drop below

32° F in the wetted region and run-back icing will result. Exact knowledge of the effect of such run back and refreezing of water on the airplane performance is not available at present. If small amounts of run-back ice are tolerable, however, it is possible to obtain an estimate of the savings in hot-gas weight flow that would result. For this purpose additional curves are given in figure 8 for the condition in which less than 100 percent evaporation is obtained. Thus, for condition 2 (fig. 8(b)) with a heated length of 10 percent chord, the required weight flow is reduced nearly 25 percent if only 80 percent of the impinging water need be evaporated. For the three percentages of water evaporation shown in figure 8, the line indicating skin temperature of 32° F shows the reduction in chordwise ice-free area accompanying the reduced evaporation percentage. If the weight flow is reduced slightly below 9.2 pounds per hour per passage in figure 8(a), run-back icing will occur aft of about 5 percent x/C; whereas, if only 80 percent of the impinging water is evaporated, run-back icing will occur aft of the 3 percent x/C station.

The effects of independent variations in the wing double-skin geometry and the inlet gas temperature on the minimum protection requirements for complete evaporation are shown in figure 9. These results are given in terms of a mean condition (condition 4) with a gas temperature of 350° F and 1/8-inch double-skin gap size. These results show that the required hot-gas flow rate can be decreased by (1) decreasing the gap size, or (2) increasing the inlet gas temperature. Similarly, the heated extent (in percent of chord) can be reduced by an increase in inlet gas temperature or by a decrease in gap size. For the range of these variables of interest, the inlet gas temperature has the greatest effect on the required weight flow. Any increase in the internal heat-transfer rate will result in considerable reduction in the heat requirement; the variations in gap size and gas temperature will be necessarily limited by practical design considerations.

The effects of independent variations in the flight speed and icing condition from those assumed for condition 4 on the requirements for a hot-gas protection system are shown in figure 10 and can be summarized as follows: The weight flow of hot gas required is decreased by either (1) a decrease in cloud liquid-water content, (2) an increase in free-stream static air temperature, or (3) a decrease in flight speed. In addition, the required heated extent (percent chord) can be reduced by a decrease in cloud liquid-water content or flight speed or by an increase in the free-stream static air temperature. The large effect on the protection requirements of the liquid-water content in contrast to the small variation with free-stream static air temperature is typical of a system designed to evaporate all the impinging water. Changes in flight speed as had previously been shown in figure 7 also greatly affect the protection requirements. Extrapolation of the required weight-flow curve as a function of flight speed indicates a maximum value occurring at approximately 750 miles per hour. At this speed the unheated equilibrium surface temperature is still below 32° F and icing protection will therefore still be required.

The results of figures 9 and 10 indicate the significance and accuracy of protection requirements computed for a specific design. If the heated length for condition 2 is limited to 10 percent chord, the increase in the required hot-gas weight flow amounts to 13 percent more than the weight flow when the airfoil is heated to 20 percent chord. The accuracy with which the meteorological and operating conditions are known is even more important to the calculation of heat loads; under certain conditions a variation of the liquid-water content of only 0.05 gram per cubic meter could result in a 40-percent change in the total heating requirement. Careful consideration should therefore be given to the performance and requirements of the protection system when operating in an off-design condition.

The protection requirements for each of the four design conditions of table I were computed for the entire wing of the turbojet transport with the use of a hot-gas double-skin anti-icing system and an inlet gas temperature of 350° F. Because of weight and structural considerations, the chordwise heated airfoil length was arbitrarily limited to 10 percent chord. Condition 1 provided results which were not critical and are therefore omitted throughout the remainder of the report. A summary of the results for conditions 2, 3, and 4 is presented in the following table:

Condition	Wing continuous hot-gas requirements for NACA 65_1-212 airfoil section (Btu/hr)
2	4,600,000
3	1,570,000
4	1,680,000

The maximum continuous wing heating requirement for complete evaporation of the intercepted water occurs at condition 2 because of the choice of flight and meteorological variables.

Cyclical De-icing of Airfoils

The heating requirements for cyclic de-icing are much lower than for ice prevention because of the different thermal processes involved and the difference in performance criterion; that is, the removal of the ice is of primary importance rather than maintaining a specified surface temperature or evaporating all the impinging water. The analytical determination of heat requirements for the cyclic de-icing process is particularly difficult because of the transient phenomena involved and the lack of knowledge relating the heat transfer and ice-removal forces. An analytical study of the problem, which employed an electric network analyzer and was primarily for propellers, is given in reference 9. Experimental investigations are reported in references 6, 7, 10, 11, and in a classified report by J. L. Orr of the National Aeronautical Establishment of Canada. The cyclic requirements presented herein are based on preliminary results from an experimental investigation (reference 7) of a typical cyclic electric de-icing system for an airfoil in the icing research tunnel of the Lewis laboratory.

The factors to be considered in the design of a cyclic de-icing system for any component are: (1) the heat or power density supplied to the cyclically heated areas, (2) the distribution of the power, (3) the extent of the cyclic area, (4) the extent and power density of continuously heated areas, and (5) the duration of the heat-on and heat-off periods. Experimental results indicate that the cyclic power densities are greater than those for continuous heating and are primarily a function of the equilibrium surface temperature during the heat-off period and the heat-on time; the cyclic power density required decreased linearly with increasing equilibrium temperature. A nonlinear inverse relation between cyclic power density and heat-on time was obtained with a sharp increase in power required for heating times of less than 10 seconds. Good removal was obtained over a range of heat-on times from 5 to 30 seconds with the most efficient removal occurring at the shorter heat-on periods; shorter heat-on periods also minimized the amount of run-back ice formations downstream of the heated area. Although large instantaneous power densities are required for the short heat-on periods, the equivalent continuous power or total energy requirement (the instantaneous power density times the ratio of heat-on to total cycle time) is greatly reduced for short heat-on periods compared with long heating periods with lower instaneous power densities. Heat-off periods from 2 to 6 minutes were found to be satisfactory for an air speed of 175 miles per hour, free-stream static air temperatures from -15° to $+15^{\circ}$ F, and water contents from 0.25 to 1.0 gram per cubic meter. Best results were obtained with an essentially uniform distribution of power in the impingement region with the power density decreasing linearly aft of the impingement zone. The exact combination of power density, heat-on, and heat-off time for a specific design will depend upon practical considerations such as generator characteristics, heater construction, and the electric circuiting and control systems.

For efficient and consistent de-icing it was necessary to use a narrow spanwise continuously heated strip at the leading edge of the airfoil (reference 7). A strip as small as 1/2 inch wide proved successful at a constant angle of attack; however, larger areas are necessary to provide for operation over a range of angles of attack. For the turbojet-powered aircraft considered herein, a continuously heated parting strip of $1\frac{1}{4}$ inches was chosen to include the required range of angles of attack. Continuously heated strips in a chordwise direction between separately cycled areas also facilitate removal by reducing the possibility of the ice anchoring to adjacent unheated surfaces. The power densities required for the continuously heated areas were found to be approximately equal to those computed for a condition of the surface maintained slightly above the freezing temperature.

As an example of the local cyclic heating requirements, the following table presents the estimated requirements for the NACA 65_1-212 airfoil with a mean chord of 15.8 feet, a span of 158 feet, and a 1:13 ratio of heat-on time to total cycle time:

Condition	Cyclic power density (w/sq in.)	Total cycled area (percent chord)	Heat-on time (sec)	Heat-off time (min)	Width of continuously heated parting strip (in.)	Continuous power density to parting strip (w/sq in.)
2	15	10	10	2	$1\frac{1}{4}$	8
3	20	10	20	4	$1\frac{1}{4}$	9
4	21	10	20	4	$1\frac{1}{4}$	11

The cycle ratio was chosen constant to permit a single circuiting and control design. In addition, the resultant heat-on and heat-off times avoided excessive power densities at the high-altitude conditions and also provided a longer period at these conditions of low liquid-water content, thereby allowing sufficient ice to form to insure good removal. Summarizing the electrical requirements for the assumed wing yields the following results:

Condition	Wing cyclic electrical requirement (total)	
	(kw)	(Btu/hr)
2	55.2	188,000
3	69.5	237,000
4	77.0	262,000

The maximum heating requirements for wing cyclic electric de-icing occur at condition 4 rather than condition 2, for which the continuous hot-gas heating requirements are a maximum. The change in the condition for maximum heating required is caused by the fact that the cyclical de-icing system heating requirements are primarily dependent on the equilibrium surface temperature, whereas the continuous hot-gas protection system is principally a function of the rate of water-droplet interception.

Although the cyclic de-icing heating requirements presented in the preceding table are based on an electrical system, a similar method of protection is possible with hot gas. Preliminary results from reference 6 indicate that the heating requirements for icing protection with a cyclic hot-gas system may be only one fourth to one sixth of those for continuous gas heating. In order that the large reduction in heating requirements (Btu/hr) can be realized from a cyclical de-icing system, such a system must be capable of rapid heating of the ice-coated surfaces; consequently, the thermal lags in the system must be maintained at a minimum, as shown in reference 6.

The feasibility of the use of a cyclic de-icing protection system for any component will not be solely dependent upon the consideration of heating requirement, but also upon the allowable icing tolerance of the particular component. Tolerable icing criteria will differ for each component and each flight condition. Pressure recovery may be the primary concern in a consideration of cyclic protection of engine components, whereas drag or lift considerations determine the usefulness of cyclic de-icing for wings. A quantitative appraisal of the drag and lift effects of ice accumulations during a cyclic de-icing process is difficult at present because of the limited amount of available data; therefore, a complete appraisal of cyclic de-icing protection for aircraft components cannot be made.

The design and operation requirements of a continuous hot-gas or cyclic electrical system for the tail surfaces of the turbojet transport airplane were found to exhibit the same general characteristics as those previously outlined for the wing. With either protection system, the total heating requirements for the tail are considerably reduced from comparable wing results in approximate proportion to the respective protected spans.

Turbojet-Engine Icing Protection

Of particular concern in providing adequate thermal icing protection for any aircraft is the protection of the propulsion system. The turbojet engine is known to be extremely susceptible to inlet icing and its operation is quickly and severely affected in a heavy icing condition.

A sketch of the inlet components of a typical axial-flow turbojet engine is presented in figure 11 with the most critical elements requiring icing protection indicated. Ice will collect on the inlet lips and on internal engine elements such as the accessory housing, island fairings, islands, screens, and compressor-inlet guide vanes. Ice accumulations have also been observed in the first stages of stator blades, but in most instances to date its presence in this region has not been significantly detrimental.

The problem of selection and design of thermal icing protection systems for the engine inlet is similar to that for the airplane wing inasmuch as the same heat-transfer processes are involved. Thus, icing protection for the engine can be accomplished by a suitable adaptation of either the hot-gas or electrical heating systems, continuously or cyclically operated.

Hot-gas bleedback. - Icing protection of turbojet engines may be obtained by addition of heat to the entire mass of air passing through the inlet; the inlet air and subcooled water droplet temperatures are thereby raised above freezing. When sufficient amounts of high-pressure, high-temperature gas are injected into the air stream at the inlet, the engine and most components in the inlet duct are afforded icing protection in one operation. A major disadvantage of this type of icing protection is that its operation imposes a severe penalty on engine performance. Accordingly, this discussion is limited to treatment of the hot-gas and electrical systems directly heating the exposed surfaces of the engine inlet components.

Local surface heating. - In the discussion of icing protection for airplane wings, it was shown that the heating requirements are partly a function of the heat density per unit area and the extent of chordwise heated area. For airplane wings, however, the impingement is generally limited to a small leading-edge region and the heated area extends only to 10 percent chord; whereas, for engine components such as screens, guide vanes, bearing struts, and island fairings, the area wetted by direct impingement of cloud droplets constitutes a major percentage of the entire surface. Calculations indicate that for cases in which the wetted area is large compared with the total component area, the most economical thermal-protection means is either by maintenance of the surface at 32° F by continuous heating or by cyclical de-icing. The energy requirement for engine components, consequently, is primarily a function of the equilibrium surface temperature. The requirement increases with decreasing equilibrium temperature. Although desirable, a uniform heated surface temperature at 32° F over the entire surface of a component is not easily obtained because of structural considerations and the inability to apply selectively the required heat to the entire surface without undue installation problems.

The amount of heat required to protect inlet screens against icing has been found to be extremely high in comparison with that of other inlet components, and, in addition, the practical problems involved in applying heat to the screen are formidable. For these reasons, it is assumed that inlet screens will be retracted during flight through icing conditions; consequently, protection requirements for screens are omitted from the present analysis.

In the absence of compressor-inlet screens, guide vanes constitute the greatest icing hazard to satisfactory engine operation; consequently, the heating requirements for a turbojet engine can be illustrated adequately by an analysis of the icing protection afforded to guide vanes for various methods of heating.

Analysis of heat requirements for engine icing protection at conditions 1 to 4 indicate that the peak heat load occurs at condition 3. A comparison of total heating requirements from a heat source necessary to protect a typical set of engine inlet guide vanes by cyclic electric, continuous electric, and continuous hot-gas systems is presented for condition 3 in the following table. The set of guide vanes consists of 28 vanes, each of 5-inch span and $2\frac{3}{8}$-inch chord.

Type of protection	Total heating requirements	
	(Btu/hr)	(kw)
Typical[a] cyclic electrical	5,230	1.53
Continuous electrical		
Ideal ($t_s = 32^\circ$ F)	16,250	4.75
Typical	23,400	6.84
Continuous hot gas		
Typical vane with insert	106,000	
Typical hollow vane	200,000	

[a]Typical indicates surface temperatures based on experimental data.

From the preceding tabulated results, the cyclic electrical requirement is about 22 percent of that for continuous electrical protection, 1.53 kilowatts as compared with 6.84 kilowatts, respectively. The savings in heat indicated for cyclic operation at this flight condition are representative of results obtained at the other conditions assumed in this analysis. Comparison between the heat required by a typical continuous electrical system with that of an ideal system which would maintain the surface temperatures at all points on the guide vanes exactly at 32° F indicates that considerable savings in heat can be attained with a good design. The preceding table also presents the heat requirements with continuous hot-gas heating for a fully hollow vane and for a guide vane containing an insert to improve heat-transfer efficiency. By means of inserts placed in the guide vanes, the heat required is decreased from 200,000 Btu per hour to 106,000 Btu per hour, a reduction of 47 percent. Guide vanes with inserts, therefore, have been assumed in the remainder of this analysis.

The calculations of the heating requirements for icing protection of island fairings, islands or bearing struts, and the accessory housing were based on directing the flow of hot gas through 1/8-inch annular passages adjacent to the outer skin and were made in a manner similar to the wing.

A study was made to determine (1) the gain in efficiency of the continuous hot-gas system which may be realized by circulating the hot gas through two or more of the engine inlet components in series, as opposed to heating all the components separately or in parallel, and (2) the advantage gained by utilizing a higher inlet gas temperature to the component, permissible if proper materials are utilized. The study was confined to the inlet guide vanes and island fairings which together account for most of the total heat load required by the engine inlet. Results of this study are given in the following table for condition 3:

Type of protection	Heating requirement for inlet guide vanes and island fairings (one turbojet engine)			
	Inlet gas temperature 350° F		Inlet gas temperature, 500° F	
	(Btu/hr)	Gas weight flow (lb/hr)	(Btu/hr)	Gas weight flow (lb/hr)
Parallel heating	181,000	2150	147,000	1250
Series heating	113,000	1350	108,000	900

At an inlet gas temperature of 350° F, the total hot-gas weight flow required can be reduced by 34 percent if the components are heated in series. If the inlet gas temperature can be raised from 350° to 500° F and series heating is utilized, a maximum weight-flow reduction of more than 50 percent is obtained. The reduction in heat required for icing protection caused by an increase in hot-gas temperature is somewhat less than the savings in weight flow.

A comparison of the total heat required for icing protection of all components within the engine inlet with a continuous electrical and with a continuous hot-gas system at the assumed flight conditions 2 to 4 is presented in the following table:

Condition	Engine requirement, continuous electrical		Engine requirement, continuous hot gas
	(kw)	(Btu/hr)	(Btu/hr)
2	8.5	29,000	140,000
3	12.7	43,400	229,000
4	10.7	36,600	176,000

For the preceding tabulated requirements, the hot-gas system was assumed to have an inlet gas temperature of 350° F and parallel heating of all components in the engine inlet. The peak heat load is reached at condition 3 and is 229,000 Btu per hour for the hot-gas system and 43,400 Btu per hour with the electrical system. The final selection of the heating system to be employed must, of course, take into account numerous practical considerations as well as system efficiency.

Windshield Icing Protection

A study was made of the icing protection requirements for a windshield commensurate with the assumed turbojet transport airplane. The windshield assumed in this analysis was a V-type configuration, and icing protection is to be accomplished by maintaining windshield surface temperatures above 32° F by continuous heating. Based on the information available in reference 12, the required heat flow from the surface for the operating and icing conditions of table I is a maximum of approximately 3200 Btu per hour per square foot at condition 4. The total source heating requirement for condition 4 was determined to be approximately 10 kilowatts for an electrical protection system and about 200,000 Btu per hour with hot gas. On a heat-requirement basis, windshield protection by electrical means appears more favorable because hot-gas or glass temperature limitations result in high required gas-flow rates; however, fabrication considerations may make the use of hot-gas protection more desirable.

Summary of Airplane Heating Requirements

Methods and operation of typical thermal icing protection systems for several aircraft components and the corresponding heating requirements have been analyzed and discussed. In order to summarize and compare these systems and component heating requirements for the turbojet transport operating over a probable and typical range of icing conditions, the total and component heating requirements for two thermal methods of icing protection are presented in figure 12. The values indicated in this figure were calculated for the turbojet transport previously illustrated and discussed and for three of the four icing conditions presented in table I; condition 1 was found not to be critical and the heating requirements for this condition are omitted. All the hot-gas requirements illustrated are for continuous heating, with the wing and tail requirements computed for a typical double-skin chordwise-flow system designed to evaporate all the intercepted water by 10 percent chord. The engine components and windshield requirements are based on maintaining the minimum surface temperatures just above freezing and independent heating of each engine element. The electrical requirements of figure 12 are based on an estimate of the performance of a cyclic de-icing system for wing, tail, and compressor-inlet guide vanes, and continuous electric heating of the remaining engine components and windshield.

In all conditions investigated, the total airplane heating requirement in Btu per hour with a cyclic electrical system of protection is considerably less than for continuous hot-gas protection, varying from a minimum of about 5 percent of the hot-gas requirement at condition 2 to a maximum of about 14 percent at condition 4. The maximum electrical requirement occurs at condition 4 and is approximately 490,000 Btu per hour or 143 kilowatts. The continuous hot-gas requirement varies from a maximum of about 7,500,000 Btu per hour at condition 2 to a minimum of about 3,400,000 Btu per hour at condition 3. The continuous hot-gas requirement for the high-speed cruising condition 4 is about equal to that obtained at climb condition 3; the decrease in cloud liquid-water content with altitude almost compensated for the increased speed. A reduction of the heat load required for the wings and tail surfaces by a factor of one fourth to one sixth obtained by use of a gas cyclic de-icing system would reduce the total hot-gas requirement by approximately 70 to 80 percent. From figure 12 it is evident that the wing and tail requirements for adequate thermal icing protection with a cyclic-electric or continuous hot-gas system represent the major portion of the total airplane requirement.

In order to attach significance to these total heating requirements for the turbojet transport airplane, the following section of this report evaluates the effects on airplane performance of adequate protection.

SOURCES OF ENERGY AND AIRPLANE PERFORMANCE

Sources of Energy

The necessity of a considerable source of heat to operate the icing protection system is evident from the large heating requirements of the turbojet-powered airplane. An obvious source of this energy is the turbojet engine. Figure 13 illustrates schematically the means by which energy can be removed from the turbojet engine.

Power may be extracted from the shaft of the engine to drive an electric generator and operate a continuous or cyclic electrical icing protection system. Air may be bled from the compressor outlet, which provides a source of high-pressure air at the desired temperature. Hot gas may also be bled from the turbine inlet or the tail pipe of the engine. These gases are normally available at higher temperatures than those usable directly in a conventional hot-gas system (350° F) and consequently must be mixed with sufficient cooling air to reduce the temperature to the allowable limit. Mixing may be accomplished by means of a jet pump or ejector, thus resulting in a slightly heavier and more complex system than in the case of compressor bleed. Turbine-inlet and tail-pipe bleed sources also have the disadvantage that the gas contains products of combustion and may present clogging and corrosion problems in the distribution system. The tail-pipe heat exchanger is a source of limited amounts of heat energy; however, the length of heat exchanger required and the resultant pressure drop cause this source of energy to appear less favorable for the quantities of energy indicated in figure 12.

All methods of extracting energy from the turbojet engine have the advantage that the energy source is readily available with a minimum weight penalty to the airplane. These sources do, however, reduce the maximum thrust that can be obtained from the engine and increase the fuel consumption.

In addition to the use of a turbojet engine as an energy source, auxiliary sources of energy such as combustion heaters and small gas-turbine auxiliary power units may be used. The two most attractive of the auxiliary power units generally available appear to be (1) a unit in which the exhaust gases from an auxiliary power unit are mixed with cooling air and used to operate a hot-gas system or (2) a unit which drives electric generators. All auxiliary sources of energy have the advantage that they may be operated at full capacity without affecting the performance of the turbojet engine. Their operation does, however, affect the total drag of the airplane since a momentum drag loss is incurred by taking in the air which operates the auxiliary systems. The use of such units also penalizes airplane performance by virtue of additional weight and fuel consumption.

Airplane Climb Performance

The extraction of energy from a turbojet engine results in a reduction in the maximum thrust available from the engine and, consequently, a reduction in rate of climb. The performance characteristics of a turbojet engine operating with various methods of heat extraction were obtained from references 13 to 15. The following table presents the total losses in rate of climb incurred through use of the various heat sources at the climb condition 2.

Source of energy	Decrease in climbing rate (percent)
Compressor bleed	44
Turbine-inlet or tail-pipe bleed	13
Hot-gas combustion heater or auxiliary power unit	6
Electric shaft power or auxiliary power unit	1/2

Losses in rate of climb due to extraction of energy from the engine by an icing protection system are most severe when hot gas is bled from the engine compressor and almost negligible with electric shaft power. Calculations indicate that the penalty imposed on rate of climb from compressor-bleed air becomes less as the engine compressor ratio is increased. An engine with a pressure ratio of 10, for example, would provide compressor-bleed air with a decrease in climbing rate of about 30 percent. The increase in fuel consumption resulting from the use of a protection system during climb is of secondary interest compared with the decrease in climbing rate due to the short period of time in which it is likely to encounter icing during a climb.

Airplane Cruise Performance

During cruise the engines are normally operated at less than maximum power, and flight speed can be maintained constant by increasing the fuel flow while the icing protection system is in operation. This increase in fuel flow, together with the installed weight of the protection equipment, reduces the allowable pay load. Figure 14 presents the decrease in pay load as a function of the percent of flight time during which the icing protection system is in operation. The ordinate intercept is a measure of the installed weight of the equipment and the slope is proportional to the additional fuel burned. From consideration of the pay load, the weight of the equipment is of particular importance if the system is to be operated for only a short period of time. For very short anticipated icing encounters, a system such as compressor bleed appears most favorable. For longer anticipated icing times the fuel flow becomes more important and a hot-gas system operated with tail-pipe bleed or an electrical system operated from shaft power become more attractive. The average length of an icing encounter may be quite small, in order of 1 or 2 percent of the total flight time. The auxiliary power units presented on figure 14 are too heavy to make them relatively attractive from the pay-load standpoint. However, if a certain amount of auxiliary equipment is needed for purposes other than icing protection, a portion of their weight may be otherwise chargeable.

Airplane Descent Performance

During climb and cruise the turbojet engines are operated at relatively high power levels; however, during the descent portion of the flight, it will be necessary to operate engines at much lower power levels in order that the placard dive speed of the airplane will not be exceeded. Therefore, the availability of energy from the turbojet engine during descent is considerably lower than in either climb or cruise. An electrical system operating with shaft power could provide adequate protection during descent provided the generators were designed to operate over a wide range of engine speeds. Also, turbine-inlet and tail-pipe bleed temperatures are sufficient to provide protection even at low engine speeds. Compressor-outlet temperatures are so low that protection of the complete airplane during descent by means of compressor bleed air is doubtful; however, sufficient energy may be available to prevent serious engine icing. Furthermore, it should be possible at any time during descent to level out for a short period of time, increase the engine power, and shed the ice formations.

CONCLUDING REMARKS

Icing protection will be required for a typical high-speed, high-altitude turbojet transport airplane operating over a probable range of icing conditions because aerodynamic heating is not sufficient to raise the temperature of an unheated surface above the freezing level.

Icing protection for the turbojet airplane may be accomplished by conventional hot-gas systems, although the heating requirements and performance penalties are considerably increased from those now associated with lower-speed aircraft. Provision for this increased heat demand necessitates a critical study of its effect on the performance of the turbojet airplane, an airplane the operating criteria of which are restricted even in ideal flight conditions.

The maximum continuous hot-gas requirement for the turbojet transport occurred near 15,000 feet and is approximately 7,500,000 Btu per hour, with wing and tail protection comprising over 90 percent of this total. The airplane protection requirement can be reduced to a maximum of approximately 490,000 Btu per hour or 143 kilowatts by using a cyclic electrical de-icing system.

The problem of providing for the maximum continuous hot-gas requirement of 7,500,000 Btu per hour is minimized by employing the turbojet engine as the heat source. This large heat requirement represents approximately a 10-percent bleed of the engine air flow, assuming a 350° F initial gas temperature to the protection system. Use of a gas cyclic de-icing system should reduce these requirements by approximately 70 to 80 percent.

The airplane performance penalties chargeable to providing icing protection vary considerably with the energy source employed. The proper selection of a heat source for an aircraft icing protection system depends on several considerations such as effect on rate of climb and on pay load, amount of time expected to be in icing, and practical design limitations. On the basis of this investigation a continuous hot-gas system with compressor-discharge air appears the most attractive for short icing encounters if the high penalty on thrust or rate of climb can be tolerated. By utilizing a gas cyclic de-icing system, the climb and thrust penalties can be reduced considerably. For longer icing times, a cyclic electrical de-icing or a continuous hot-gas system with turbine-inlet or tail-pipe gas appears more feasible.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 25, 1952

APPENDIX A

SYMBOLS

a distance measured spanwise between center line of adjacent heating channels in a typical double-skin icing protection system (fig. 8(a)), in.

b spanwise width of one chordwise-flow heating channel (fig. 8(a)), in.

C airfoil chord length, ft

c_p specific heat of air at constant pressure, 0.24 Btu/(lb)($^{\circ}$F)

D diameter of leading-edge equivalent cylinder, ft

D_h hydraulic diameter of chordwise-flow heating channel, equal to four times the cross-sectional area of flow divided by the wetted perimeter, ft

E_M collection efficiency of airfoil, percent

e vapor pressure of saturated air, in. Hg

g acceleration due to gravity, 32.2 ft/sec^2

h height of chordwise-flow heating channel (fig. 8(a)), in.

h_c dry-air external convective heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)

$h_{c,g}$ internal convective heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)

J mechanical equivalent of heat, 778 ft-lb/Btu

K surface area wetted, percent

k thermal conductivity of air, Btu/(hr)(sq ft)($^{\circ}$F)/ft

L latent heat of vaporization of water, Btu/lb

M_a weight rate of water droplet impingement per unit of surface area, lb/(hr)(sq ft)

M_e weight rate of water evaporated from surface per unit of surface area wetted, lb/(hr)(sq ft)

n exponent of Prandtl number: 1/2 for laminar flow; 1/3 for turbulent flow

Pr Prandtl number, $3600c_p\mu/k$, dimensionless

p pressure, in. Hg

q unit rate of heat flow, Btu/(hr)(sq ft)

Re_d Reynolds number, $VD\gamma/\mu$, based on diameter of equivalent cylinder and free-stream conditions, dimensionless

Re_s Reynolds number, $Us\gamma/\mu$, based on surface distance and local surface conditions, dimensionless

s distance measured chordwise along airfoil surface from stagnation point, ft

t temperature, $^{\circ}F$

$\overline{T}$ or $\overline{t}$ arithmetic average of inlet and outlet temperature, $^{\circ}R$ or $^{\circ}F$

U local velocity just outside boundary layer, ft/sec

V free-stream velocity, ft/sec

W weight flow of gas, lb/hr

w weight flow of gas per unit cross-sectional area, lb/(hr)(sq ft)

x distance measured chordwise along airfoil chord line from leading edge, ft

γ specific weight of air, lb/cu ft

μ viscosity of air, lb/(sec)(ft)

Subscripts:

e evaporative heat transfer

g heated gas

i inlet or initial

s conditions at airfoil surface

0 free-stream conditions

1 conditions at outer edge of boundary layer

Superscripts:

' wet-air equilibrium

'' dry-air equilibrium

APPENDIX B

EQUILIBRIUM TEMPERATURE OF A SURFACE

The equilibrium temperature of a surface in an air stream can be determined for any condition by the solution of an appropriate heat balance (reference 16). The equilibrium temperature is the temperature a surface not artifically heated would assume in a steady-state condition. In a wet-air stream or cloud, an equilibrium surface temperature equal to at least 32° F (and with no ice considered to have formed) precludes the need for artificial heating. The appropriate heat balance for this limiting condition, with a fully wetted surface assumed, can be written as

heat gain to surface = heat loss from surface

$$\begin{bmatrix}\text{frictional heating in}\\ \text{boundary layer}\end{bmatrix} + \begin{bmatrix}\text{conversion of the}\\ \text{kinetic energy of}\\ \text{the droplets to heat}\end{bmatrix} = \begin{bmatrix}\text{convective}\\ \text{heat}\\ \text{transfer}\end{bmatrix} +$$

$$\begin{bmatrix}\text{evaporative}\\ \text{heat}\\ \text{transfer}\end{bmatrix} + \begin{bmatrix}\text{sensible heating}\\ \text{of impinging}\\ \text{water}\end{bmatrix}$$

or

$$\frac{h_c U^2}{2gJc_p}\left(Pr^n\right) + \frac{M_a V^2}{2gJ} = h_c\left(t_s' - t_1\right) + \frac{0.622 h_c L}{c_p p_1}\left(e_s' - e_1\right) + M_a\left(t_s' - t_0\right) \tag{B1}$$

With the assumption that the flow process from the free stream to the surface is isentropic and that no change of phase in the air which is initially saturated and remains so throughout the boundary layer, occurs, then, from reference 18,

$$t_1 = t_0 + \frac{V^2 - U^2}{2gJc_p}$$

and

$$e_1 = e_0 \frac{p_1}{p_0}$$

The equilibrium surface temperature in an air stream containing liquid water t_s' from equation (B1) then becomes

$$t_s' = t_0 + \frac{\frac{V^2}{2gJc_p}\left[1 - \left(\frac{U}{V}\right)^2 (1 - Pr^n) + \left(\frac{M_a}{h_c}\right)c_p\right] - \frac{0.622L}{c_p}\left[\left(\frac{e_s'}{p_1}\right) - \left(\frac{e_0}{p_0}\right)\right]}{\left[1 + \left(\frac{M_a}{h_c}\right)\right]} \tag{B2}$$

and the solution for the minimum flight speed, that is, V for t_s' equal to 32° F (and no ice), is

$$V^2 = \frac{2gJc_p\left\{(32 - t_0)\left[1 + \left(\frac{M_a}{h_c}\right)\right] + \frac{0.622L}{c_p}\left[\left(\frac{e_s'}{p_1}\right) - \left(\frac{e_0}{p_0}\right)\right]\right.}{\left[1 - \left(\frac{U}{V}\right)^2 (1 - Pr^n) + \left(\frac{M_a}{h_c}\right)c_p\right]} \tag{B3}$$

Because e_s' is the saturation vapor pressure at t_s', and M_a, h_c, U, and p_1 are functions of body geometry and flight speed V, equations (B2) and (B3) are solved by trial and error. The importance of and complexity in determining the rate of water droplet impingement M_a and the convective and evaporative heat-transfer terms (see equation (B1)) warrant separate and detailed discussion in the section Water droplet impingement and in appendixes C and D.

In a dry air stream (no liquid water), equation (B2) for the equilibrium surface temperature reduces to

$$t_s'' = t_0 + \frac{V^2}{2gJc_p}\left[1 - \left(\frac{U}{V}\right)^2 (1 - Pr^n)\right]$$

where t_s'' is defined as the equilibrium surface temperature in dry air. Solving for the minimum flight speed V for t_s'' equal to 32° F results in

$$V^2 = \frac{2gJc_p(32 - t_0)}{\left[1 - \left(\frac{U}{V}\right)^2 (1 - Pr^n)\right]}$$

APPENDIX C

EVAPORATIVE HEAT TRANSFER

The total amount of water evaporated from a surface in an air stream containing liquid water is equal to the product of a mass transfer coefficient for water vapor and the vapor pressure difference across the thermal boundary layer. The total water evaporated has two components, the evaporation due to kinetic heating and that due to aritificial heating. The expression for the total water evaporated from a fully wetted surface can be simply derived from reference 17 to give

$$M_e = \frac{0.622h_c}{c_p p_1}(e_s - e_1) \tag{C1}$$

If no phase change is assumed in the air which is initially saturated, then equation (C1) becomes

$$M_e = \frac{0.622h_c}{c_p}\left[\left(\frac{e_s}{p_1}\right) - \left(\frac{e_0}{p_0}\right)\right] \tag{C2}$$

Since the rate of heat transfer per unit area due to evaporation is given as

$$q_e = M_e L$$

then

$$q_e = \frac{0.622Lh_c}{c_p}\left[\left(\frac{e_s}{p_1}\right) - \left(\frac{e_0}{p_0}\right)\right] \tag{C3}$$

These evaporation relations apply only to a fully wetted ice-free surface. If the surface is only partly wet, such as downstream of direct impingement of the water droplets (see reference 8), the reduced area from which evaporation occurs must be considered. Similar consideration should be given evaporation terms in the calculation of the equilibrium surface temperature for a partly wetted surface (see appendix B). Because an exact description of the evaporation process from a partly wetted surface is lacking, the expressions for evaporative heat transfer, equations (C1), (C2), and (C3), are modified by a factor K, the percentage of the surface area which is actually wetted. Limited experimental evidence (references 8 and 18) indicates that K decreases sharply from a value of unity near the limit of impingement to a mean value of approximately 25 percent 1 inch downstream of the impingement limit and decreases slowly thereafter. These investigations (references 8 and 18) also indicate that this use of K to determine the evaporation area yields reasonably accurate results.

APPENDIX D

EXTERNAL CONVECTIVE HEAT-TRANSFER COEFFICIENT

Detailed methods of determining the external dry convective heat-transfer coefficient h_c have been developed in references 19 to 21. Sufficient accuracy for an airfoil heating-requirement study is usually obtained with the assumption that the convective heat-transfer coefficient from the airfoil leading-edge surface is equal to that over the forward half of a cylinder with a diameter similar to that of the leading edge and the remaining upper and lower airfoil surface equal to the heat-transfer coefficients from flat plates. The empirical equations of Martinelli (reference 21) used herein to determine h_c are for a cylinder

$$h_c = \frac{1.14(Pr)^{0.4} \ (Re_d)^{0.5} \ k}{D}\left[1 - \left(\frac{\theta}{90}\right)^3\right] \tag{D1}$$

(where θ is the angle in degrees from air stagnation to the point of interest)

for a flat plate with laminar flow

$$h_c = \frac{0.332(Pr)^{1/3} \ (Re_s)^{0.5} \ k}{s} \tag{D2}$$

for a flat plate with turbulent flow

$$h_c = \frac{0.0296(Pr)^{1/3} \ (Re_s)^{0.8} \ k}{s} \tag{D3}$$

The properties of the air in these equations are assumed to be an arithmetic average of free stream and surface, as in reference 21. A quantitative comparison of the convective coefficients based on the solution of equations (D1) to (D3) is presented in figure 15 for the NACA 65_1-212 airfoil with mean chord of 15.8 feet operating at conditions 2 and 4.

The presence of water on an airfoil surface produces an earlier transition from a laminar to turbulent heat-transfer coefficient as does an increase in air speed (references 8 and 18). In an icing condition it is doubtful that transition will be delayed more than the 10-percent chord point indicated by this typical transition curve shown in figure 15(a); the actual location of transition in icing will probably fluctuate but should occur between the leading-edge cylinder curve and the transition curve shown. Because no definite basis for the determination of the transition region other than limited data in references 8 and 18 is available, a straight-line transition from the stagnation point to the turbulent flat-plate value at 10 percent chord (fig. 15) may be assumed for convenience in calculations. The validity of using a straight-line-transition curve and the magnitude of error obtained may be determined by a comparison of the total-heat-requirement calculations for an airfoil based on the two transition curves shown in figure 15(a).

The use of the straight-line-transition curve yielded an increase of about 25 percent in gas weight flow necessary for evaporating all the impinging water for condition 4 but decreased the chord heated extent by 15 percent. Because these percentages of error are in at least the same order of magnitude as are the errors in the assumptions of meteorological variables, the straight-line-transition curve is used in all calculations pertinent to the results reported herein.

APPENDIX E

INTERNAL HEAT TRANSFER IN CONTINUOUS HOT-GAS SYSTEM

The heat balance which describes the heat-transfer processes involved in a hot-gas system (fig. 5) is approximated by the following equation:

$$q\left(\frac{a\Delta s}{12}\right) = (h_{c,g})(\overline{t}_g - t_s)\left(\frac{2b\Delta s}{12}\right) \tag{E1}$$

When heat is transferred to the skin or surface, the gas temperature decreases as it flows chordwise through the double-skin passage. This process is described by

$$q\left(\frac{a\Delta s}{12}\right) = Wc_p\Delta t_g \tag{E2}$$

The term $h_{c,g}$ (equation (E1)) is the internal convective heat-transfer coefficient of the hot gas in the shallow heating channels. For this analysis, $h_{c,g}$ is determined for the entrance region to the double-skin passages by the following equation:

$$h_{c,g} = \frac{0.1217k}{s^{0.3}}\left(\frac{w}{3600\mu}\right)^{0.7} \tag{E3}$$

Equation (E3) is a modification of the empirically determined equation by J. K. Hardy and R. Morris for the entrance region. A curve of equation (E3) intersects the one for fully developed turbulent pipe flow about 25 hydraulic diameters downstream of the entrance. After the point of intersection, the following equation from reference 22 is used:

$$h_{c,g} = 0.022(Pr)^{1/3}\left(\frac{w}{3600\mu}\right)^{0.8}\frac{k}{(D_h)^{0.2}}$$

$$= 5.4\times10^{-4}(\overline{T}_g)^{0.3}\frac{(w)^{0.8}}{(D_h)^{0.2}} \text{ (turbulent)} \tag{E4}$$

The term $\overline{T}_g$ is an estimated value of the mean gas temperature in the turbulent flow region.

Some experimental data concerning the local value of the internal convective heat-transfer coefficient $h_{c,g}$ for typical double-skin anti-icing systems (reference 23) indicate that the values calculated from equations (E3) and (E4) may be too high by 20 to 30 percent. Because of the uncertainties in the determination of the local internal coefficient, no complete recalculation of the results was performed. A few points, however, were recalculated with the lower value of the internal coefficient and they indicated that the value of the internal coefficient has a significant effect on the heating requirement for complete evaporation of the intercepted water. From the limited number of calculations performed, the heat required to evaporate all the intercepted water was increased by about 20 percent when the local internal heat-transfer coefficient was assumed decreased by 30 percent.

The term q in equations (E1) and (E2) is the unit rate of heat flow also described by equation (1) of the text; and the three equations, (1), (E1), and (E2), are solved simultaneously to satisfy the heat balance from the heat source to the free air stream. This solution is considered to be an adequate approximation in the determination of the weight flow of hot gas required, but is based on the assumption of negligible chordwise conduction in the thin metal skin. Preliminary calculations including the conduction effects provided results not substantially different from those in which conduction is neglected; therefore, equations (1), (E1), and (E2) were solved by a step-by-step trial-and-error manner as follows.

For a condition in which the factors in equation (1) affecting the external heat-transfer rate are known, and the internal passage configuration is also known, the first step is to select a value of hot-gas weight flow W. By assuming a drop in hot-gas temperature in a small increment of length, a trial value of q can be calculated from equation (E2). With this trial value of q and a mean value of gas temperature $\bar{t}_g$ of $(t_{g,i} - \frac{1}{2}\Delta t_g)$, the heated surface temperature t_s can be calculated from equation (E1). With this value of surface temperature the external heat-transfer rate can be determined from equation (1) and compared with the trial value obtained from equation (E2). If the two values of q do not agree, a new value of Δt_g must be assumed and the process repeated until a heat balance is obtained.

For each chordwise length increment assumed, the amount of water being evaporated from the heated surface can be calculated from appendix C as

$$M_e = \frac{0.622}{c_p} h_c \left[\left(\frac{e_s}{p_l}\right) - \left(\frac{e_0}{p_0}\right)\right] K$$

From a knowledge of the amount of water impinging on the wing M_a and the amount being evaporated M_e, the quantity of water running aft on the the wing can be calculated. This step-by-step process is continued in a chordwise direction until all the water has been evaporated or until the surface temperature is reduced to 32° F. By this method of calculation, the chordwise distance which must be heated in order to evaporate all the water intercepted by the wing, and the minimum amount of weight flow of hot gas that will evaporate all the water before the surface temperature drops to 32° F, can be determined.

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TABLE I - ICING AND OPERATING CONDITIONS FOR HYPOTHETICAL

TURBOJET TRANSPORT

Condition	Flight speed (mph)	Pressure altitude (ft)	Altitude	Liquid-water content (g/cu m)	Droplet[1] diameter (microns)	Free-stream static air temperature (°F)
1	350	0 to 10,000	Climb and descent	0.6	15	20
2	350	10,000 to 20,000	Climb and descent	.4	20	0
3	350	20,000 to 30,000	Climb and descent	.2	15	-25
4	500	30,000	Cruise	.1	15	-40

[1]Uniform droplet size distribution.

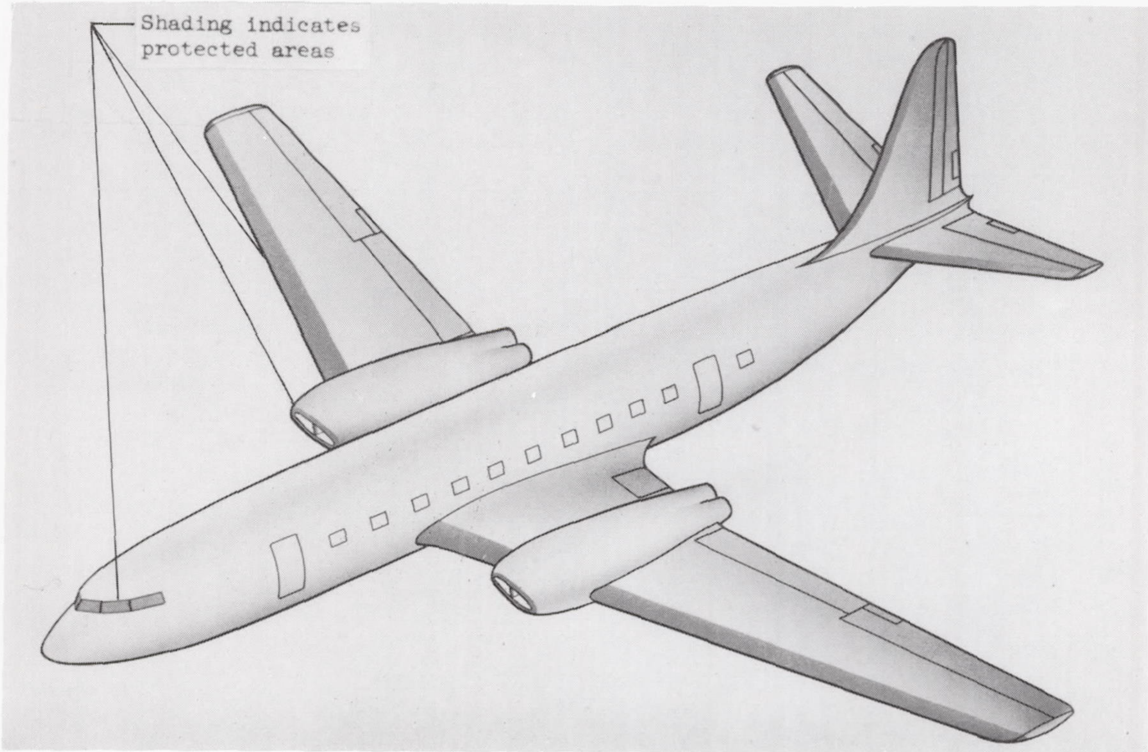
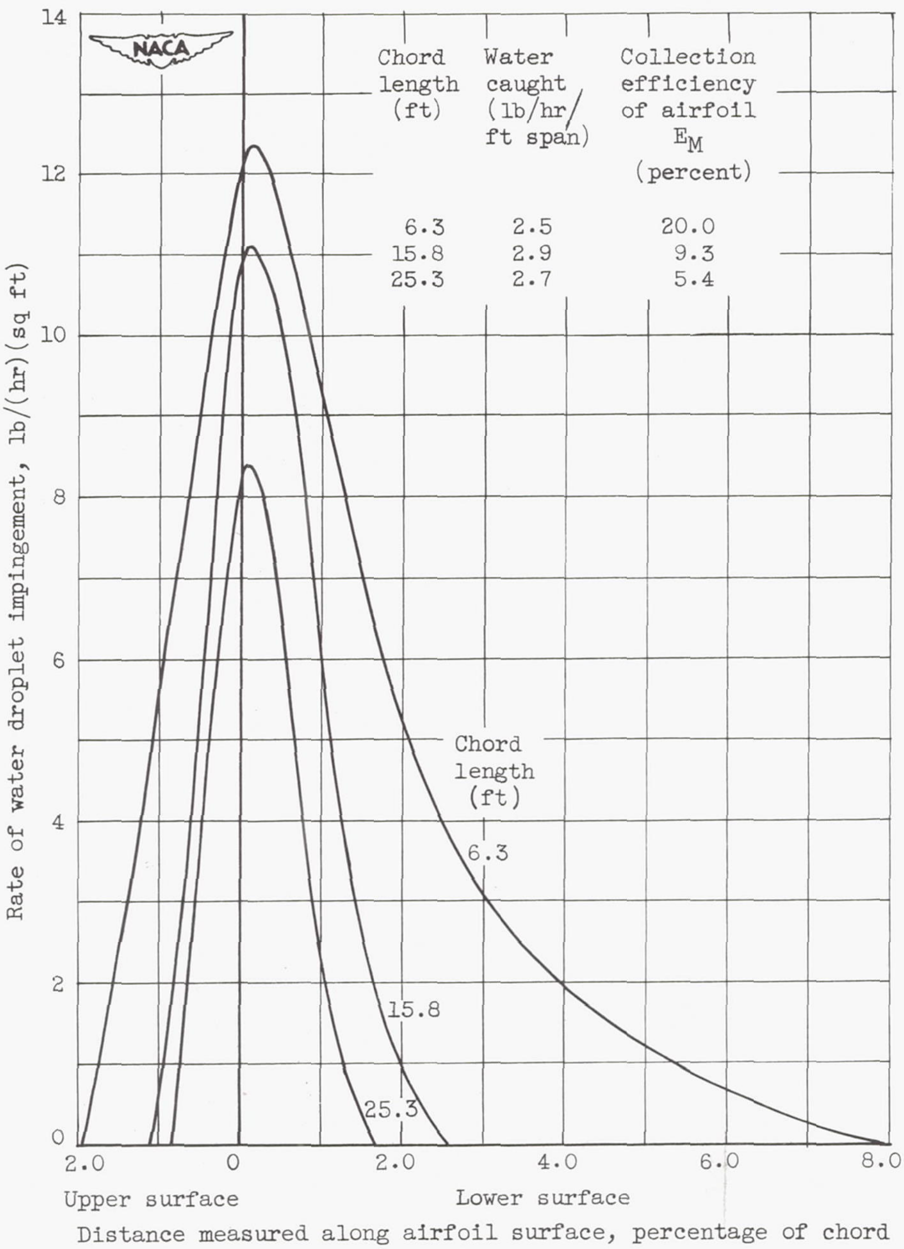


Figure 1. - Hypothetical turbojet transport airplane assumed in calculations. Gross weight, 125,000 pounds; wing span, 158 feet; wing section, NACA 65_1-212; wing taper, 4:1; cruising speed, 500 miles per hour.

(a) Conditions 1 to 4. Chord, 15.8 feet.

Figure 2. - Estimated rate and area of water droplet impingement. Airfoil, NACA 65_1-212. (Based on extrapolated results from reference 3.)



(b) Condition 4. Three chord sizes.

Figure 2. - Concluded. Estimated rate and area of water droplet impingement. Airfoil, NACA 65_1-212. (Based on extrapolated results from reference 3.)

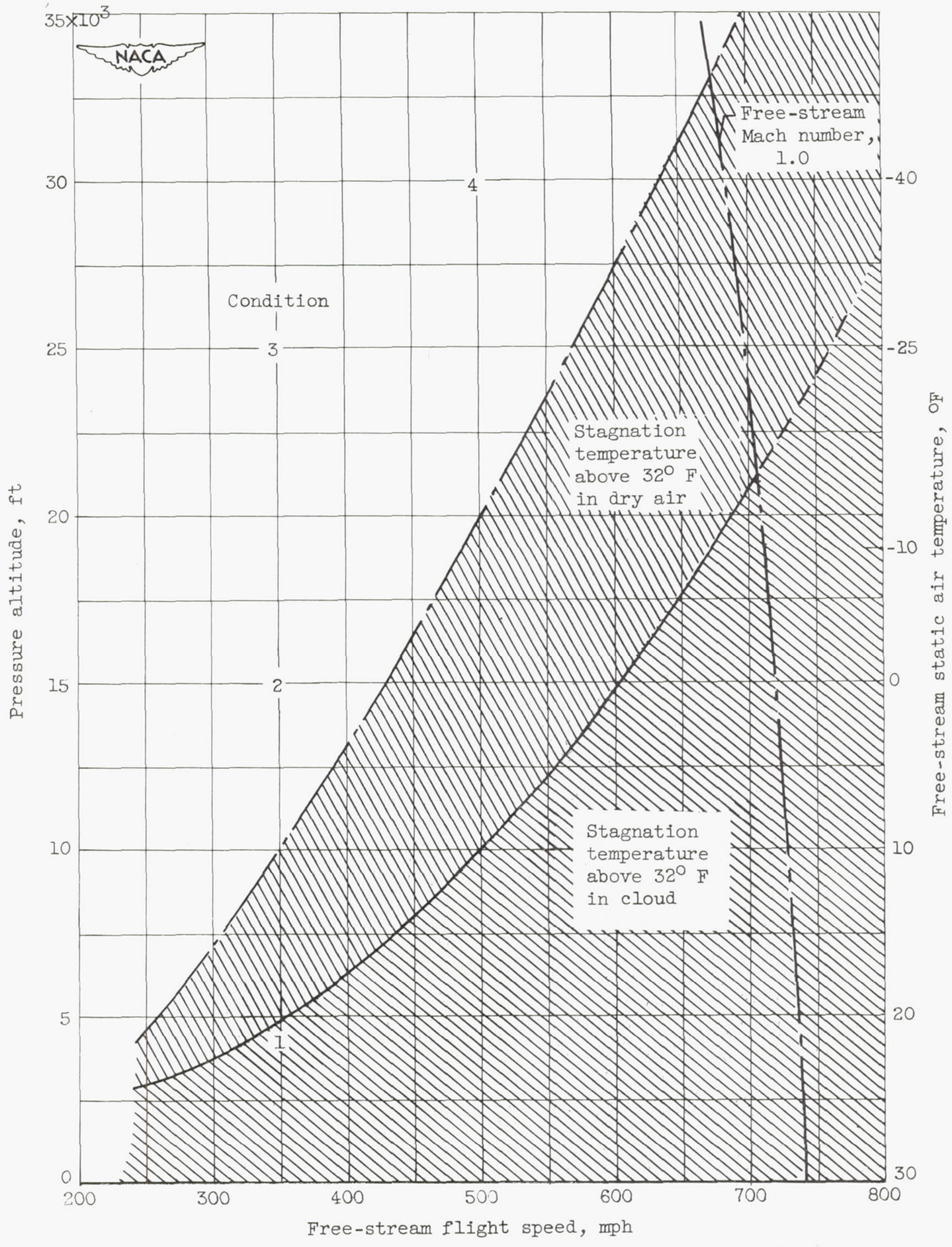


Figure 3. - Minimum flight speed required to attain 32° F ice-free equilibrium surface temperature at stagnation point. Airfoil, NACA 65_1-212; chord, 15.8 feet. (Appropriate icing clouds defined in table I.)

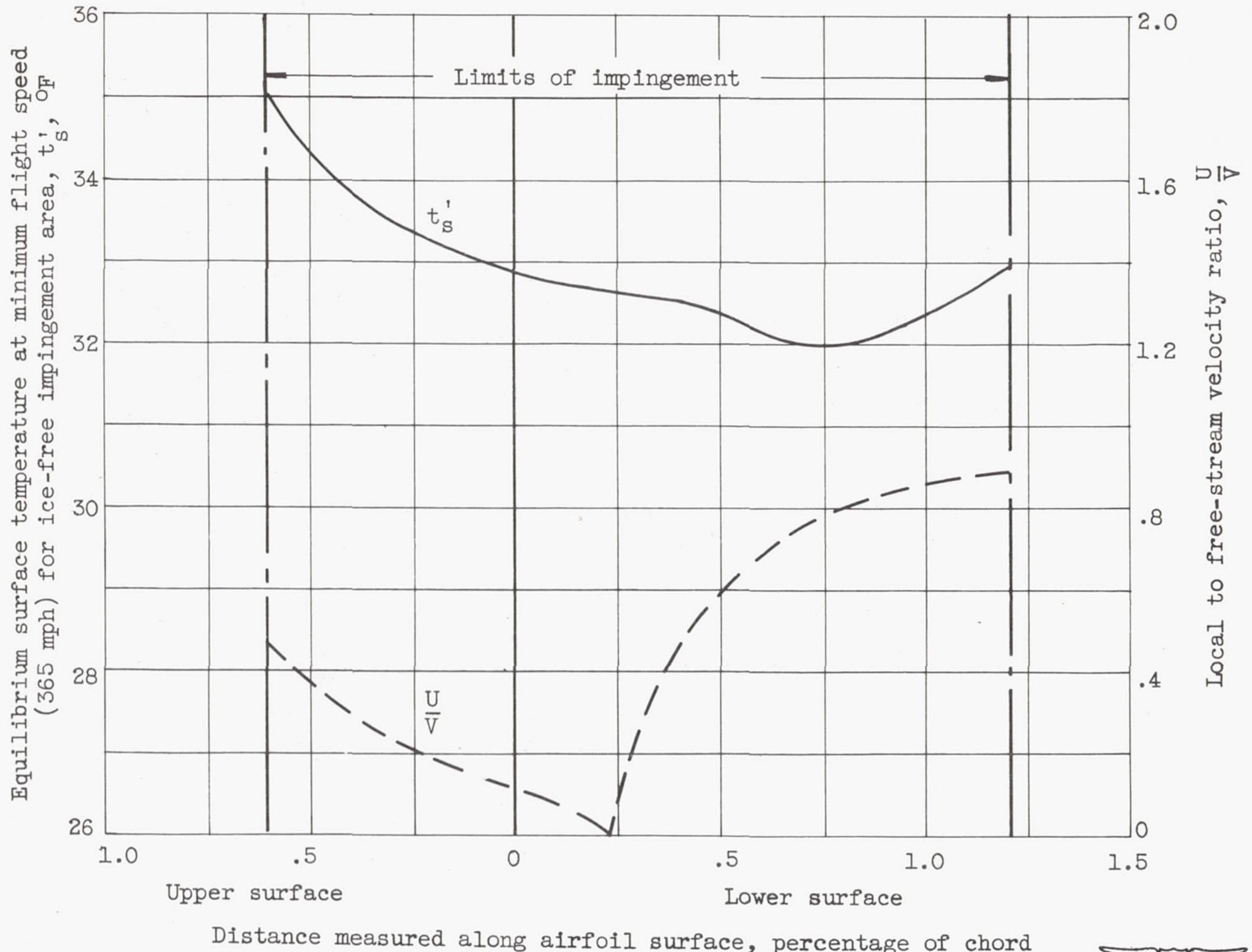


Figure 4. - Profile of equilibrium surface temperatures at minimum flight speed for ice-free impingement area and velocity ratio profile for airfoil operating in icing cloud. Condition 1; airfoil, NACA 65_1-212; chord, 15.8 feet.

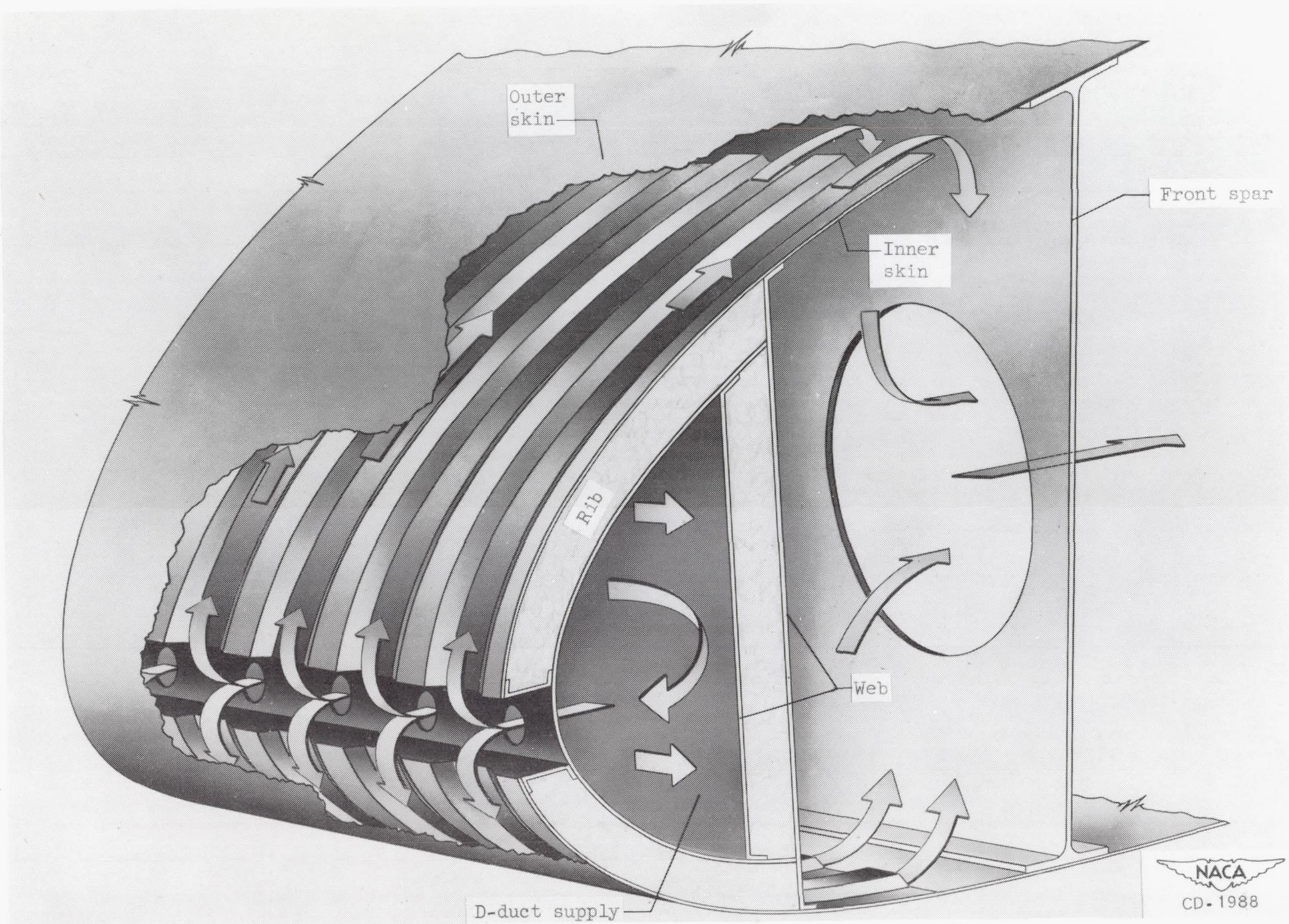


Figure 5. - Typical chordwise-flow, hot-gas wing icing protection system.

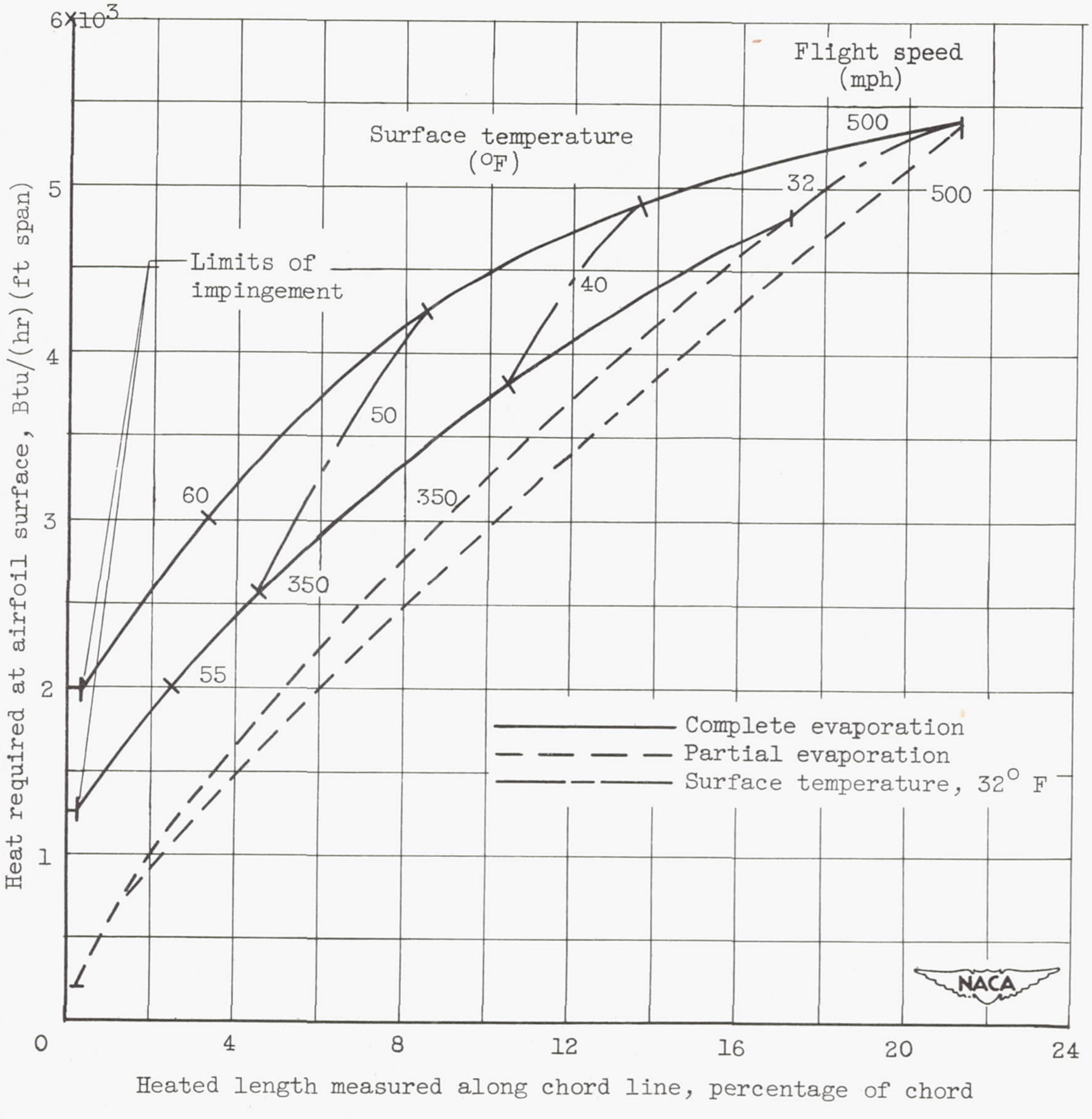


Figure 6. - Variation in heat and heated chordwise distance required (at upper surface of airfoil) for complete and partial evaporation of intercepted water at various uniform surface temperatures and two flight speeds. Airfoil, NACA 65_1-212; chord, 15.8 feet; altitude, 30,000 feet; air temperature, -40° F; liquid-water content, 0.1 gram per cubic meter; drop size, 15 microns.

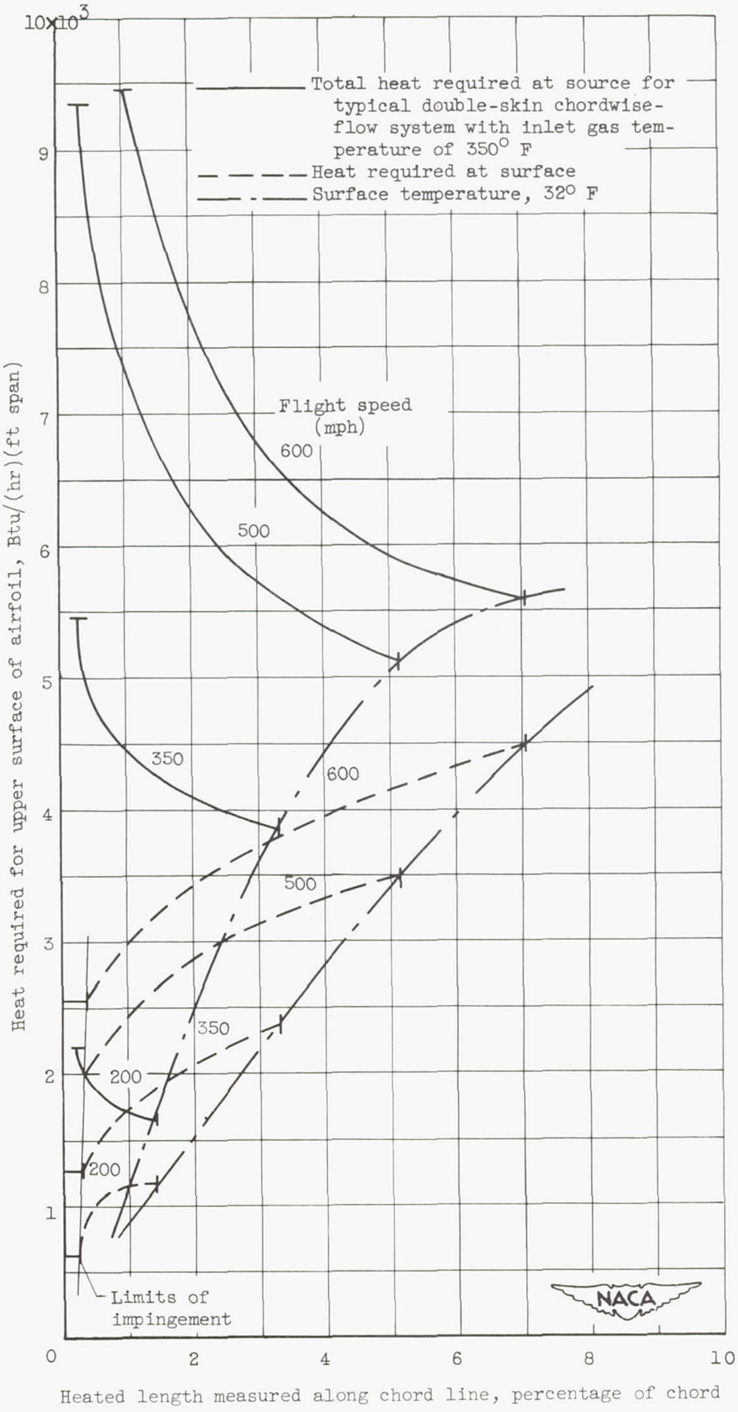
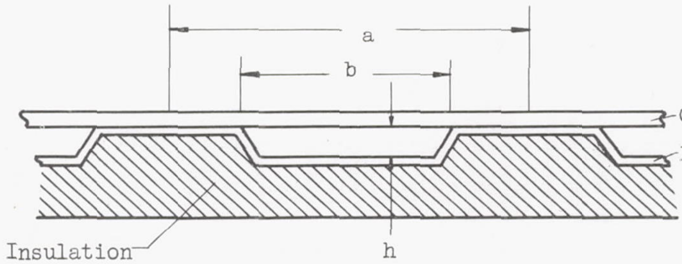
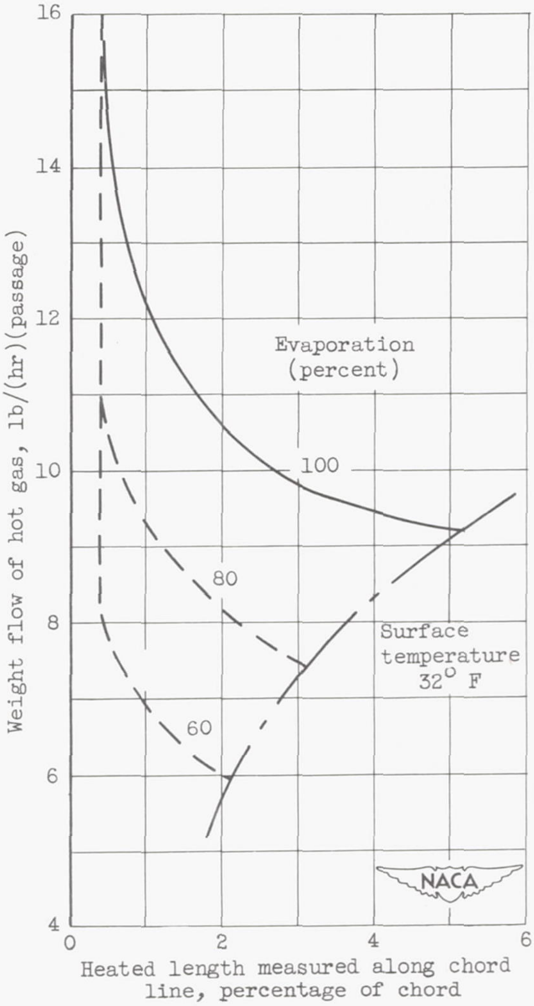


Figure 7. - Variation with flight speed of heat required at airfoil surface and total heat required at source for complete evaporation of water intercepted by NACA 65_1-212 airfoil. Chord, 15.8 feet; altitude, 30,000 feet; air temperature, -40° F; liquid-water content, 0.1 gram per cubic meter; drop size, 15 microns.



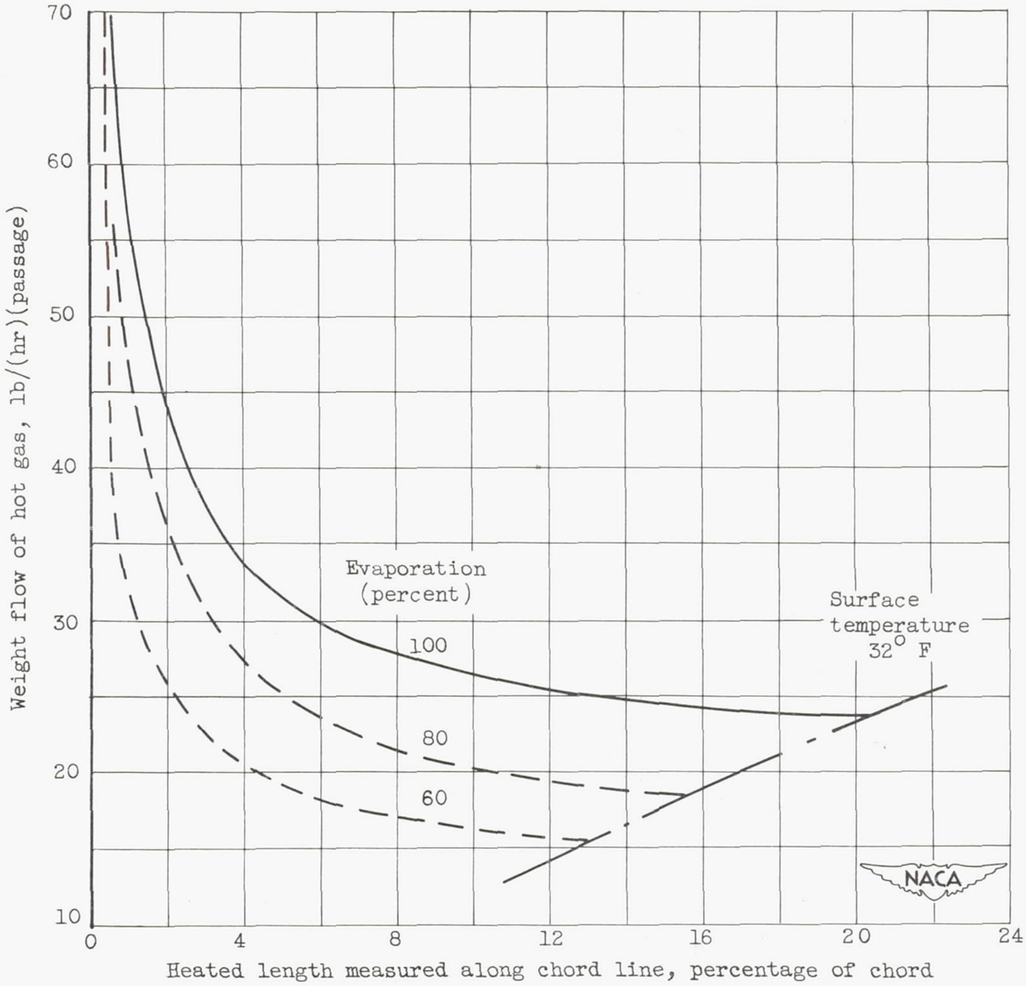
Typical double-skin chordwise-flow cross-sectional view

a = 1.75 in., b = 1.0 in., h = 0.125 in.



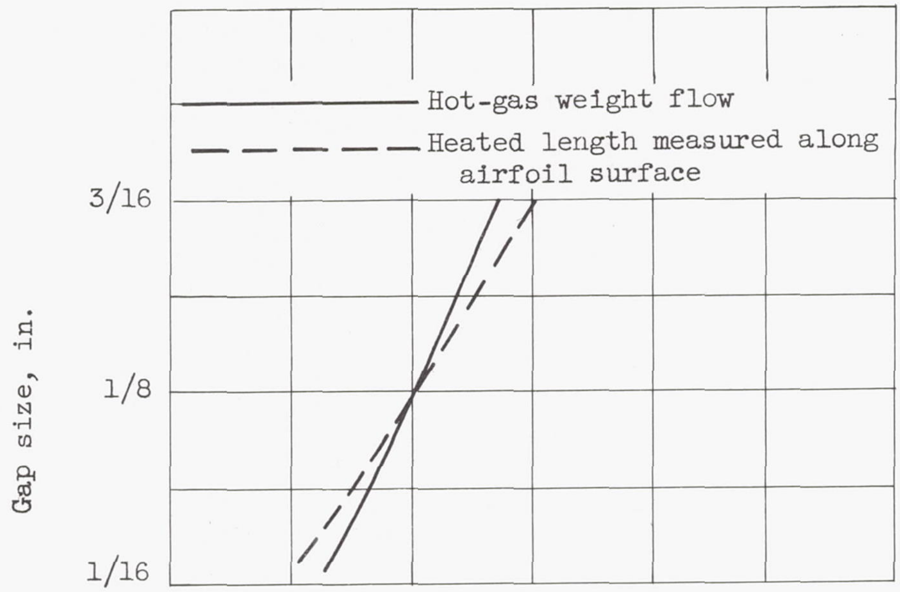
(a) Condition 4.

Figure 8. - Variation of weight flow with heated length for continuous hot-gas chordwise-flow wing icing protection system. Upper surface of NACA 65_1-212 airfoil; chord, 15.8 feet; inlet gas temperature, 350° F.

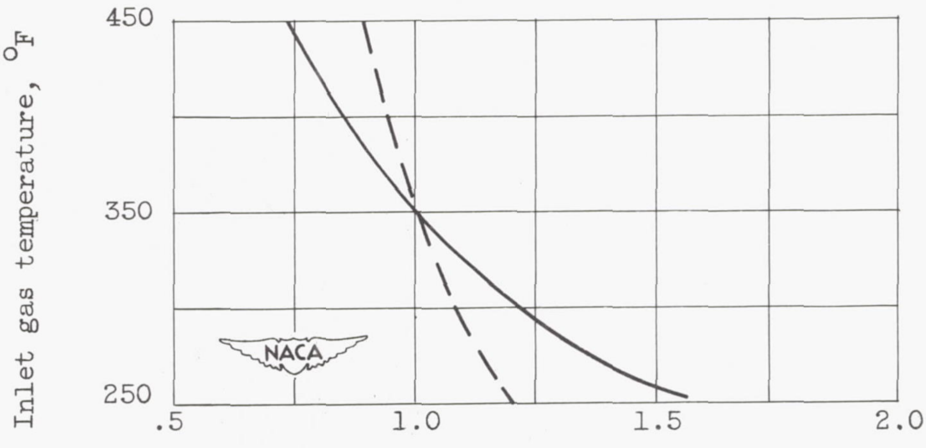


(b) Condition 2.

Figure 8. - Concluded. Variation of weight flow with heated length for continuous hot-gas chordwise-flow wing icing protection system. Upper surface of NACA 65_1-212 airfoil; chord, 15.8 feet; inlet gas temperature, 350° F.



(a) Gap size.



(b) Inlet gas temperature.

Figure 9. - Effects of variations in internal design characteristics on minimum requirements for complete evaporation. Typical chordwise-flow wing icing protection system. Condition 4; airfoil, NACA 65_1-212; chord, 15.8 feet; inlet gas temperature, 350° F; gap size, 1/8 inch.

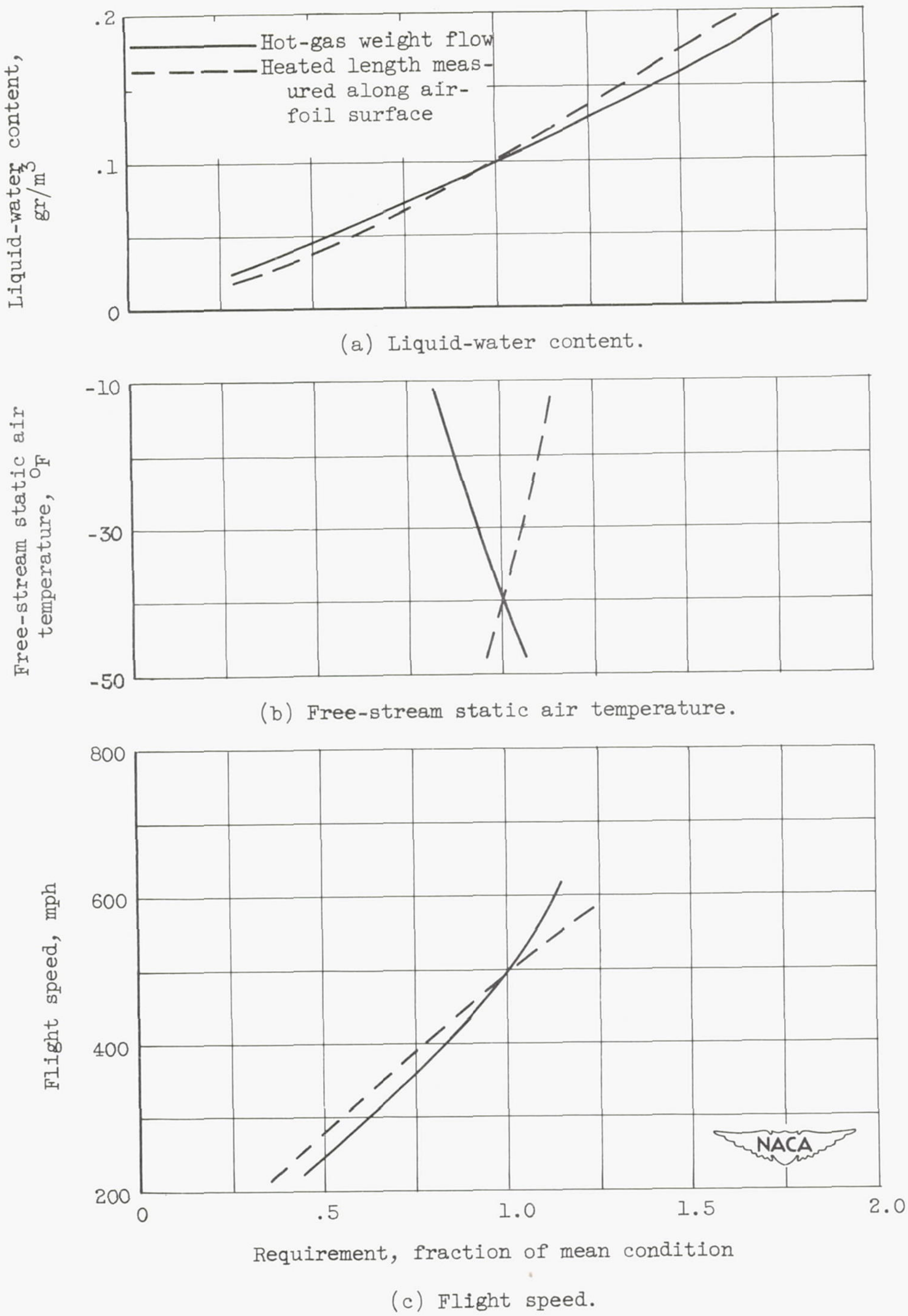


Figure 10. - Effects of variations in meterological and flight conditions on minimum requirements for complete evaporation. Typical chordwise-flow wing icing protection system. Condition 4; airfoil, NACA 65_1-212; chord, 15.8 feet; inlet gas temperature, 350° F; gap size, 1/8 inch.

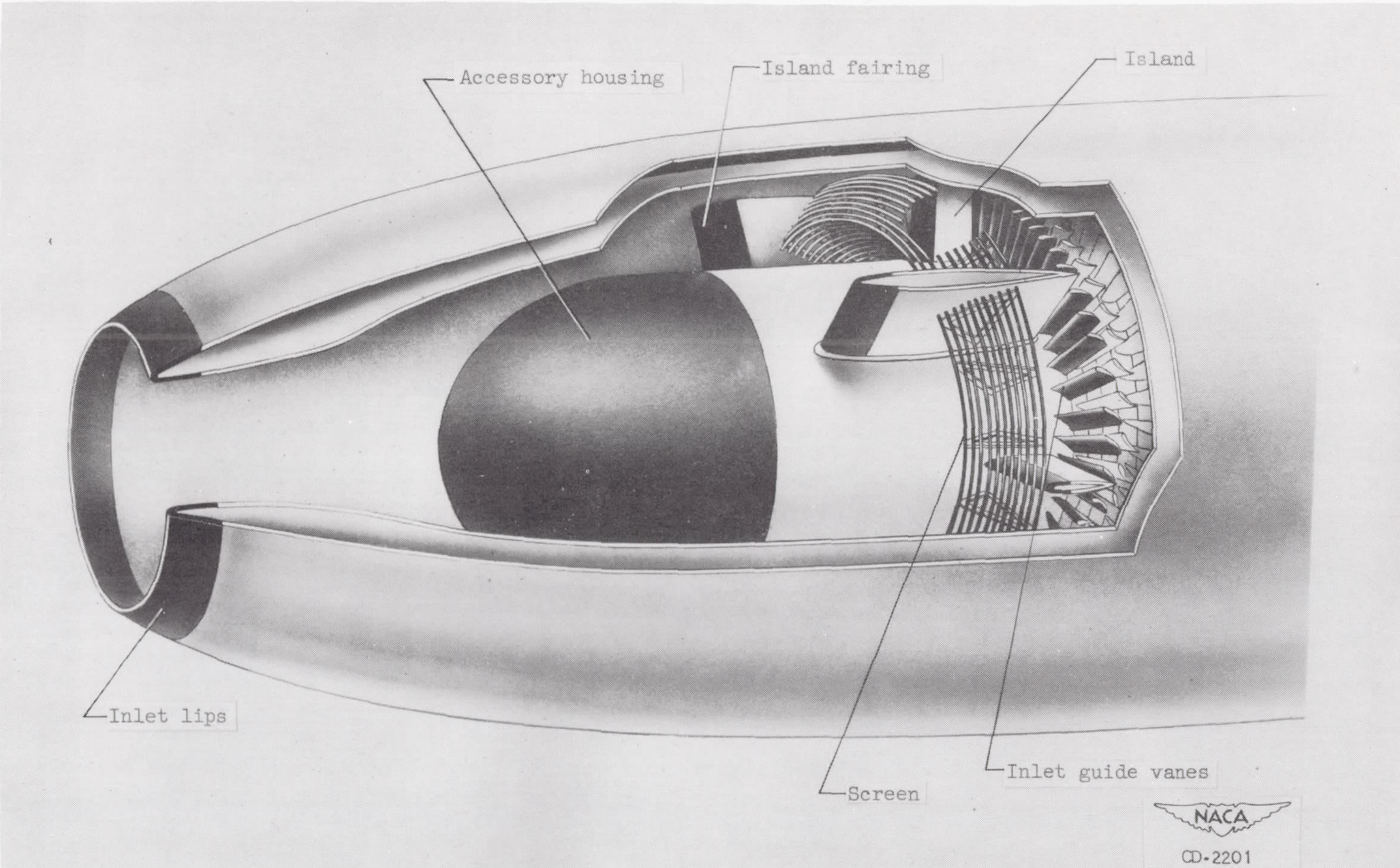


Figure 11. - Typical turbojet-engine inlet showing surfaces requiring heat for icing protection.

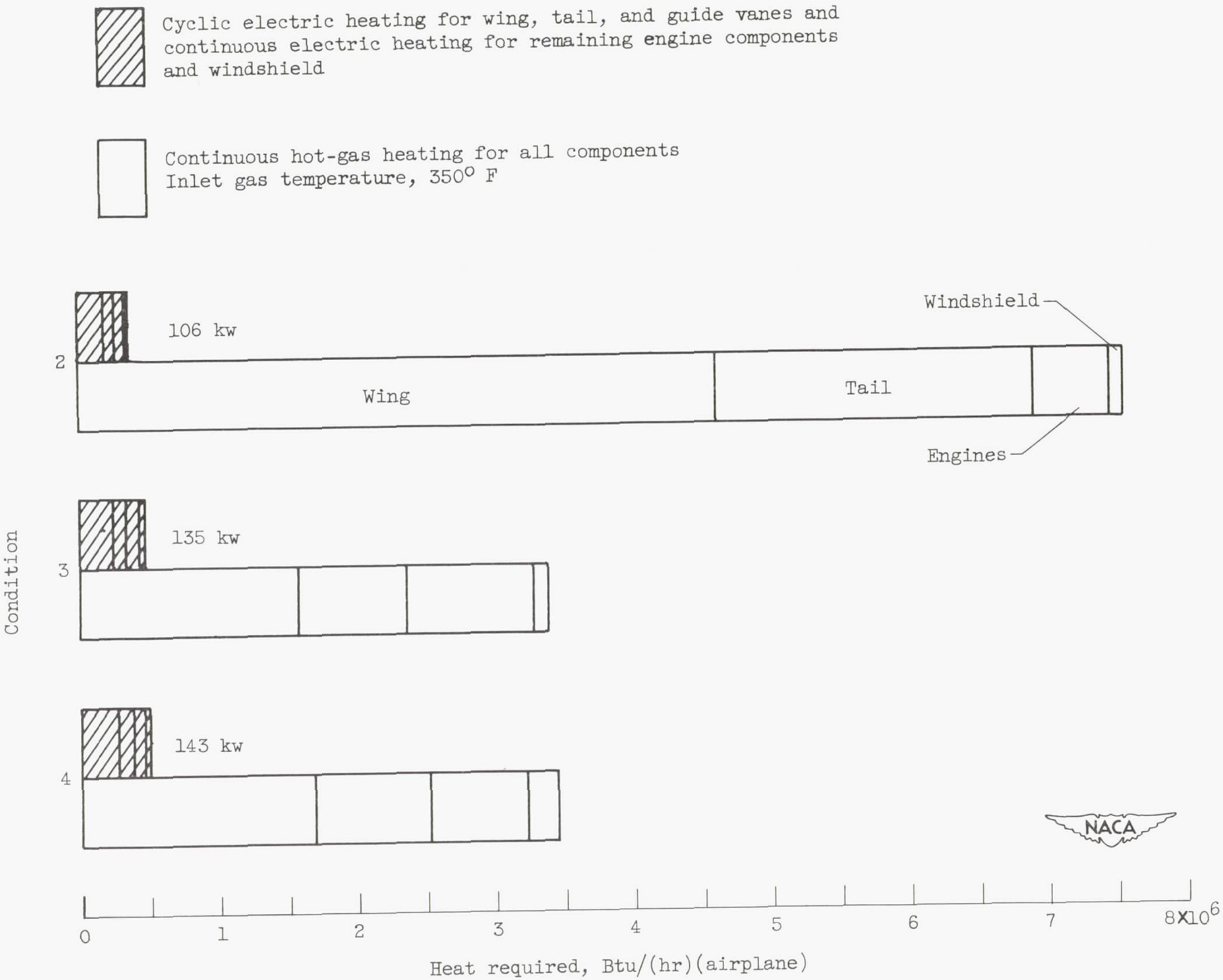


Figure 12. - Summation of heating requirements for a turbojet transport airplane.

1 Shaft power extraction
2 Compressor-outlet air bleed
3 Turbine-inlet gas bleed
4 Tail-pipe gas bleed
5 Tail-pipe heat exchanger

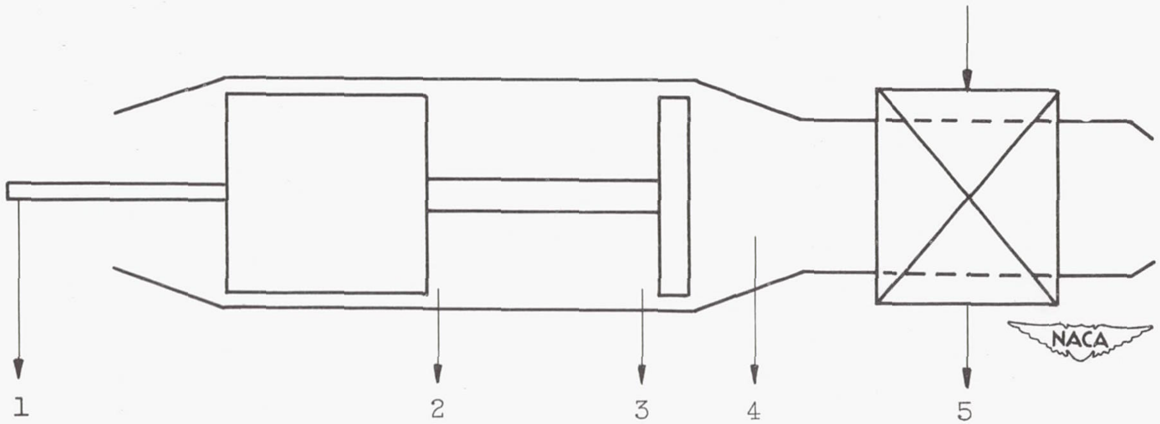


Figure 13. - Methods of heat and power extraction from turbojet engine.

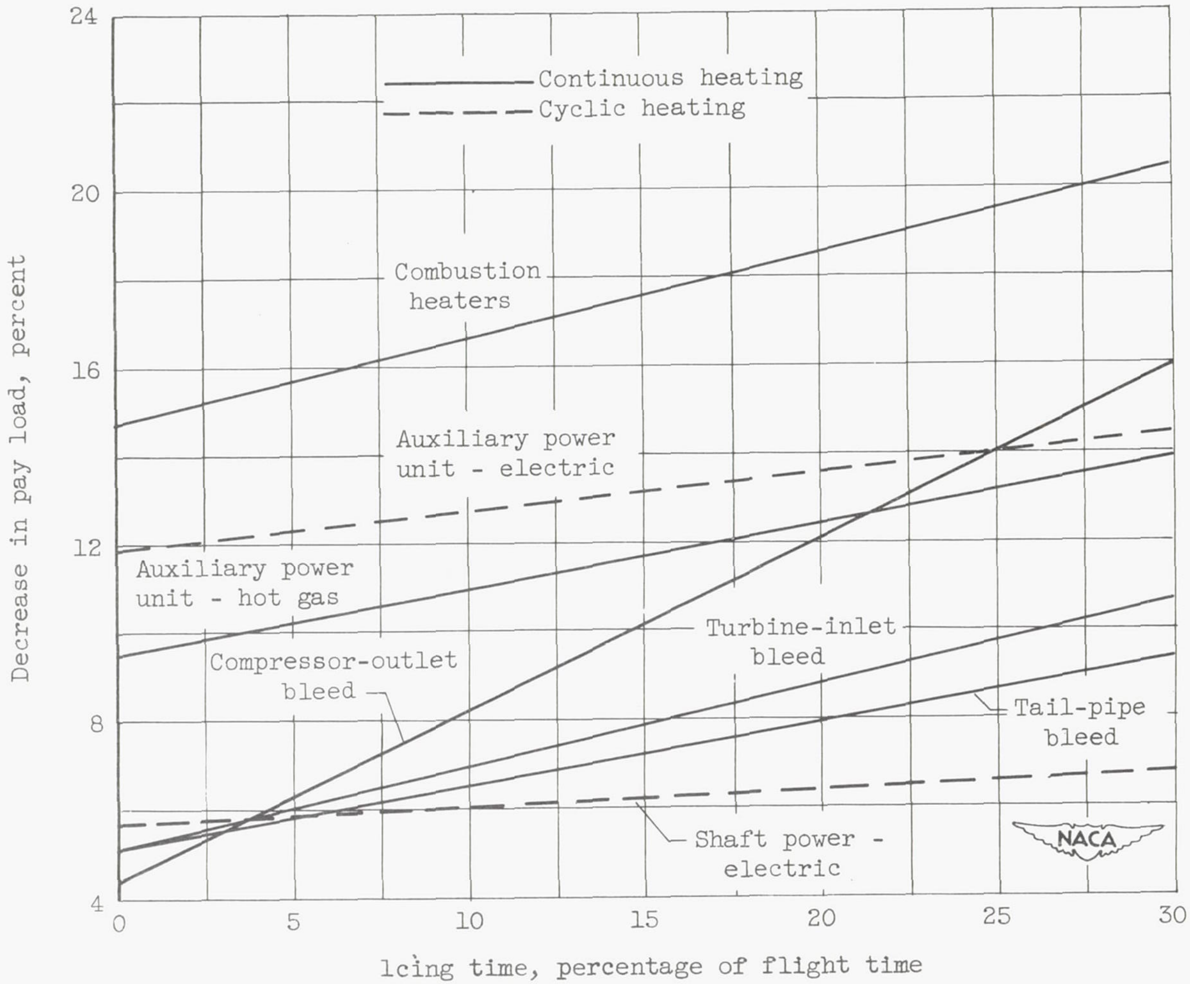
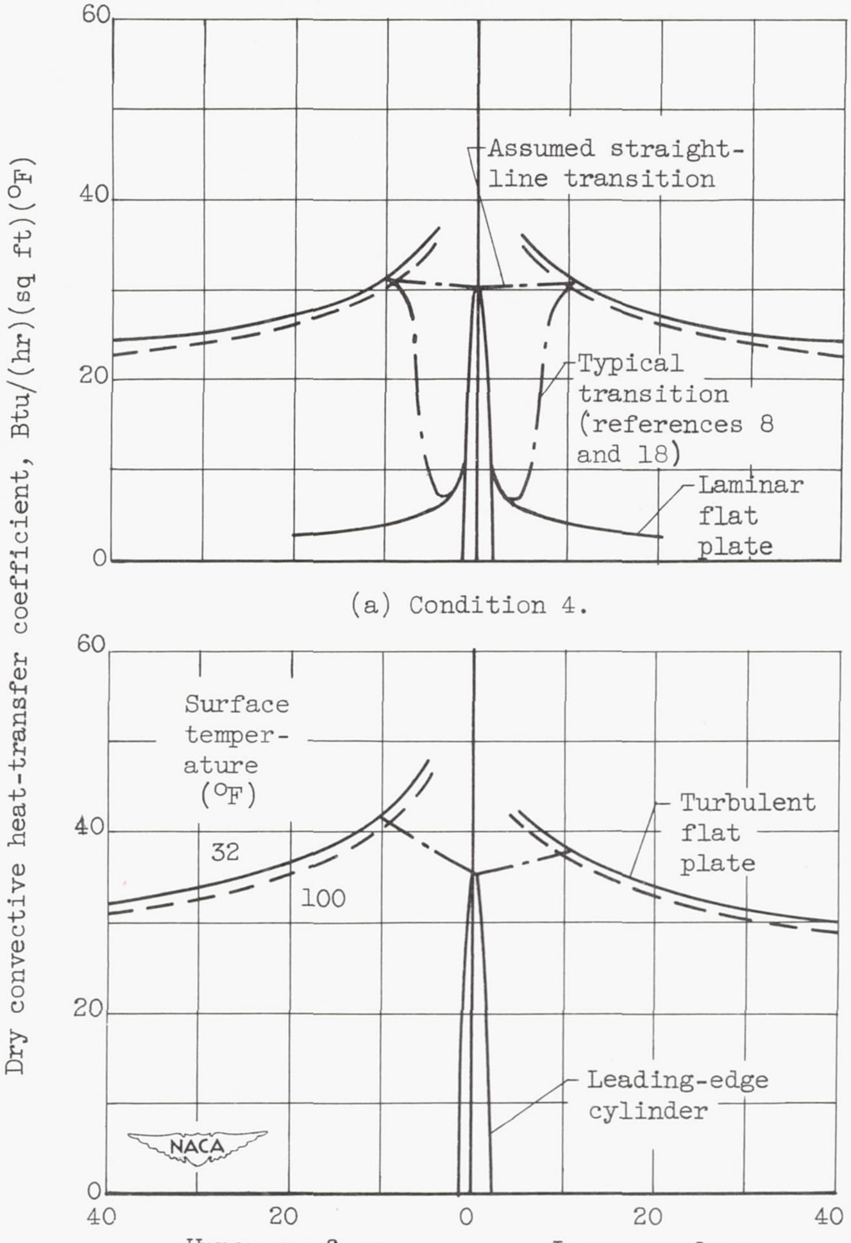


Figure 14. - Effect of providing thermal icing protection on turbojet transport cruise performance as a function of icing time and heat source. Condition 4; 3000-mile cruising range at 30,000 feet.



(b) Condition 2.

Figure 15. - Comparison of calculated dry convective heat-transfer coefficients for leading-edge region of airfoil at two operating conditions. Airfoil, NACA 65_1-212; chord, 15.8 feet.