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REVIEW OF TECHNOLOGY RELATING TO THE X-15 PROJECT

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INTRODUCTION

From recent studies of the possibilities of flight at very high supersonic speeds there has developed a general consensus that we are on the threshold of an era in which the speed of manned aircraft is likely to increase by an order of magnitude, ultimately exceeding the velocity required for an earth satellite. A primary factor influencing these studies has been the achievement of rocket engines capable of large thrusts in the range needed for boosting long-range manned aircraft.

These appraisals of hypersonic flight have clearly established the urgent need for research on high-temperature structures, hypersonic aerodynamics, stability and control, and piloting problems. Because of the inadequacy of existing facilities for research in many of the problem areas, the National Advisory Committee for Aeronautics initiated a study in February of 1954 to determine the extent to which a manned research airplane could contribute toward solution of these problems. An important requirement specified at the outset of the study was that a period of only about 3 years be allowed for design and construction in order to provide the maximum possible time lead for application of the research results. This requirement, of course, allowed little or no time for the development of new materials, radical new methods of construction, or new techniques for launching. Also, it was obviously impossible that the proposed aircraft be in any sense an optimum hypersonic configuration.

The purpose of this paper is to review the considerations that established in a general way the main features, the performance, and the research missions which appeared feasible in an airplane to be constructed within the specified time limitation.

PERFORMANCE

The National Advisory Committee for Aeronautics performance study indicated that a maximum speed of about 6,800 feet per second could be achieved, if launching from the B-36 airplane was assumed. The altitude-speed performance envelope which appeared feasible is shown in figure 1 in relation to those of typical previous research airplanes and possible future manned aircraft. The maximum speed, which is more than double

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that achieved by the X-2, places this airplane in a region where heating is the primary problem of structural design, and where little background information exists for aerodynamic design.

Winged aircraft capable of carrying human beings at hypersonic speeds are referred to in figure 1 as "rocket gliders." The upper limit of the zone in which they are likely to operate corresponds to lightly loaded aircraft with high optimum C_L, while the lower limit corresponds in general to low optimum C_L and high wing loadings. As the speed increases, an increasingly large proportion of the weight is borne by centrifugal force until, at satellite velocity, no aerodynamic lift is needed and the aircraft may be operated completely out of the atmosphere. At these speeds the pilot must function for long periods in a weightless condition, which is of considerable concern from the aeromedical standpoint. Attitude control of the aircraft for this condition is an additional problem. The proposed research airplane, although its speed is far below the satellite value, can be used to investigate both of these problems. By employing a high-altitude trajectory extending to about 250,000 feet, the aircraft at low angles of attack will operate in an essentially weightless condition for about 2 minutes. The dynamic pressure during this period is less than 10 pounds per square foot and reaches a minimum of less than 1 pound per square foot, so that the use of small auxiliary rockets for attitude control can be investigated under conditions approximating those of space flight.

Broadly speaking, rocket gliders operating within the atmosphere at sub-satellite speeds have two additional major problems: first, aerodynamic heating, and second, the problem of achieving as high a lift-drag ratio as possible. The wind tunnel is better suited than flight for configuration studies bearing on the L/D problem. However, the research airplane can contribute to one important phase of L/D research by providing information on the extent to which laminar boundary layers can exist in a realistic aerodynamic environment and for typical surface conditions which are generally impossible to simulate properly in wind tunnels. This question of the extent of laminar flow becomes, of course, even more critical as it affects the heating problem. In addition to these transition studies, determination of aerodynamic heating rates for both laminar and turbulent boundary layers over a wide range of flight conditions - in many cases far beyond those which can currently be duplicated in wind tunnels - will be another major research area for this airplane.

CONFIGURATION

Considerations of stability and control problems throughout the whole speed range, including low-speed launching and landing, led to selection of a more-or-less conventional arrangement (fig. 2). The configuration shown is not the X-15, but rather one which embodies all of the features indicated to be desirable in the NACA study.

It was found that inordinately large tail areas were required at the highest speeds if thin sections were used, because of the rapid loss in lift-curve slope of thin sections as the Mach number increased. The variable-wedge tail section was proposed as a means of restoring the lift-curve slope at high speeds, thus permitting the conventional tail areas shown. These wedge surfaces also act as dive brakes to reduce the Mach number and heating during reentry. Both the braking effect and the stability derivatives can be varied through wide ranges by variable deflection of the wedge surfaces. The flexibility made possible by variable wedge deflection was thought to be of great value because a primary use of the airplane will be in studies of stability, control, and handling characteristics through extreme ranges of speed and altitude.

Preliminary hypersonic wind-tunnel studies revealed the need for a ventral tail to provide directional stability and control at high angles of attack where the upper tail becomes immersed in the low-pressure flow fields from the wing and body. These studies also revealed that the horizontal-tail location should lie in a narrow range close to the wing chord plane.

It was recommended that the airplane be statically stable for all flight conditions and that artificial damping be incorporated in view of the many uncertainties in the area of dynamic stability at the extreme flight conditions of this airplane.

For operation at high altitudes where the aerodynamic controls become ineffective, hydrogen-peroxide rockets were proposed for attitude control.

Studies of the heating problems of this airplane pointed toward an Inconel X heat-sink structure with blunt leading edges.

The size of the airplane was chosen as approximately the largest that could be conveniently accommodated in a B-36 mother airplane. Weight estimates indicated that such an airplane would have a gross weight of about 30,000 pounds and a weight of 12,000 pounds without fuel. The resultant weight ratio of 2.5, together with an initial thrust-weight ratio of 1.8, provided a maximum burnout velocity of about 6,800 feet per second with the B-36 launching technique. This thrust level is much higher than in any previous manned aircraft. It results in a final longitudinal acceleration at burnout of about 4.5g, which approaches the maximum value currently believed to be acceptable by pilots. This velocity of 6,800 feet per second thus represents about the maximum performance achievable with this technique of launching from the B-36 airplane.

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STRUCTURAL CONSIDERATIONS

Because of the paramount importance of the heating considerations in the design and uses of this airplane, the rest of this paper is devoted to a discussion of the structural and heating problems. An idea of the air-temperature environment of this airplane as a function of Mach number can be obtained from figure 3. The temperature shown is the recovery temperature of the air at the surface of an insulated flat plate in the absence of radiation, based on the assumption of a recovery factor of 0.9 for the turbulent boundary layer. Air temperatures of about 3,500° F are encountered. At this temperature appreciable imperfect-gas effects exist as a result of vibrational excitation of the molecules. Dissociation, however, starts to occur at a Mach number beyond the reach of this airplane. For the assumed range of skin temperatures a large temperature potential exists for heat flow into the skin at $M = 7$ (vertical line in figure 3), the ratio of air to wall temperatures ranging from about 3 to about 10. These large temperature ratios are characteristic of the hypersonic regime and provide a stabilizing influence on the boundary layer which is the principal basis for the hope that long runs of laminar boundary layer may exist at high speeds. An airplane with a Mach number capability of, say, only 3 or 4 would be unable to achieve a significantly wide range of values of this parameter.

During a typical flight the recovery temperature of course varies with changes in Mach number, Reynolds number, and angle of attack (fig. 4). The flight assumed here is one in which burnout occurs in climb at an altitude of about 130,000 feet, where the first peak value in the air temperature on the upper curve of figure 4 occurs. The airplane then coasts along a zero-lift path to a peak altitude of 250,000 feet and then reenters, encountering a second peak in speed and temperature. Because of the beneficial effect of radiation of heat away from the surface, the actual skin temperature is much lower than the boundary-layer recovery temperature during most of the flight. The dashed curve applies to a structure in which no heat is absorbed by the skin - either an insulated structure or one having a very thin skin of negligible heat capacity. A relatively high radiation coefficient ($\epsilon = 0.8$) was used in this case, corresponding to a darkened surface condition. The temperatures shown thus represent about the lowest that could be achieved in practice for the insulated type of structure. A peak temperature of about 1,850° F is reached on reentry, presenting very difficult material and fabrication problems for this type of structure.

If a metal skin of appreciable thickness is used, much of the imposed heat will be absorbed by the skin under the transient conditions of this type of flight and the resulting temperatures are thus reduced to more tractable levels, as shown by the lowest curve in figure 4. This type of construction is usually called a "heat-sink" structure.

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For the contemplated flight conditions any one of several metal alloys might have been used in a heat-sink design, provided the skin gage was sufficiently thick to permit absorption of the heat load without exceeding the design temperature of the material. The principal considerations which pointed toward Inconel X as the most suitable material for this research airplane are indicated in figure 5. At a design temperature of 1,200° F, Inconel X has suffered only a negligible deterioration of its strength and stiffness properties. All of the other materials shown in this figure have significantly lower design temperatures - 300° for aluminum alloy, 500° to 600° for certain magnesium alloys, and perhaps 850° for stainless steel. The high design point for Inconel X permits complete freedom of operation up to nearly 4,000 feet per second, at which speed the recovery temperature is of the order of 1,200° F. Up to this speed, therefore, there need be no heat or temperature restrictions on operating altitude, angle of attack, or duration of flight. By contrast, if an aluminum alloy had been used the corresponding limiting speed would be less than 2,000 feet per second, and full-throttle, full-fuel flights would generally be impossible below an altitude of about 100,000 feet with a skin designed for the specified high-speed and high-altitude missions of this airplane.

A second advantage of the high design temperature of Inconel X stems from the significant amount of heat which can be radiated rather than absorbed by the skin. The dashed curve of figure 5 indicates that over three times as much radiation occurs at 1,200° F as at 850° F, the design temperature selected for stainless steel. No radiation benefit occurs for aluminum or magnesium alloys. The total amount of heat radiated from Inconel X in a typical flight is indicated in figure 6. The dashed curve indicates the heat absorbed by the skin as the skin temperature rises. A temperature of 1,350° F would be required to absorb the design heat load in the absence of radiation, in contrast to 1,200° F with the benefit of radiation.

As is well known, there are at present many uncertainties in the estimation of heat-transfer coefficients for a project of this kind. In addition, deviations from design flight trajectories, both intentional and accidental, will probably occur. It is imperative, therefore, that the structure be designed with the capability of absorbing excess heat loads. If a 50-percent excess heat load is assumed in a typical flight, it is found that the temperature increases by only 25 percent to 1,500° F. Thus about half the excess heat is radiated from the structure. At 1,500° F the material still retains about 60 percent of its design strength. The other structural materials, under similar circumstances, would lose a much larger fraction of their strength and stiffness.

A question of considerable interest in a heat-sink structure is "How much otherwise useless metal is carried solely for heat-sink purposes?" Figure 7 indicates the situation for this airplane at 6,600 feet per second with an Inconel X skin; the solid line shows the metal required for a uniform maximum temperature of 1,200° F along the wing chord, and the dashed line is the approximate skin thickness required for strength and stiffness near the wing root. Over much of the wing, more than enough skin is seen to be available, and thus the maximum temperatures in this area will be less than 1,200° F. Over the foremost portions of wing and fuselage, however, and near the wing tips some extra material is required.

If a higher speed had been chosen, say 12,000 feet per second, two or three times as much material would be required for a heat sink, and a heavy penalty in skin weight would then be involved.

The leading edge itself develops the highest heating rates found on the aircraft, although over a relatively small area. It appeared from the NACA study that either a heat-sink design or a non-load-carrying very-high-temperature material such as one of the carbides would be feasible for the leading edge.

Under the rapidly changing heating environment of this airplane thermal stresses present a major problem for all types of structure. The NACA study of the heat-sink type indicated that a number of modifications could be made to a conventional structure which would reduce the thermal stresses to tolerable levels. It was thought that such schemes could be incorporated without an extended period of development.

There were two final important research considerations favoring the proposed heat-sink structure:

(1) The heat-sink structure offered a reasonable possibility for maintaining the smooth external surface necessary in heat-transfer and boundary-layer-transition research.

(2) Accurate heat-transfer measurements can be obtained readily from the temperature time histories of an Inconel X heat-sink structure.

FLIGHT TRAJECTORIES AND HEATING RATES

With the proposed structure this airplane was found to be capable of widely varying research missions, some of which are shown in figure 8. The design altitude mission extending to 250,000 feet followed by a reentry pull-up in which the dive brakes are not used produces the maximum heating rate of about 20 BTU/sq ft/sec on the lower surface of the wing when a turbulent boundary layer is assumed. Maximum speed is achieved at a lower altitude which produces a maximum heating rate of about 15 BTU/sq ft/sec. If the airplane is operated at best L/D for maximum range, the initial heating rate is about 6.5 BTU/sq ft/sec but the time of appreciable heating is much greater than in the previous cases.

In all the flights shown in figure 8 the upper surface of the wing was subject to much lower heating rates, with the result that temperature differentials of the order of 500° F developed between upper and lower surfaces. This differential and the high local heat rate combine to produce the condition of maximum thermal stress in the design altitude flight. Less extreme heating conditions with maximum heating rates of about 5 BTU/sq ft/sec can be achieved in low-angle-of-attack reentries in which deceleration is accomplished mainly by use of the dive brakes. It is evident that a wide variation in heating conditions can be achieved by varying the angle-of-attack schedule and flight trajectories. Conversely, careful adherence to planned schedules is essential if excessive heating is to be avoided.

In figure 9 it is of interest to compare the range of heating rates encountered in trajectories of this kind with typical rates likely to occur at higher speeds in rocket gliders operating near their best L/D. For the same wing loading, 60 pounds per square foot, and the optimum angle of attack, 12°, of the airplane assumed in the NACA study, the rocket gliders operate at ever-increasing altitude as the speed increases. The heating rate does not increase indefinitely but reaches a maximum of roughly 20 BTU/sq ft/sec. This maximum is a consequence primarily of the effect of centrifugal force in nullifying an increasing fraction of the weight and thereby permitting operation at lower dynamic pressures and higher altitudes.

The heating rate for the airplane at 6,600 feet per second and at the angle of attack for best L/D is about one-third of the maximum; however, in a reentry pull-up a maximum rate of the same order as for the rocket glider at $M \approx 15$ can be obtained.

In conclusion, none of the figures are meant to imply that this first hypersonic airplane will solve all the problems of the future. The conclusion was reached from this study that a significant first step toward the era of long-range rocket-propelled man-carrying aircraft was feasible and desirable, and that the proposed airplane would be capable of research in many areas which could not be adequately explored in any other way.

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FLIGHT REGIMES

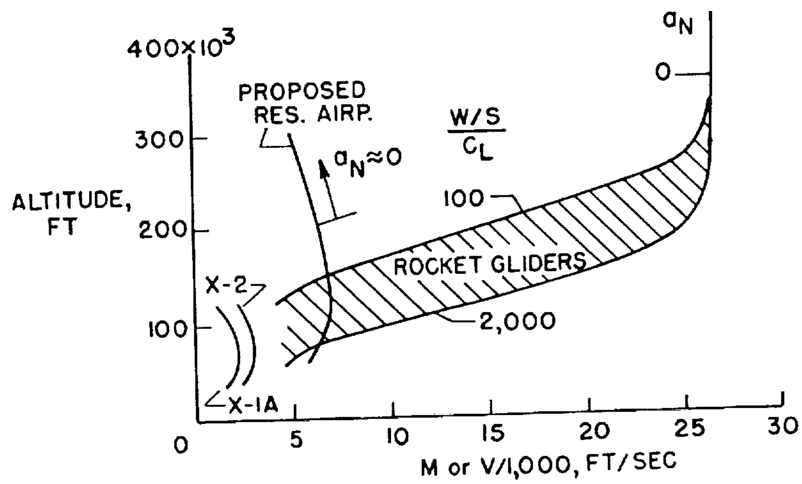
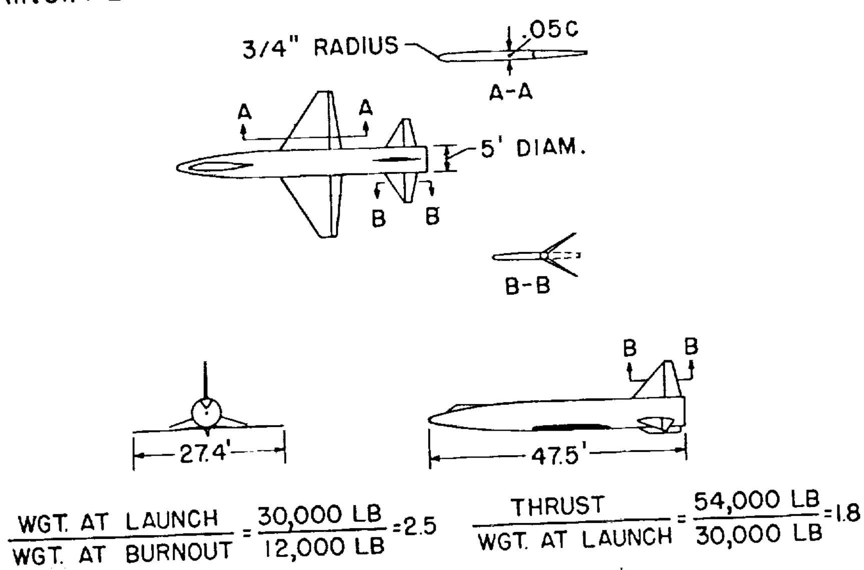


Figure 1

PRINCIPAL FEATURES OF PROPOSED RESEARCH AIRPLANE



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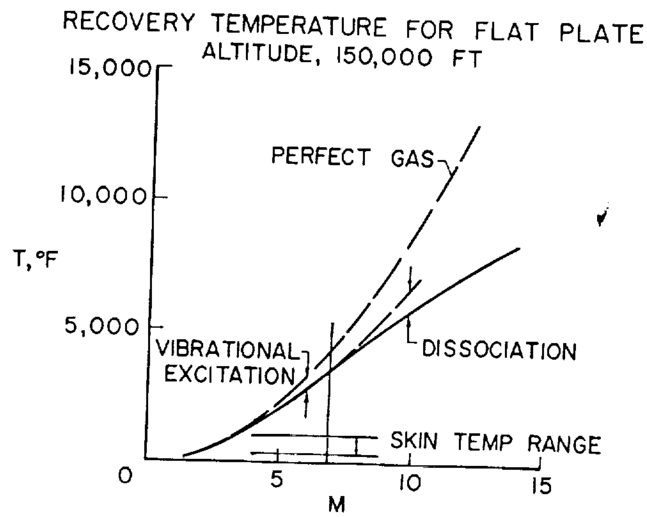

Figure 3

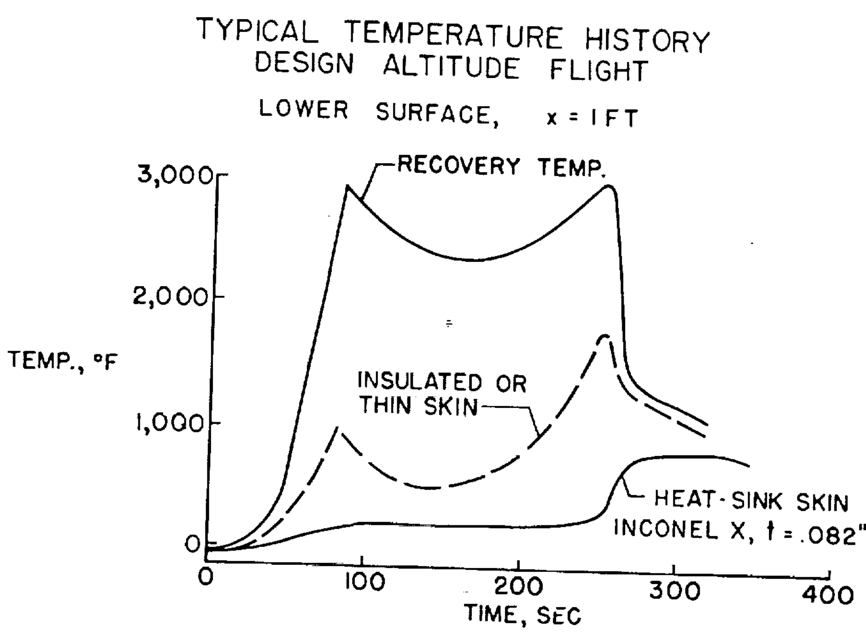

Figure 4

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COMPARISON OF INCONEL X WITH OTHER ALLOYS

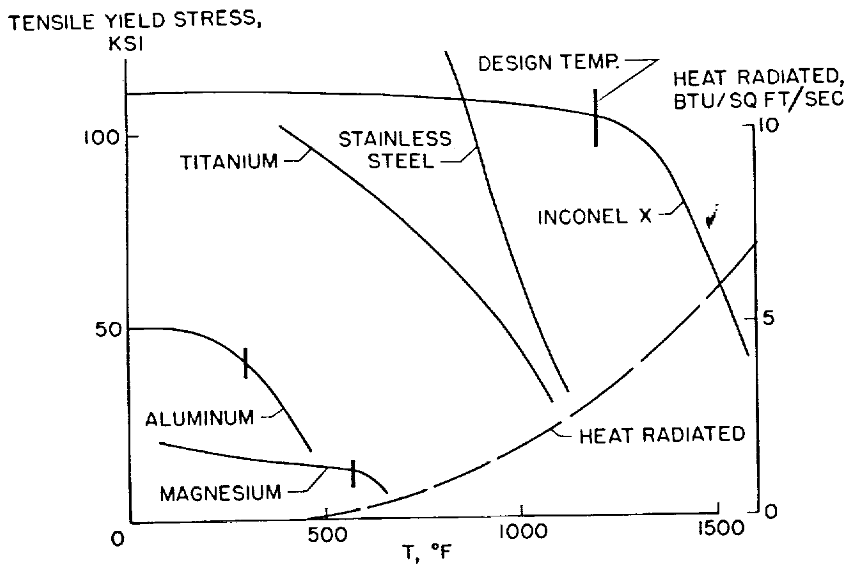

Figure 5

EFFECT OF RADIATION ON SKIN TEMP.
INCONEL X, t=.082"

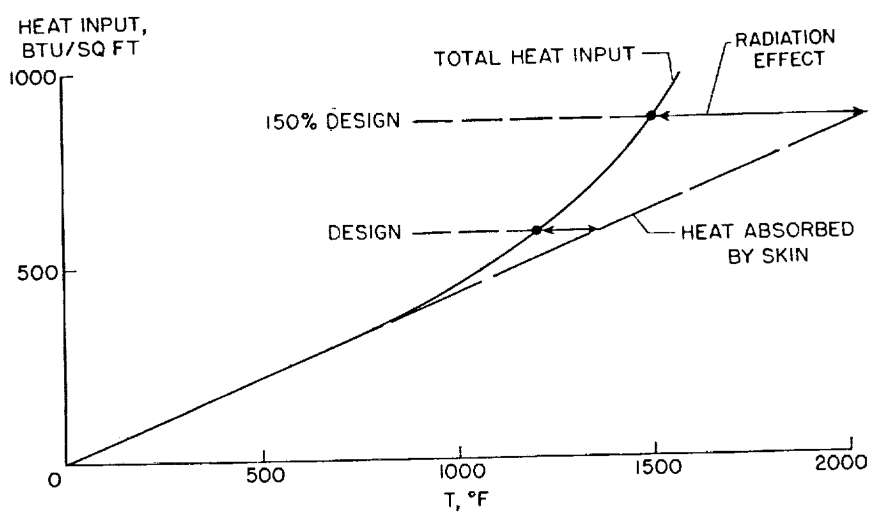

Figure 6

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WING SKIN THICKNESS REQ'D FOR HEAT SKIN

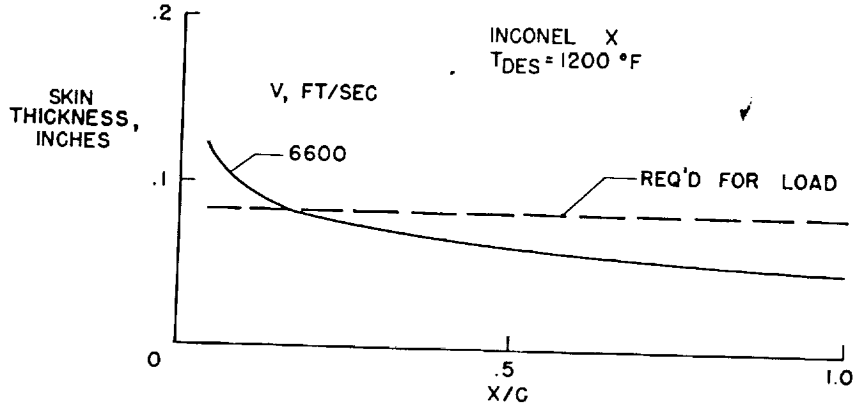

Figure 7

TYPICAL FLIGHT PATHS AND HEATING RATES

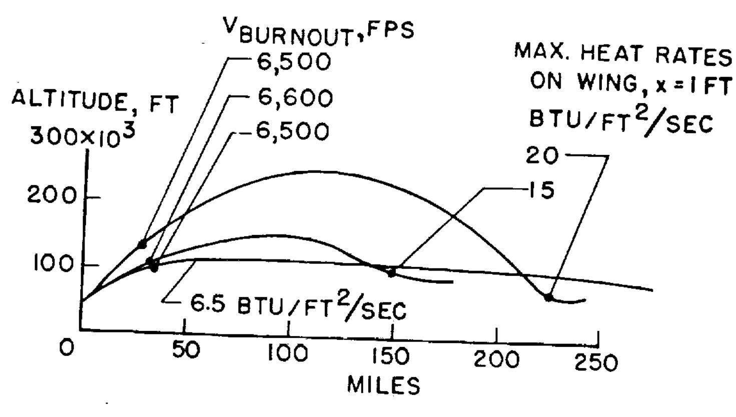

Figure 8

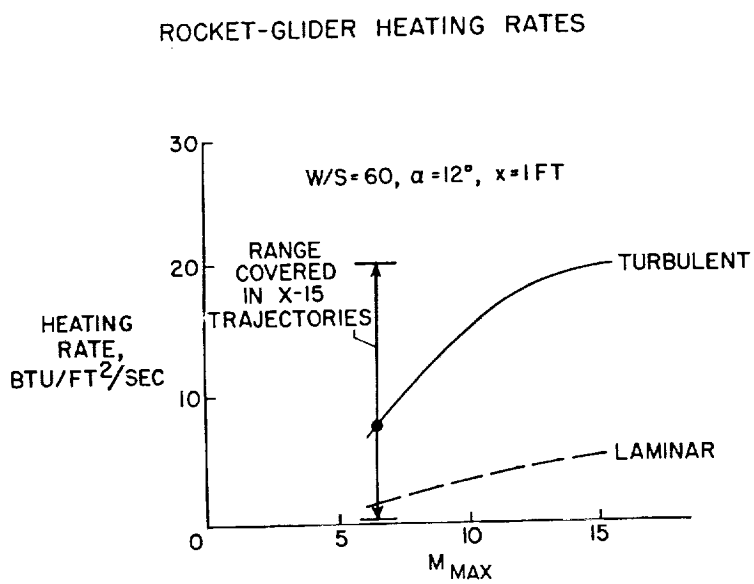
ROCKET-GLIDER HEATING RATES
W/S=60, α=12°, x=1 FT
RANGE COVERED IN X-15 TRAJECTORIES
TURBULENT
LAMINAR
HEATING RATE, BTU/FT²/SEC
30
20
10
0
5
10
15
M MAX

Figure 9