NASA TECHNICAL MEMORANDUM

NASA TM X-3125

NASA TM X-3125

(NASA-TM-X-3125) FAIL-SAFE SYSTEM FOR ACTIVITY COOLED SUPERSONIC AND HYPERSONIC AIRCRAFT (NASA) 21 p HC $3.25 CSCL 01C
N75-14722
Unclas
H1/02 08107

FAIL-SAFE SYSTEM FOR ACTIVELY COOLED SUPERSONIC AND HYPERSONIC AIRCRAFT

Robert A. Jones, Dorothy O. Braswell, and Christine B. Richie

Langley Research Center
Hampton, Va. 23665

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1975

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3125		
4. Title and Subtitle FAIL-SAFE SYSTEM FOR ACTIVELY COOLED SUPERSONIC AND HYPERSONIC AIRCRAFT		5. Report Date January 1975 6. Performing Organization Code
7. Author(s) Robert A. Jones, Dorothy O. Braswell, and Christine B. Richie		8. Performing Organization Report No. L-9685 10. Work Unit No. 760-66-01-02
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23665		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

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On the basis of results obtained in the present study, it appears that this fail-safe-system concept warrants further consideration, inasmuch as a fail-safe system could possibly replace a redundant active cooling system with no increase in weight and would offer other potential advantages.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Active cooling Liquid-hydrogen fuel Fail-safe thermal protection system	Unclassified – Unlimited STAR Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	19	$3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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By Robert A. Jones, Dorothy O. Braswell, and Christine B. Richie
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SUMMARY

A preliminary study was made of a fail-safe-system concept as an alternative to a redundant active cooling system for supersonic and hypersonic aircraft which use the heat sink of liquid-hydrogen fuel for cooling the aircraft structure. This concept consists of an abort maneuver by the aircraft and a passive thermal protection system (TPS) for the aircraft skin. The abort maneuver provides a low-heat-load descent from normal cruise speed to a lower speed at which cooling is unnecessary, and the passive TPS allows the aircraft skin to absorb the abort heat load without exceeding critical skin temperature.

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INTRODUCTION

Hydrogen fuel for supersonic and hypersonic aircraft offers many advantages, some of which are described in reference 1. In addition to alleviating oil requirements, improving performance, and reducing exhaust emissions, hydrogen fuel when carried as a cryogenic liquid has a very large cooling capacity which can be utilized as a heat sink to reduce the aircraft skin and structural temperatures.

Previous work (for example, refs. 2 to 4) has shown that active cooling systems in which liquid-hydrogen fuel is used as a heat sink could be the lightest and most effective thermal protection system for large transport aircraft at speeds as high as Mach 6. In this type of system the liquid-hydrogen fuel, on its way to the engines, is pumped to pressures far in excess of its critical value. It then passes through a heat exchanger where heat is absorbed from a secondary coolant fluid. This secondary coolant fluid (probably water-glycol) is pumped through a distribution system to all external surfaces where it absorbs heat from the skin.

The aircraft skin is made up of panels having discrete coolant passages and manifolds in an integral structural arrangement. One possible arrangement is indicated in figure 1. Other designs for actively cooled skin panels are possible, and several have been studied. Some would be extruded with integral coolant passages; others would employ discrete coolant tubes sandwiched between two layers of skin which are bonded together.

Concepts in which the coolant flows through the aircraft skin have one serious drawback: if, for any reason, the active cooling system or even just one skin panel should fail to operate properly, the skin temperature could increase so rapidly as to cause failure of the structure. At Mach 6 cruise conditions, the time required for failure of a minimum-gage aluminum skin would be less than a minute. Malfunction of a pump or heat exchanger, a plugged distribution line or panel passage, and a leak through a cracked passage are possible modes of failure. In consideration of this fact all presently proposed active cooling systems employ redundancy.

The system proposed in references 1 to 4 uses two complete sets of coolant passages in the skin panels, two distribution systems, and two sets of pumps and heat exchangers to provide redundancy. A redundant system of this type results in a significant increase in cooling-system weight and, more important, some failures could cause a loss of both systems. Examples of such failures are cracks in a skin panel or loss of coolant due to a damaged skin panel. If a crack developed in a skin panel so that there was a loss of coolant in the primary set of coolant passages, then it is very likely that adjacent redundant coolant passages would be subject to cracks simultaneously. Thus, it is desirable to explore other means of insuring the safety of the aircraft in the event of failure in the active cooling system.

This paper describes a preliminary study of a fail-safe-system concept for use in conjunction with actively cooled supersonic and hypersonic aircraft. Low-heat-load abort trajectories are evolved, and calculations are presented for four passive thermal protection systems that can absorb the abort heat loads for cruise Mach numbers from 2.5 to 6.

SYMBOLS

C_p heat capacity of metal skin material

g acceleration due to gravity

Q_{av} average abort heat load per unit area

q_{ins} average heating rate to coated metal skin

$q_{(no\ ins)}$ average heating rate to bare metal skin

T_{aw} adiabatic wall temperature

T_{max} maximum allowable temperature of aluminum skin

T_c metallic skin temperature at cruise

T_s surface temperature of coating at cruise

T_w wall temperature

ΔT temperature change

t skin thickness

ρ density of metal skin material

FAIL-SAFE ABORT CONCEPT

The fail-safe-system concept proposed herein consists of an abort maneuver by the aircraft and a passive thermal protection system (TPS) for the aircraft skin. The abort maneuver provides a low-heat-load descent from normal cruise Mach numbers to a Mach number at which thermal protection is unnecessary, and the passive TPS allows the skin to absorb the abort heat load without exceeding the maximum allowable skin temperature. Some type of failure detection system is needed. Such a system might monitor the aircraft skin temperature at critical locations in each panel. This study does not consider failure detection systems but, instead, is aimed at determining the potential of the fail-safe-system concept by means of a preliminary evaluation of the amount of heat involved in an abort and the passive TPS which would be required to absorb this heat without exceeding the critical skin temperature.

CONFIGURATION AERODYNAMICS AND HEATING

The configuration used for this preliminary fail-safe abort study was a research-aircraft concept recently studied at the Langley Research Center. A brief description of this vehicle is given in reference 5, and a computer drawing of its configuration is shown in figure 2. Basically, this research aircraft was conceived to demonstrate several of the new technologies needed for supersonic and hypersonic hydrogen-fueled air-breathing aircraft of the future, one of which is a skin made of aluminum and maintained at a temperature of 366 K (200° F) by an active cooling system of the type previously discussed.

In the computer drawing of figure 2, the aircraft is represented by many flat panels. The coordinates of these panels were the geometry input for calculation by means of the methods of references 6 and 7 of both aerodynamic characteristics and aerodynamic heating rates to the vehicle. Aerodynamic characteristics and instantaneous heating rates to a cool (366 K (200° F)) vehicle were inputs (in table form) as functions of Mach number, angle of attack, and dynamic pressure for a trajectory program which defined a low-heat-load abort trajectory for various cruise Mach numbers. The heating rates used for this study were the average instantaneous turbulent heating rates to the entire vehicle. This average value was determined by summing the panel heat loads over the entire vehicle and dividing by the total area of the vehicle. Because of the small size of this research aircraft in comparison with a hypersonic transport, the average heating rates and heat loads are larger than those for a transport. Thus, the present study is a conservative estimate of average abort heat loads. Although the calculations and measurements were made in U.S. Customary Units, the values herein are presented in both SI Units and U.S. Customary Units.

Abort Maneuvers

Various types of abort maneuvers including the use of drag brakes and banked turns were considered. The trajectory used to study the feasibility of fail-safe aborts is illustrated in figure 3 for a descent from a cruise Mach number of 5. Aborts were assumed to be initiated from the end of cruise where the cruise conditions for each Mach number were taken to be the conditions at a constant dynamic pressure of 19 152 N/m^2 (400 lb/ft^2). This dynamic pressure was selected since it is typical of cruise conditions suitable for hypersonic transports. Two other restraints on the abort trajectories were thought to be realistic: a maximum load of 2g (1g = 9.81 m/sec^2) and a maximum angle of attack of 0.349 rad (20°). The abort is initiated by shutting off the engines and making a pitch-up maneuver to the maximum g condition. The angle of attack is steadily increased to maintain a constant 2g pullup until the maximum allowable angle of attack is reached. Then the angle of attack is held constant until the vehicle again assumes a zero flight-path angle at which time the angle of attack is changed to the equilibrium glide angle. The angle of attack is held constant at the equilibrium glide angle during the rest of the descent to a Mach number of approximately 2.2. As shown in figure 3, the result of this maneuver is a rapid loss of speed and an initial increase in altitude both of which reduce the heating rate. A comparison of this low-heat-load descent with a normal descent is shown in figure 4. A normal descent is one in which the engine is shut off and the aircraft continues to fly or glide at its cruise attitude. With the exception of a short time before end of descent when the pullup maneuver increases the heating rate, the rates for the normal descent are significantly larger. The time-integrated values of heat load for cruise Mach numbers from 2 to 6 are compared in figure 5. For Mach 5 cruise, the abort descent reduces the heat load by a factor of approximately 3.5.

Fully turbulent boundary-layer flow was assumed over the entire vehicle surface in the heat-transfer calculations. The increase in altitude and the reduction in speed during abort result in Reynolds numbers much lower than those for the cruise condition. Thus, a large portion of the boundary-layer flow may be laminar during the abort. The heating rates used are therefore conservative. Furthermore, if the criteria for determining the onset of boundary-layer transition were known and taken into account during abort, the trajectory could be altered to reduce the heat load even further. Changes in the cruise Mach number, allowable surface temperature, maneuver limitations, or the configuration (i.e., the aerodynamic characteristics) would alter the trajectory required for a low-heat-load abort, but a substantial reduction in heat load would still be obtained.

Heat-Sink Capacity of Bare Metal Skin

Perhaps the simplest thermal protection for absorbing the descent heat load is the inherent heat capacity of the skin itself. Figure 6 presents results of a study of the heat-sink capacity of the aircraft skin. The maximum allowable temperature was assumed to be 422 K (300° F) for aluminum and 589 K (600° F) for an aluminum-beryllium composite material. The curves show the average skin thickness required to absorb the abort heat load at various Mach numbers. Although average skin thickness and weights based on average heat loads are used herein to investigate the feasibility of the fail-safe-system concept, any actual aircraft design would have a varying skin thickness depending on the local heat loads. The heat-sink capacity of the skin, which must be equal to the abort heat load, is

$$Q_{av} = \rho C_p t \, \Delta T \qquad (1)$$

The skin temperature at cruise would probably be maintained at about 366 K (200° F). As shown in figure 6, an average skin thickness equal to the minimum-gage value is sufficient to absorb the abort heat load for cruise Mach numbers up to 3.2 for aluminum and up to 6 for the aluminum-beryllium composite material. By subcooling an aluminum skin to a temperature of 311 K (100° F) during cruise, an average skin thickness equal to the minimum-gage value would absorb the abort heat load for cruise Mach numbers up to 3.8. Of course by increasing the thickness of the skin above the minimum-gage value, the cruise Mach number from which an abort can be made is increased, but so is the weight. An average skin thickness of 0.508 cm (0.2 in.) is required for abort from Mach 5 if the skin is aluminum and its temperature at cruise is 366 K (200° F). Three concepts for using a bare metallic skin to provide increased abort heat-sink capability are thus illustrated in figure 6. The first is to subcool the skin during cruise to provide a larger ΔT. The second is to employ a material, such as the aluminum-beryllium composite, which has a higher specific heat and a higher allowable temperature than aluminum. The third is simply to increase the thickness of the skin. Each concept has some advantages for actively cooled aircraft. For example, if the fail-safe-system concept was used rather than a redundant active cooling system and if the incremental weight of the redundant active system was used to thicken the skin, then, for the same weight aircraft, the abort heat-sink capacity would be increased, the skin and thus the active cooling passages would be less susceptible to cracks and other damage, and the overall safety and reliability of the aircraft would be enhanced.

Overcoat TPS Concept

In view of the relatively low total heat loads involved in these fail-safe aborts and of the rapid decrease in total temperature of the free-stream flow during abort, several other TPS concepts can be considered in addition to metallic heat sinks. For example, phase-change materials can be applied to the skin panels, and skin overcoats or undercoats of various materials could be added to provide insulation, increased heat capacity, or both. These and other concepts for heat-sink TPS are described in reference 8.

An overcoat of organic insulating material appears attractive, especially for lower cruise Mach numbers. To explore the feasibility of such an overcoat, a transient thermal analysis was made of a two-layer skin during abort. The overcoat material was assumed to have a density of 2198 kg/m^3 (0.0794 lb/in^3), a thermal conductivity of 0.0049 W/m-K (0.034 $Btu/hr\text{-}ft^2\ {}^oF$), and a specific heat of 1046 J/kg-K (0.25 Btu/lb-^oF). The metal portion of the skin was assumed to be aluminum. Initial values for the transient analysis were taken as steady-state cruise conditions, and at cruise the two-layer skin was assumed to be in an equilibrium-temperature condition. As indicated in figure 7, the metal layer, which has a much larger thermal conductivity than the overcoat, was assumed to be held at a uniform temperature throughout by the active cooling system. The overcoat was taken to have a linear temperature distribution determined from a simple heat balance, where the aerodynamic heat input was equal to the heat radiated from the surface of the coating plus the heat conducted through the overcoat to the constant-temperature metal skin. The aerodynamic heat input was always the average value over the aircraft surface at cruise conditions.

The heat-balance equations were programed, and computations were made for various cruise Mach numbers. Overcoat surface temperature as a function of overcoat thickness is presented in figure 8, and reduction in heat load to the active cooling system is shown in figure 9. A comparison of these two figures indicates that for a cruise Mach number of 4.5, a 0.0508-cm-thick (0.020-in.) overcoat produces a 467-K (380^o F) surface temperature and a 20-percent reduction in heat load to the active cooling system. For a cruise Mach number of 6, a 0.0508-cm-thick (0.020-in.) overcoat gives a surface temperature of 522 K (480° F) and a 15-percent reduction in heat load. Thus, in addition to any benefits the overcoat may provide during abort, it also provides a significant reduction in heat load to the active cooling system during cruise.

A modified version of the computer program of reference 9 was used for the transient analysis of the overcoated skin during abort. The temperature distribution at the beginning of the abort maneuver was taken to be the steady-state distribution at cruise (fig. 7); the maximum allowable surface temperature of the overcoat was assumed to be 700 K (800° F) during cruise and 811 K (1000° F) during abort. Also, approximations were made for overcoat thickness and for aluminum-skin thickness based on data of figures 8 and 9 and of figure 6, respectively. The transient-analysis program then computed the temperature-time history of many points in the two skin layers. Inputs to the transient-analysis program were the aerodynamic heat-transfer coefficient and adiabatic wall temperature as functions of time from initiation of abort. The program computed by iteration the minimum aluminum-skin thickness for which the temperature of the skin did not exceed the maximum allowable temperature of aluminum, T_{max} = 422 K (300° F). After the thickness of the aluminum layer required to give T_{max} for the assumed overcoat thickness was determined, a new value was assumed for overcoat thickness, and the iteration process was repeated. This procedure was continued for varying thicknesses of coating to find the minimum weight of overcoated skin for which the coating surface temperature did not exceed 811 K (1000° F). This double iteration process thus gave the minimum combined weight of the two skin layers for which the temperature during abort exceeded neither the maximum allowable temperature of the coating nor the maximum allowable temperature of the metal skin.

Figure 10 presents the transient-analysis results for overcoated skin and for bare skin. The average weight of the optimized overcoated skin is shown for abort at cruise Mach numbers from 3 to 8. The solid curves are the previous results for a bare aluminum skin, and the dashed curves are the results for the overcoated skin. Note that the overcoat either provides a significant reduction in weight or for the same weight allows a higher cruise Mach number.

For this overcoat system to be most effective, the surface temperature of the coating should reach its maximum allowable value during abort. Thus, the maximum amount of aerodynamic heat would be radiated away, and the aerodynamic heat rate would be reduced to a minimum as a result of the lower driving temperature potential $T_{aw} - T_s$. However, a minimum-weight combination for the overcoat and skin does not allow the surface temperature of the overcoat to reach its maximum allowable value during aborts from lower cruise Mach numbers. Thus, a lighter material with lower conductivity or lower allowable surface temperature can be used as the overcoat at lower cruise Mach numbers.

CONCLUDING REMARKS

The preliminary study of a fail-safe-system concept as an alternative to a redundant active cooling system indicates that this concept warrants further consideration. It appears possible that a passive thermal protection system (TPS) can absorb abort heat loads and that this passive TPS could be provided with no increase in weight. Several TPS concepts could be used and they may offer other advantages, such as reducing the heat load to the active cooling system during cruise, making the active-cooling-system passages less susceptible to cracks and other damage, and increasing the overall safety and reliability of the aircraft.

Langley Research Center,
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Hampton, Va., December 10, 1974.

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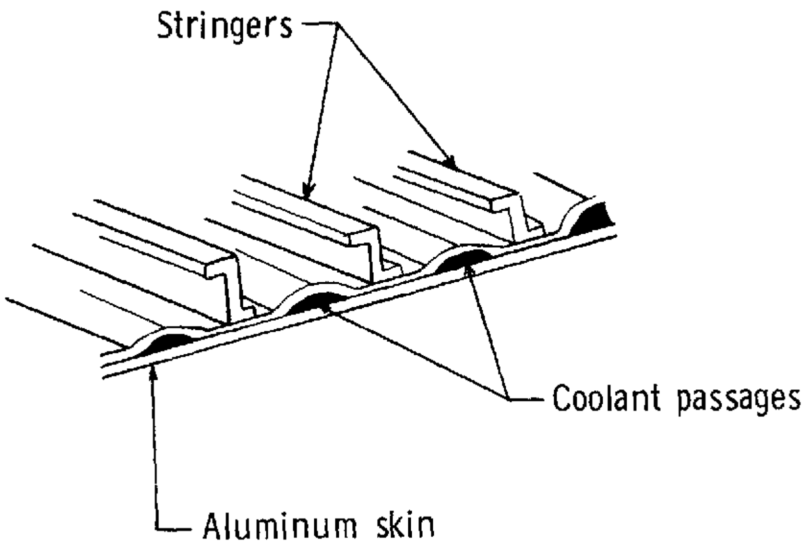

Figure 1.- Sketch of possible skin panel.

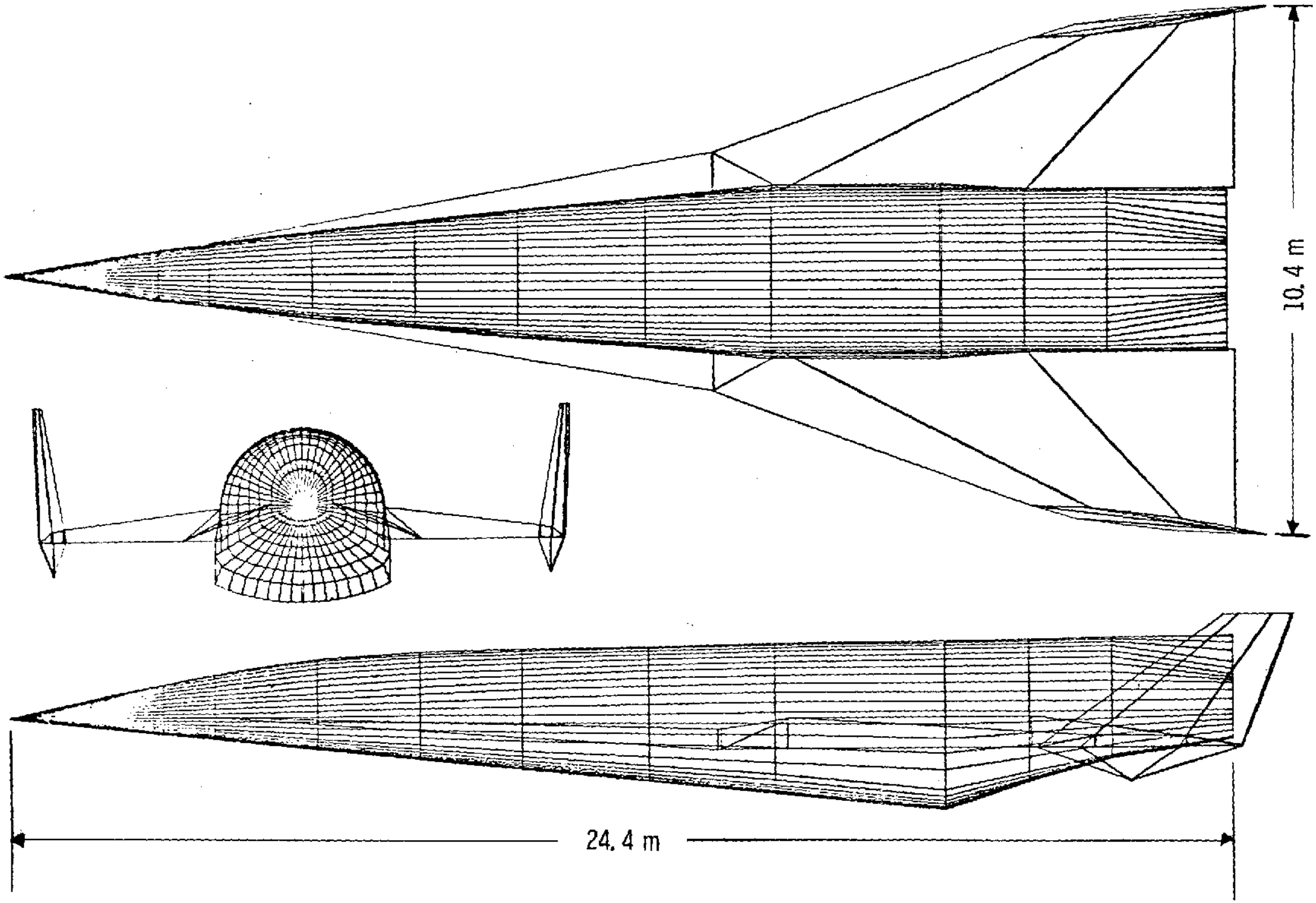

Figure 2.- Research-aircraft configuration.

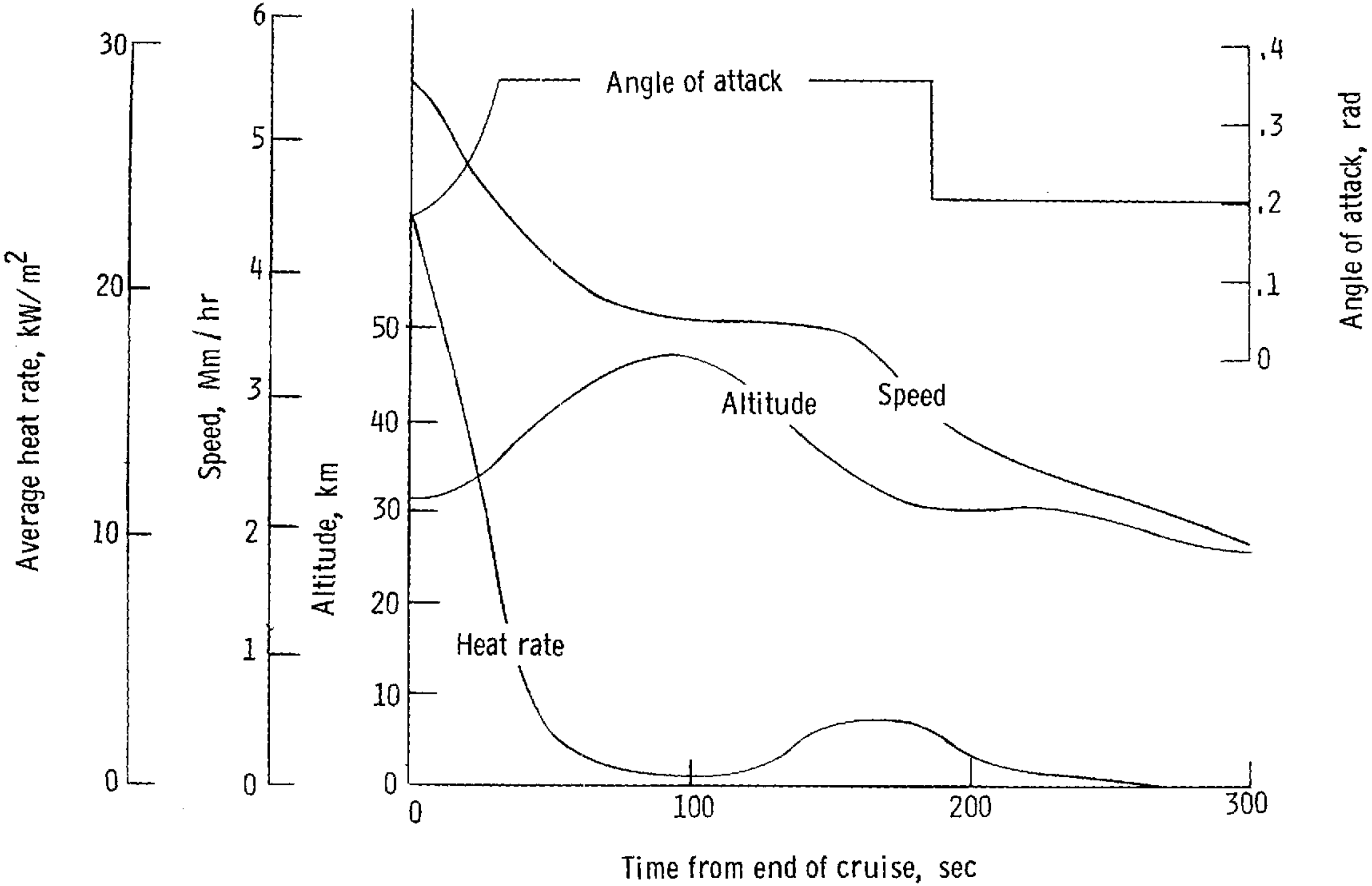

Figure 3.- Low-heat-load descent from Mach 5 cruise. T_W = 366 K (200° F).

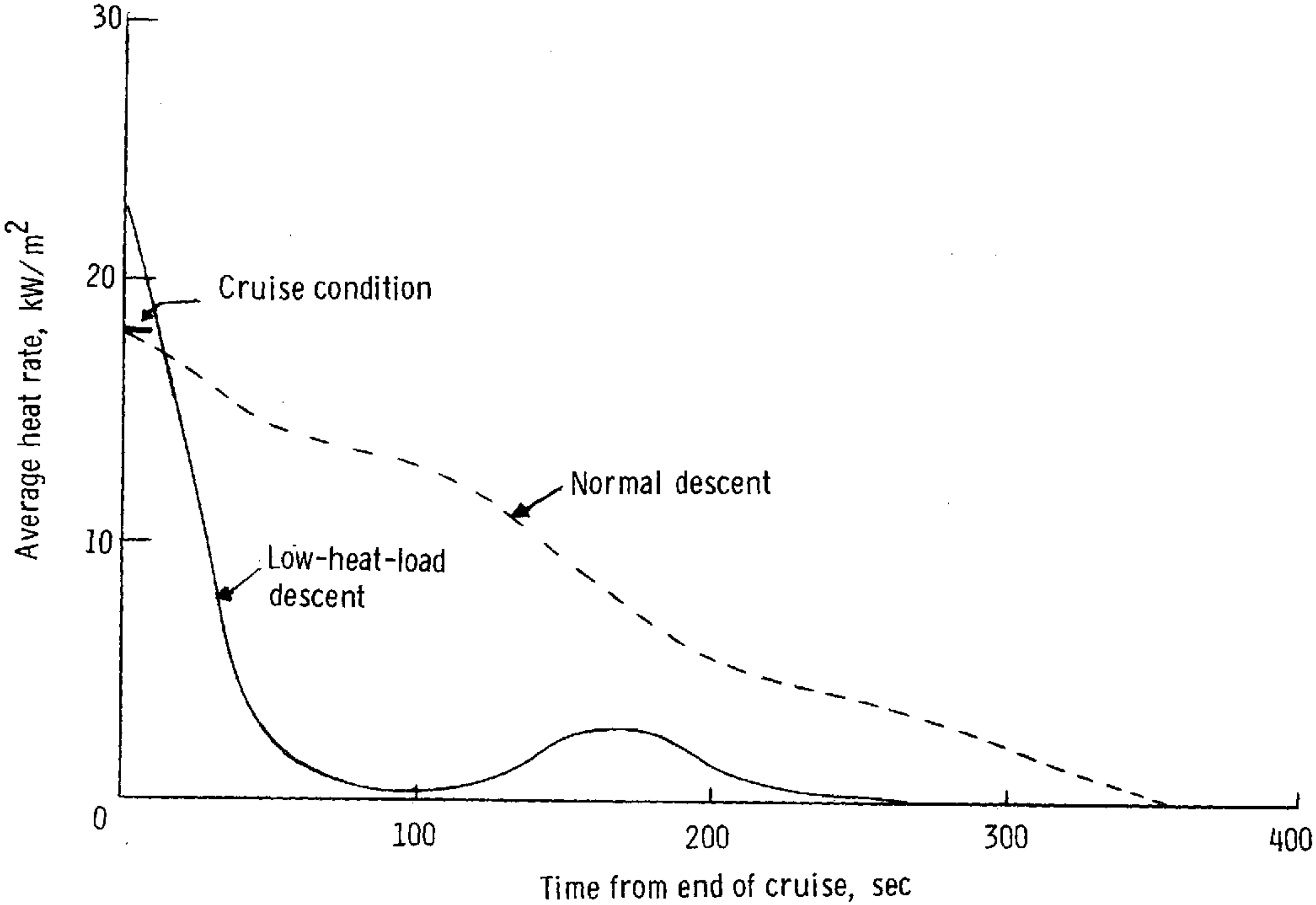

Figure 4.- Normal and low-heat-load descent heat rates from Mach 5 cruise. T_W = 366 K (200° F).

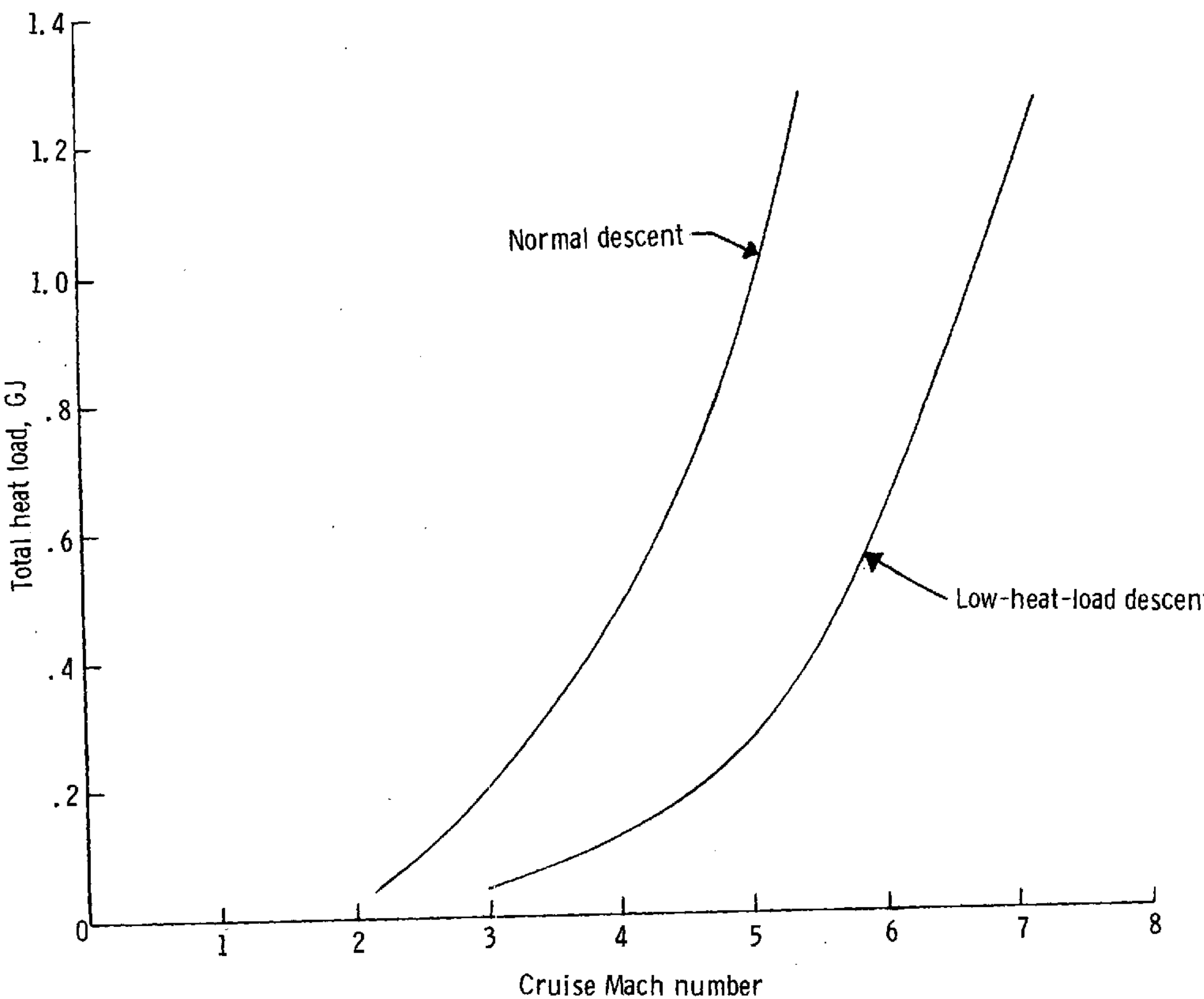

Figure 5.- Total descent heat loads.

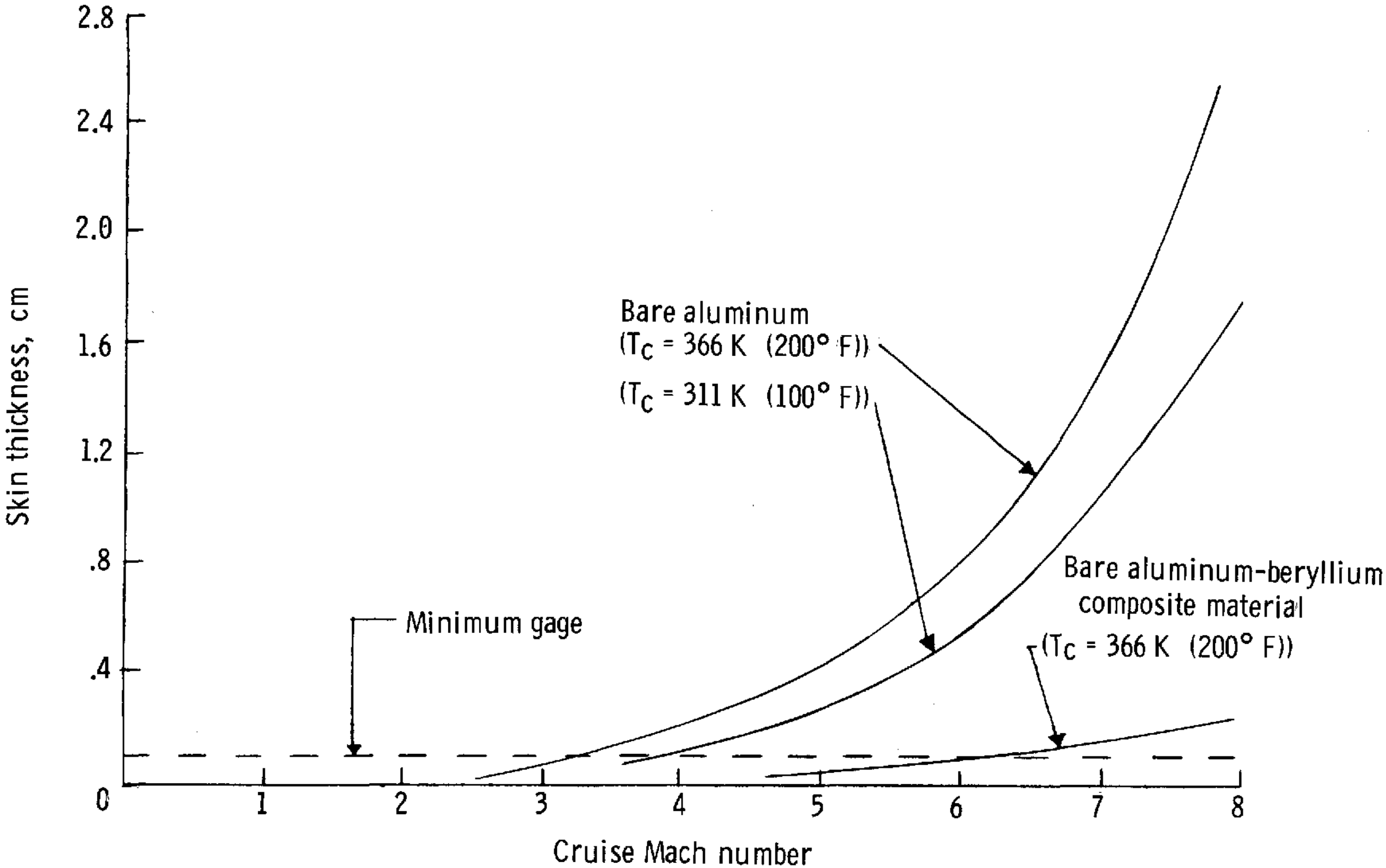

Figure 6.- Required skin thickness for fail-safe abort.

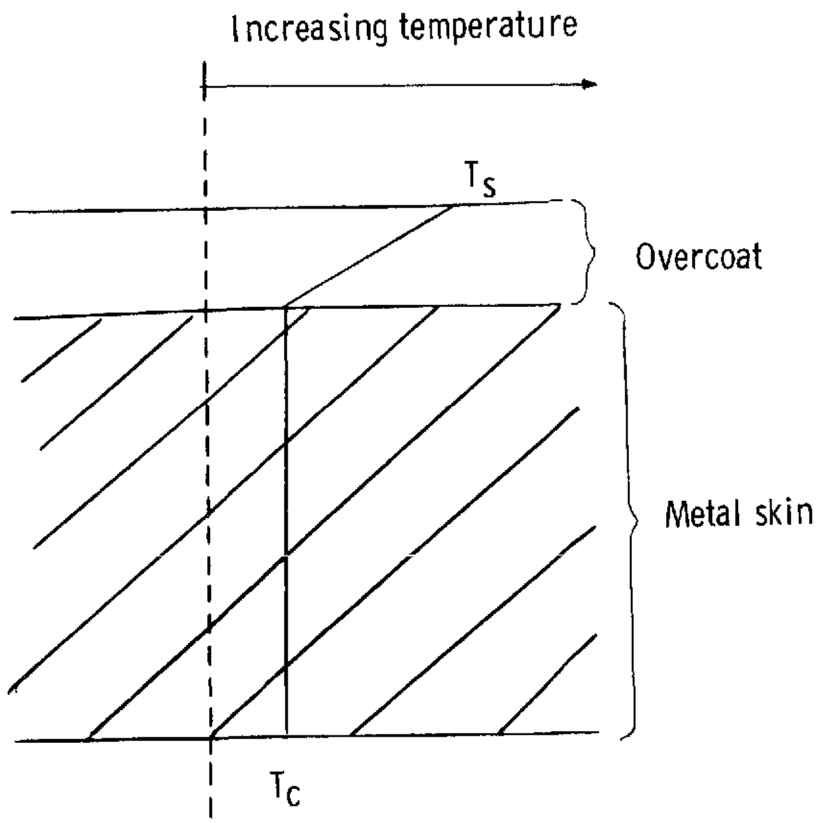

Figure 7.- Temperature distribution in overcoated skin during cruise.

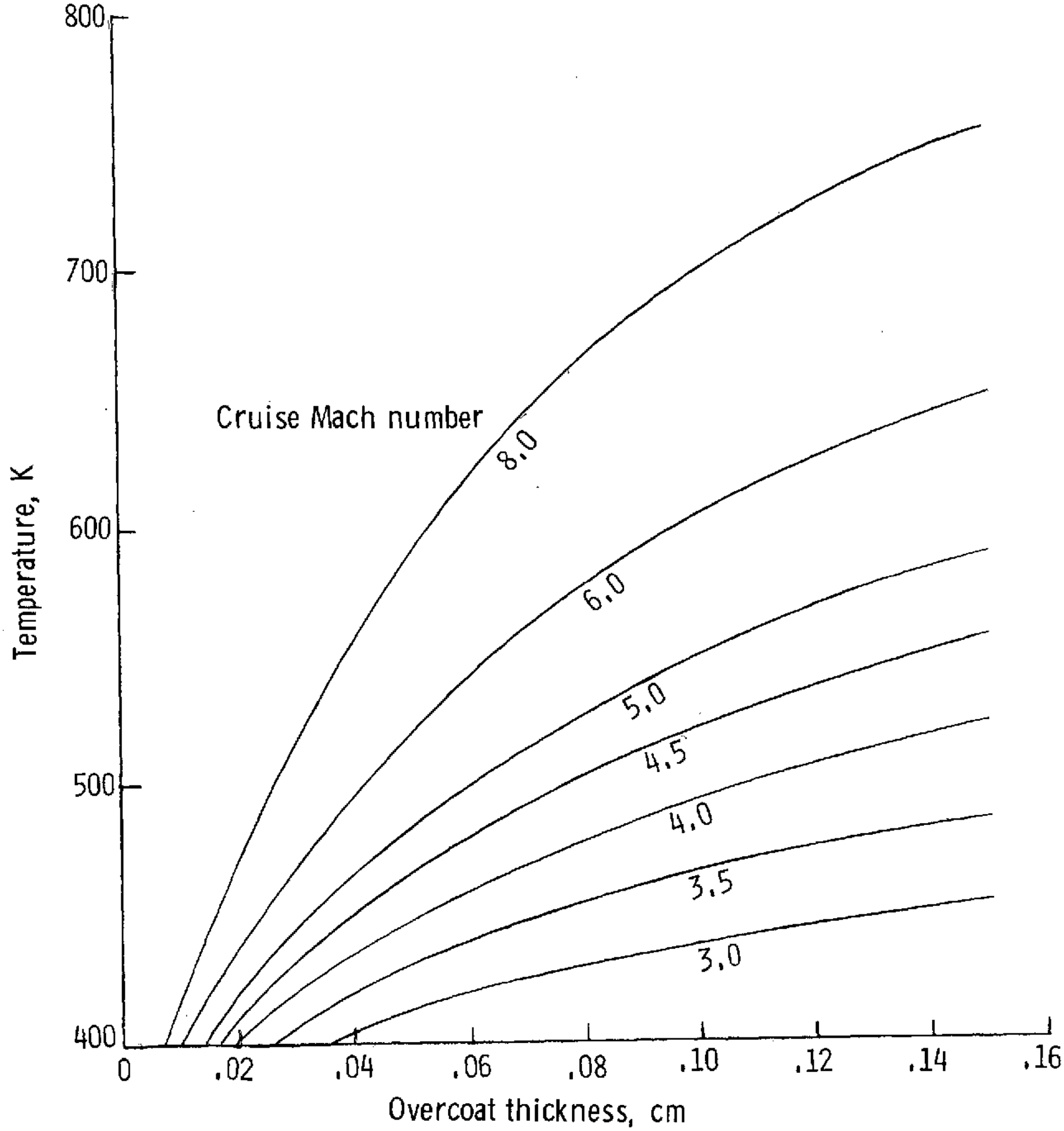

Figure 8.- Average surface temperature at cruise. T_c = 366 K (200° F).

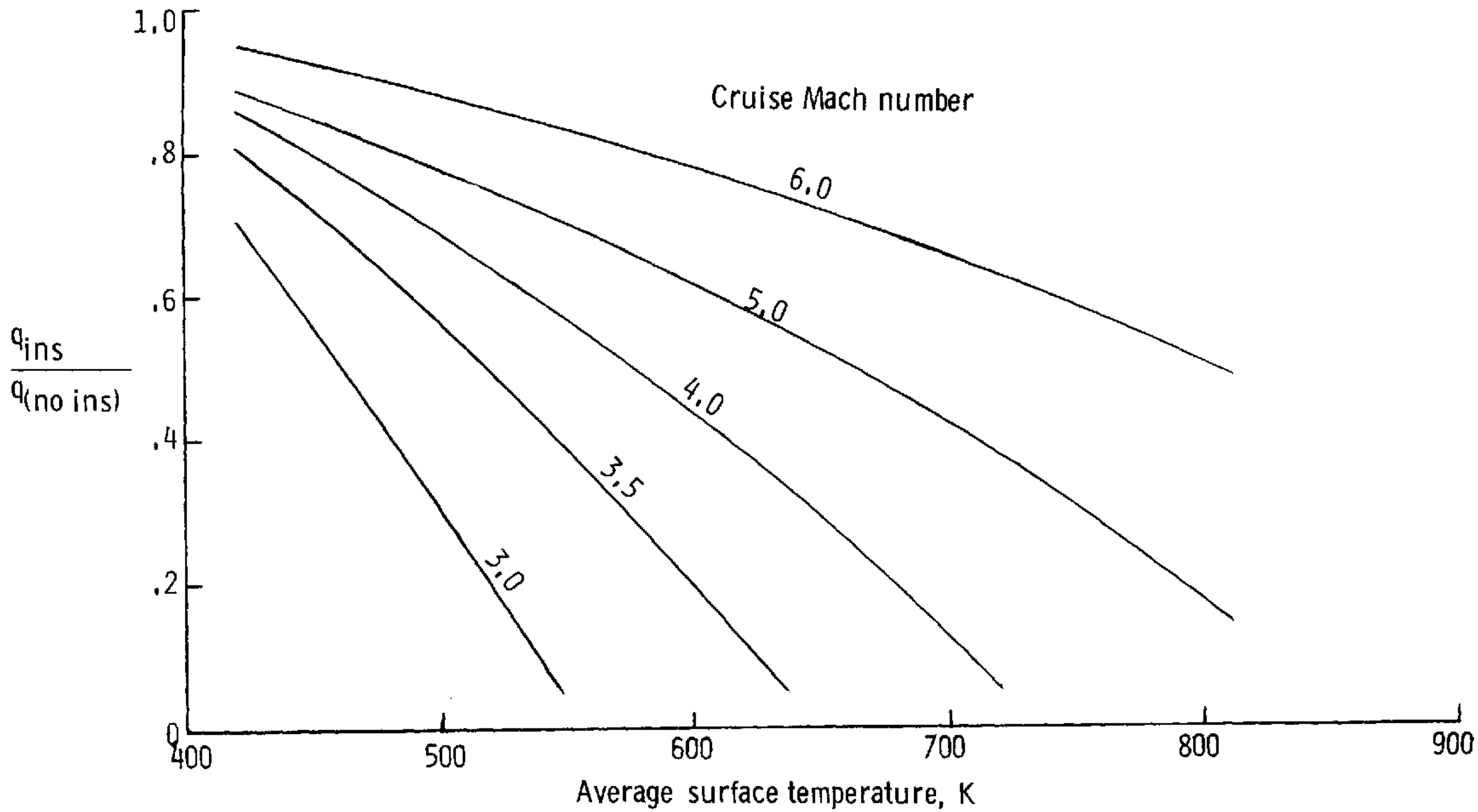

Figure 9.- Heat reduction at cruise for overcoated skin. T_c = 366 K (200° F).

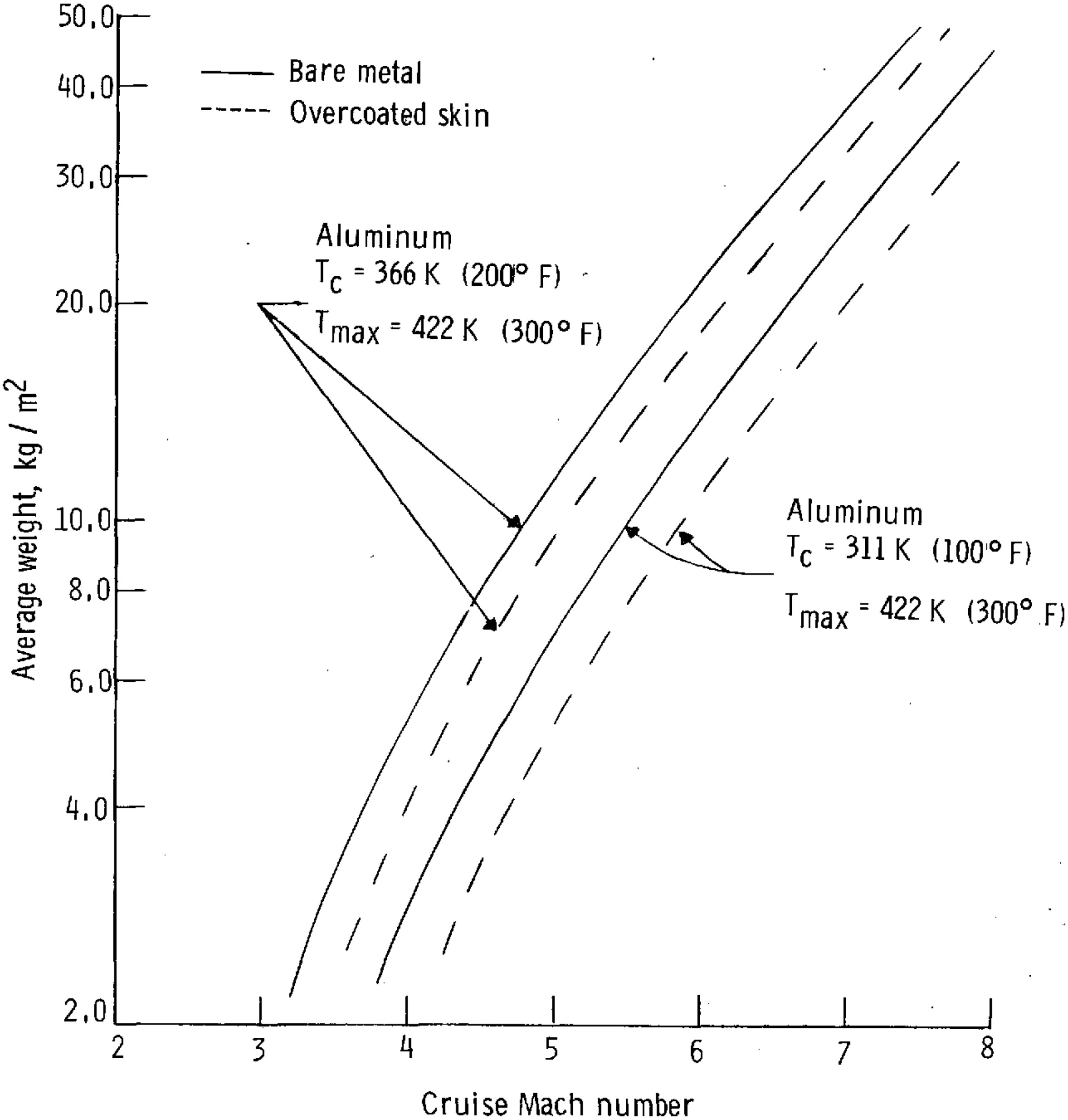

Figure 10.- Weight of overcoated skin for fail-safe abort.