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STUDY OF THERMAL PROTECTION REQUIREMENTS FOR A LIFTING BODY ENTRY VEHICLE SUITABLE FOR NEAR-EARTH MISSIONS

Summary Report

by

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1. INTRODUCTION

There is considerable interest in lifting-body entry vehicles for future manned space vehicle missions. These missions are usually constrained to orbits lower than synchronous and, in general, to performance requirements that can be satisfied by moderate L/D capability, such as exhibited by the M2-F2 vehicle (Figure 1).

Considerable variations exist in heating rates over the vehicle surface for most lifting bodies of the moderate L/D class. In addition, a wide variation in thermal environment exists along the flight path. These variations and the likely existence of turbulent flow over portions of the vehicle surface complicate the design of efficient thermal protection systems for lifting entry vehicles. This study (References 1 and 2) was conducted to assess the thermal protection requirements and to obtain accurate evaluations of shield weight requirements.

2. DESCRIPTION AND SCOPE OF STUDY

This study evaluated the heat protection system weights for the NASA M2-F2 lifting vehicle. It encompassed a variety of vehicle weights and sizes, capable of re-entry at a variety of flight entry velocities. The analysis included the study of vehicle capability for launches and aborts from a number of boosters with a variety of heat protection systems and allowable backface temperatures.

The boosters considered in the study were Titan II, Titan III-C, and Saturn I-B. One subcircular and two supercircular re-entry trajectories, namely, 7468, 9144, and 10,363 m/sec (24,500, 30,000, 34,000 ft/sec) were considered in the analysis. Nominal vehicle sizes were varied from 6.71, 7.91 and 9.14 m (22, 26 and 30 ft) and 3172, 4536 and 6804 kg (7000, 10000 and 15000 lb). Heat protection systems included ablation, re-radiation, and ablation over re-radiation. The materials were an elastomeric shield material (ESM) and microballoon phenolic nylon (MPN) for the ablation material, a super alloy (René 41), and a refractory alloy (TZM) for the re-radiation system, and micro-quartz and foamed pyrolytic graphite for insulation of the re-radiation systems. The heat protection system weights were evaluated for backface temperature constraints of 422 and 589^{o}K (300^{o} and 600^{o}F).

3. STUDY OBJECTIVES

Accurate estimates of the weight of various thermal protection systems were obtained for a representative lifting body (NASA M2-F2) configuration capable of entry from a range of near-earth orbits as the primary objective of this study. Both ablative and combined ablative-re-radiative thermal protection systems with refurbishable capability were considered. As an additional objective, the effect of problem areas associated with the design of efficient heat shields for lifting bodies was determined and indications were made how the associated uncertainties could affect the weight estimates.

4. RELATION TO NASA PROGRAMS

This study is related to several NASA programs concerned with research on manned lifting body entry vehicles designed to perform missions in a near-earth orbit. It provides an evaluation of the thermal protection requirements for the Minimum Manned Lifting Body Entry Vehicle system studies sponsored by the NASA Flight Research Center.

Results of the study (i.e., preferred materials and attachment methods, environmental test requirements, and critical trajectory requirements) are also applicable to NASA's Scout Entry Test Program. In the NASA material research area, the study shows the adequacy of both MPN and ESM for the mission requirements. Current research efforts can be oriented toward optimizing a thermal protection system based on either of these ablative materials.

Although there is no direct relationship between this effort and the Apollo Program, the difference in cost of the refurbishable system (based on advanced materials) described herein and the reported cost of the thermal protection system for the Apollo Command Module are pointed out. The roughly \$1.5+ million cost for each Apollo Command Module heat shield is largely a result of the requirements to hand-fill each cell of the honeycomb core. Using an advanced material, such as ESM, eliminates this painstaking and costly procedure, thus reducing the predicted cost to less than a tenth of this sum. Further, the system is refurbishable for multiple usage.

5. BASIC ASSUMPTIONS AND METHODS OF APPROACH

An orderly flow of information was required in each of the study areas to permit the proper evaluation of the heat protection weights for this wide range of applications:

(1) Aerodynamic force coefficients, pressure distributions, and flow field information were provided for the vehicle applications. The reference point for the performance coefficients and pressure distributions was NASA-supplied test data. Areas in which test data were not available or available only for the earlier M2-F1 configuration were evaluated by various analytical methods, including flow field solutions, as required to meet the needs of trajectory and thermodynamic analysis.

(2) A trajectory analysis was performed for all the specified re-entry conditions. Variations of weight and length were considered for subcircular and supercircular flights. The supercircular flights considered the $L/D = 1$ overshoot boundary condition. The subcircular flights were operated at $L/D = 1$, L/D max, and C_L max conditions. Critical ascent-abort flights were determined for the three selected boosters for the study. Maximum dynamic pressure abort and a number of undershoot boundary flights were also examined.

(3) Heat flux distributions were obtained from both NASA data and Rhodes and Bloxsom tunnel tests. The comparison of calculations and test results showed good agreement.

(4) The heat flux time histories and total heating were established, as a function of $W/C_L A$, for all of the specified flight paths of the study. Corresponding maximum heat flux and total heating were determined for each flight path and were obtained for the critical abort flights. The heating was evaluated for both laminar and turbulent flow at various pitch angles of attack. The selected transition criteria was based on correlated ground and flight test data employing local Reynolds number as a function of local Mach number. The influence of transition on the total heating and heat flux was determined for each basic re-entry trajectory.

(5) Properties were collected for all study materials. They included all available physical and thermal properties needed for ablation analysis, heat protection system application, refurbishment, and structural analyses.

(6) The basic analysis of the ablation material was obtained by the Reaction Kinetics Ablation Program (REKAP). The model for ESM was well founded, based on extensive analytical and test data for the material. The performance of MPN was obtained by an adaptation of a phenolic nylon model, and its adequacy was demonstrated by comparison of calculations with ground test results. The ablation performance for each material was determined by evaluating erosion, degradation, and insulation performance for a number of typical heating conditions. For each case, detailed temperature and density profiles were determined as a function of time and position.

(7) The ablation system performance was determined, as a function of total heating for each re-entry condition (based on the REKAP analysis for each material and backface temperature). The ablation requirement was established for the nominal case with a 1.2 safety factor. This safety factor, based on design experience, was provided on degradation but not on the insulation thickness.

(8) The requirements for the re-radiation heat protection system were established by use of standard conduction solution programs. The weight of the system was examined for micro-quartz and foamed pyrolytic graphite insulation for each re-entry trajectory, with and without an air gap and cooling. The insulation thickness and weight were determined for each system, to obtain the various backface structural temperatures. The total weight performance for the system was then correlated with total heating.

(9) The combined ablation-over-re-radiation system performance was determined by analyzing the performance of each individual portion of the system. Over-all ablation performance was obtained (by REKAP analysis) for a given time, relative to the total flight time, for each flight. Data concerning the re-radiation portion of the shield were determined from conduction solutions based on the total heating utilized for the application. The total weight for the combined system was then provided as a function of total heating.

(10) The application of the various heat protection systems was based on the key limiting parameter(s) for each system. Ablation can be utilized over any portion of the vehicle. The re-radiation system was limited by the maximum allowable surface temperature for René 41 1255°K (1800°F), and TZM 1755°K (2700°F). The allowable areas on the vehicle

for each of these materials were established. The combined systems using ablative over re-radiative material was also used to extend the areas for which re-radiative materials could be employed.

(11) Refurbishment techniques were established for each system. Accurate weights and reliable systems were determined. Methods and techniques for joining and attaching the various systems were also established.

(12) Requirements for the supports and clips for the re-radiation system were defined. The adequacy of the ablation system under cold soak thermal stress conditions was specified.

(13) The weight of the heat protection systems were established for a number of areas over the vehicle. The weight requirement was correlated with total heating for each condition. The re-entry condition, vehicle weight and size, material, transition, and backface temperature determine the total heat input at a given location. The performance of each system (for a safety factor of 1.2) determines the weight of each of these sections. The total weight is a summation of each section weight, including refurbishment. The location of the re-radiation system was based on the maximum heat flux for all flight conditions.

(14) An error analysis was made for each of the primary areas to evaluate the effect of uncertainties on the over-all calculated heat shield weight.

6. RESULTS OF STUDY

The study (References 1 and 2) provided detailed technical data in the areas of flight mechanics, aerodynamics, thermodynamics, materials, and structures as discussed in Section 5. This data was required for the evaluation of the shield weight of the M2-F2 vehicle for the variety of conditions specified in Section 2.

The heat protection system weights depend on both the re-entry and abort trajectories. (The maximum heat flux and total heating for the applicable re-entry and critical abort conditions are shown in Figure 2.) The application of the ablation system was essentially based on the re-entry trajectories which imposed the highest total heating (greatest shield requirement). The re-radiation system application was primarily limited by the critical abort flights which imposed the highest heat flux.

The ablation over re-radiation system was limited by both re-entry and abort. The minimum ablation thickness for this combined system was determined by the abort requirement, while maximum thickness was determined by re-entry total heating requirements. The heat protection requirements were determined primarily for the three trajectories used as nominal flight paths with three basic phases (pull out, constant altitude, equilibrium glide). The nominal supercircular flights were based on the overshoot boundary. The subcircular flights were investigated for several variations, and those requiring the heaviest heat shield were used in the study (constant altitude phase to L/D max). Flights with a constant altitude phase to C_L max showed appreciably lower total heating and therefore lower shield weight requirements. Operation at bank angle with C_L max requires a still lighter shield.

The heat protection systems of particular interest in this study included ablation; ablation plus re-radiation; and ablation, re-radiation, and ablation over re-radiation. Figure 3 shows typical applications of these systems to the M2-F2 vehicle. An ablation system (ESM or MPN) must be used on the nose, canopy, fin leading edge, and flap, but may also be used for all or any other desired areas. The re-radiation system (René 41 and TZM) is limited in use to leeward surfaces, aft portions, and fin locations. The combined ablation over re-radiation system can be used on the windward conical surface.

The shield weight, including provision for refurbishment for an ablation system, is shown on Figure 4 as a function of vehicle length for a nominal vehicle (see section 2). The shield weights, based on a safety factor of 1.2, vary from about 8 to 25 percent of the total vehicle weight. Backface temperature was the major influence on the shield weight requirement.

For the low backface temperature condition of 422°K (300°F), the all-ablation type of heat protection system requires about 17 to 25 percent of the total vehicle weight. Of the two ablation materials investigated, MPN requires somewhat less weight than ESM for the low backface temperature case. A comparison of the shield weights for the various systems and materials is shown on Figure 5 for a nominal vehicle size and entry condition. The TZM material utilizing a maximum allowable temperature of 1755°K (2700°F) requires a shield of less weight than that for René 41 (maximum temperature 1255°K (1800°F). The combined ablation, re-radiation, and ablation over re-radiation system requires the lowest-weight shield.

A comparison of weights for the higher backface temperature, 589°K (600°F), shows the opposite trend. The high allowable backface temperature considerably reduces the ablation system requirements. The ablation shield is by far the lightest and consists of about 8 to 17 percent of the total vehicle weight. The heat shield using ESM is considerably lighter than using MPN. The systems utilizing re-radiation and ablation over-re-radiation show higher weights than the all-ablation system.

Both heat shield systems were refurbishable; however, ESM is more adaptable for this requirement. The weight penalty associated with refurbishment varies from about 3 to 12 percent depending on the material, system, backface temperature, and application. The refurbishment system for the all-ablation ESM system can utilize several approaches, such as perforated scrim for all conditions, and tape for the lower backface temperature condition. Where turn-around time is not critical, the ESM system may be bonded directly to the structure (with a resultant weight saving) and still be considered refurbishable.

The MPN ablation material requires an approach such as the elastomeric-pillar system. The maximum refurbishment system weight requirement for ESM is about 58 percent of that for MPN and about 66 percent of that for the re-radiation system using rods and clips. The ease of refurbishment is clearly reflected in the cost estimate for these typical systems. A typical cost (rough estimate) of the ESM ablation system for the nominal 4536 kg (10,000 lb) vehicle will be about $85,000 for the 408 kg (900 lb) shield and $175,000 for the 1070 kg (2285 lb) shield. A comparable cost of the MPN system is estimated at about $420,000 to $530,000 for the similar shields.

The heat protection system study shows that the local heat flux is sufficiently high that ablation must be used for specific portions of the vehicle (nose, flaps, fin leading edge, canopy, etc). Although re-radiation may be used for some portions of the vehicle, it is also far more sensitive to changes in the flight path. The ablation system has more versatility and shows definite weight savings for the higher backface temperature condition. The ESM material, besides being less expensive, has a definite advantage not only in manufacture and refurbishment but is more adaptable to cold soak (thermal cycling). MPN is generally limited to about 150°K (-190°F) cold soak and requires local expansion gaps over the vehicle. ESM does not have this limitation.

The ablation type of heat protection system is considered to be the most reliable at the present time. The use of the materials, their manufacture, and repair present high confidence in this system for the intended application. The re-radiation system, which can be used for only part of the vehicle, basically depends on local heat flux which is closely dependent on the flight path requirements. The coatings required for TZM make the handling and re-use capability of special concern. The ablation over re-radiation system for low-backface-temperature applications appears very attractive. The use of micro-quartz for insulation, compared to foamed pyrolytic graphite, resulted in a weight advantage of about 5 percent. The clean removal of the outer ablation layer and its effect on the coating for TZM is of some concern for the proper application of this system. The necessity of an active cooling system with the re-radiation system adds somewhat to its complexity and reduces its reliability.

The error analysis of this study indicates that the weight evaluations are reasonable for the intended application. Individual variations in the various study parameters were readily evaluated in terms of heat shield weights. Future work recommendations have been established for the M2-F2 application in each of the major technical areas.

The study shows the advantage of higher backface temperature design. About 24 percent of the vehicle weight represents the shield at the low backface temperature of 422°K (300°F). This can be lowered to about 8 percent when the backface temperature is raised to 589°K (600°F) for ESM. It is suggested that in special areas such as the fins, flaps, and aft sections of the vehicle (away from the pilot area), the local backface temperature should be increased to even higher values utilizing structures such as beryllium or boron fibers to further reduce the shield weight.

7. FUTURE WORK RECOMMENDATIONS

Additional work is required in specific areas to improve the capability to predict performance and to aid in the design of future lifting body entry vehicles such as the NASA M2-F2. These items are summarized as follows:

Trajectory Analysis

(1) Abort escape studies from booster blast propagation
(2) Footprint studies for a greater variety of re-entry velocities including both overshoot boundaries
(3) Terminal landing maneuvers for desired touchdown mode.

Aerodynamic Analysis

(1) Perform model tests to obtain detail pressure, force and moment data, and flow field information (Schlieren photographs) with and without mass addition at a variety of conditions (Mach numbers, Reynolds numbers, pitch and yaw angles of attack) for both laminar and turbulent flow
(2) Perform three-dimensional flow field studies for the M2-F2 configuration.
(3) Initiate feasibility study of flight test bed design and experimentation.
(4) Investigate possible ablation contamination on special areas (windshield, vents, gaps, etc).

Heating Analysis

(1) Obtain detailed heat transfer distributions with temperature-sensitive paint at angles of attack of from 0 to 40 degrees and yaw angles of 5 and 10 degrees for both laminar and turbulent flow.
(2) Obtain quantitative heat transfer data at a variety of Mach numbers and Reynolds numbers with Schlieren photographs for conditions mentioned in item (1).
(3) Obtain heat transfer data in selected areas (such as leeward surfaces, fins, flaps, canopy, and interaction areas) for specific high-Mach-number conditions by both ground and flight test programs.
(4) Mass addition effects should be investigated over portions of the vehicle.
(5) Transition criteria studies for asymmetrical bodies such as the M2-F2 should be made by ground and flight tests.

Heat Protection Systems

(1) Obtain additional ablation performance tests for ablation materials, especially MPN, at various facilities that cover a range of enthalpy, heat flux, and shear levels.
(2) Investigate by test and analysis the ablation over re-radiation system, the bonding of the ablation system, the removal of this layer during flight, and the effect on the re-radiation surface and coating.

(3) Test and analyze the various joint concepts between dissimilar heat protection systems to determine their adequacy for a design. Conditions at gaps and joints should be included.
(4) Investigate the optimum heat protection system and materials for special areas of the fin, rudder, flaps, gaps, and canopy. Investigate the ultilization of transpiration or film cooling techniques for these areas.
(5) Efficient composite shield materials should be investigated for applications at the nose, fin leading edge, and flap.

Materials

(1) Investigate fabrication of representative shield sections for MPN for the M2-F2 application.
(2) Investigate the bonding and removal technique for the combined ablation over re-radiation system.
(3) Investigate the refurbishment of the large sections of the M2-F2 (ESM and especially MPN).

Structures

(1) Investigate the optimum structural temperature design for minimum total weight by defining detailed weight versus backface temperature trade-off curves. Temperatures up to 810°K (1000°F) should be included.
(2) Determine the cold soak capability of MPN and its structural compatibility for the application.

8. BASIC DATA APPLICABLE FOR GENERAL USE

Detailed aerodynamic, thermodynamic, trajectory, material, and structure data are presented in References 1 and 2. These data are pertinent to moderate L/D lifting vehicles. The use of this information is specifically aimed at the NASA M2-F2 vehicle when exposed to a given set of re-entry and abort environments. The generated data, of course, directly applies only to the specific conditions used in the study. Applications of the data to conditions other than those of the study depend on the specific application and on the similarity of the environment to that used for the study. Hence, use of these data for other than the study conditions, in general, must be made with due caution.

The overall total heat protection system M2-F2 weights for re-entry conditions between the two supercircular flights may be obtained by interpolation, since the flight modes are similar. Attempted interpolation with the lower subcircular-velocity flight results, however, may not provide adequate results because of the basic difference in flight paths.

The basic material properties and the refurbishment system weights can be utilized for any vehicle and system using similar materials. The basic aerodynamic, heat flux, and trajectory data depend primarily on the vehicle shape. The performance of the individual heat protection systems are closely related to materials and environmental conditions. Of course, the over-all results of this study may be used both as a guide and for reference purposes, even for applications to totally different vehicles involving quite different re-entry and abort conditions.

9. REFERENCES

1. Brunner, M., et al, Final Report, "Study of Thermal Protection Requirements for a Lifting Body Entry Vehicle Suitable for Nearh-Earth Missions," GE 66SD253, May 12, 1966.
2. Brunner, M., and Barté, G., Jr., Auxiliary Final Report, "Study of Thermal Protection Requirements for a Lifting Body Entry Vehicle Suitable for Near-Earth Missions (U)", GE 66SD254, May 12, 1966 (Confidential).

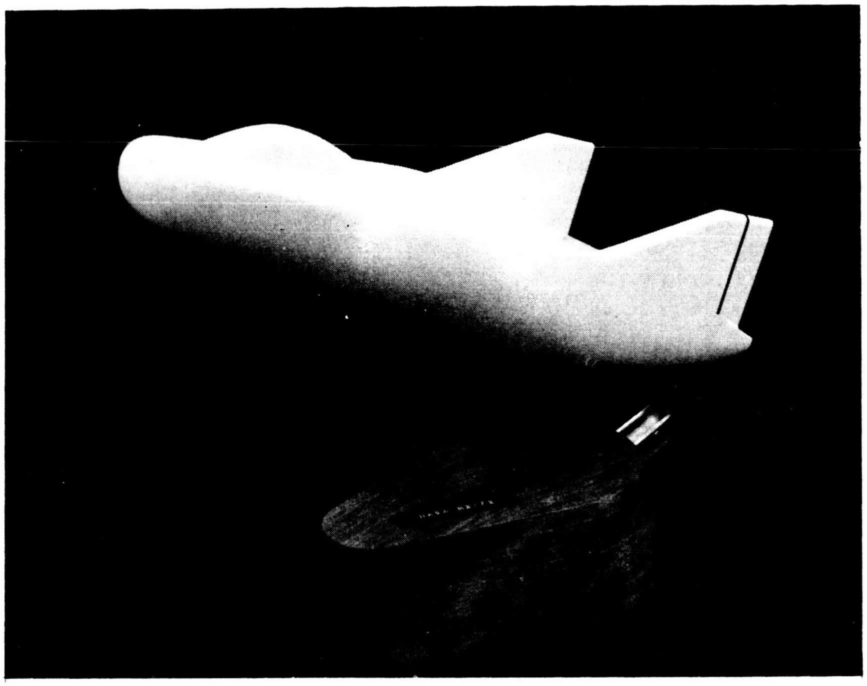


Figure 1. NASA M2-F2 Vehicle

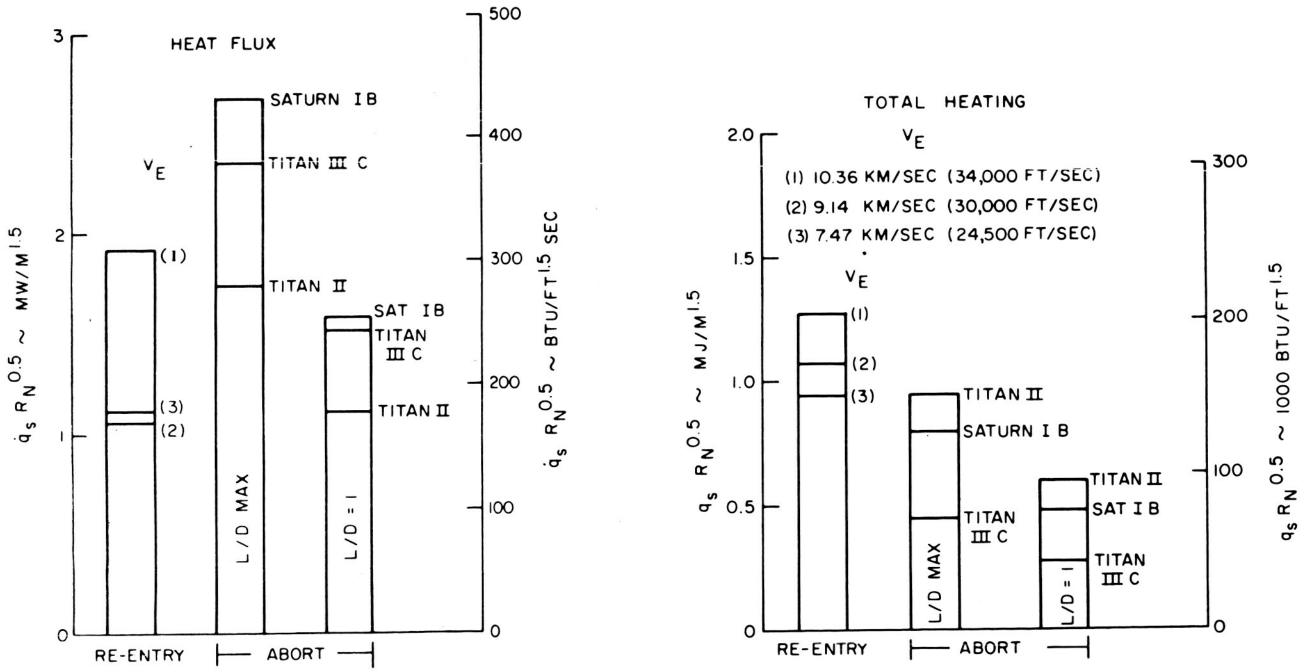
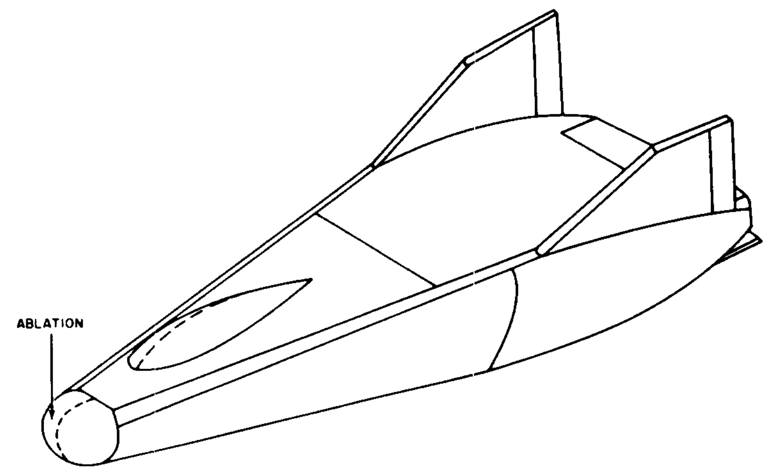
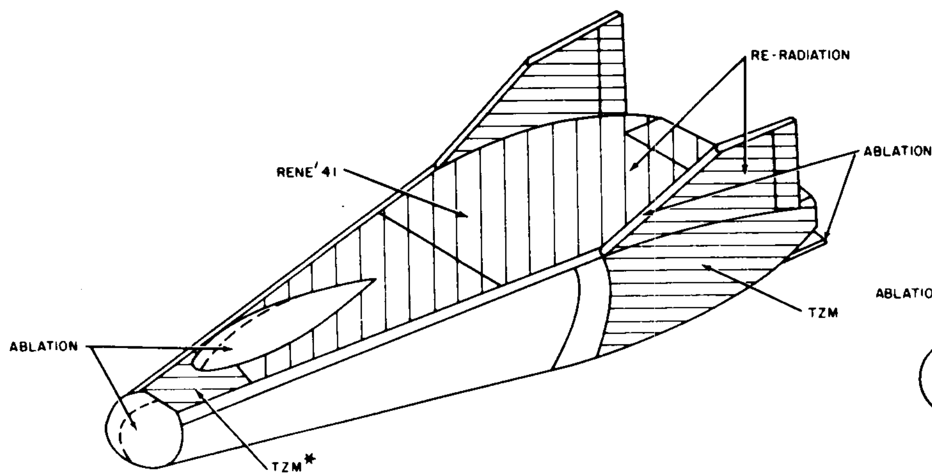


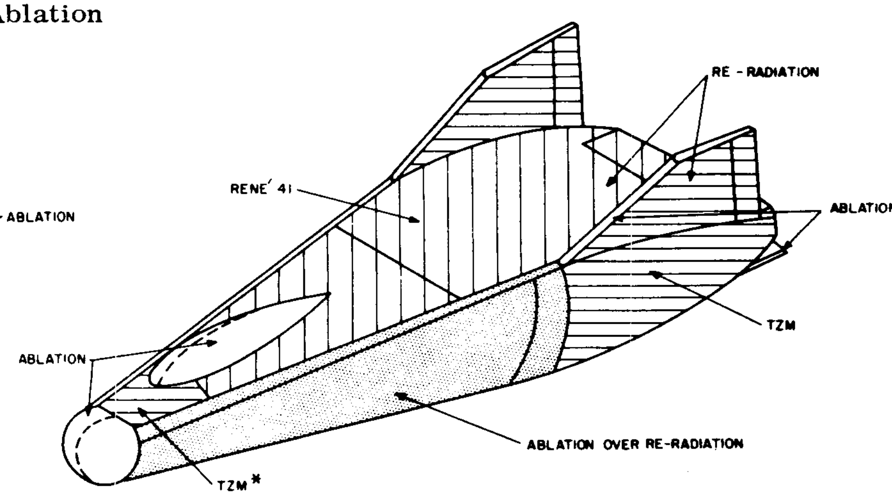
Figure 2. Comparison of Maximum Heat Flux and Total Heating for Re-entry and Abort



A. Ablation



B. Ablation and Re-Radiation



* WHEN REQUIRED

C. Ablation, Re-Radiation, and Ablation over Re-Radiation

Figure 3. Heat Protection System Application (Ablation, Re-radiation, and Ablation over Re-radiation)

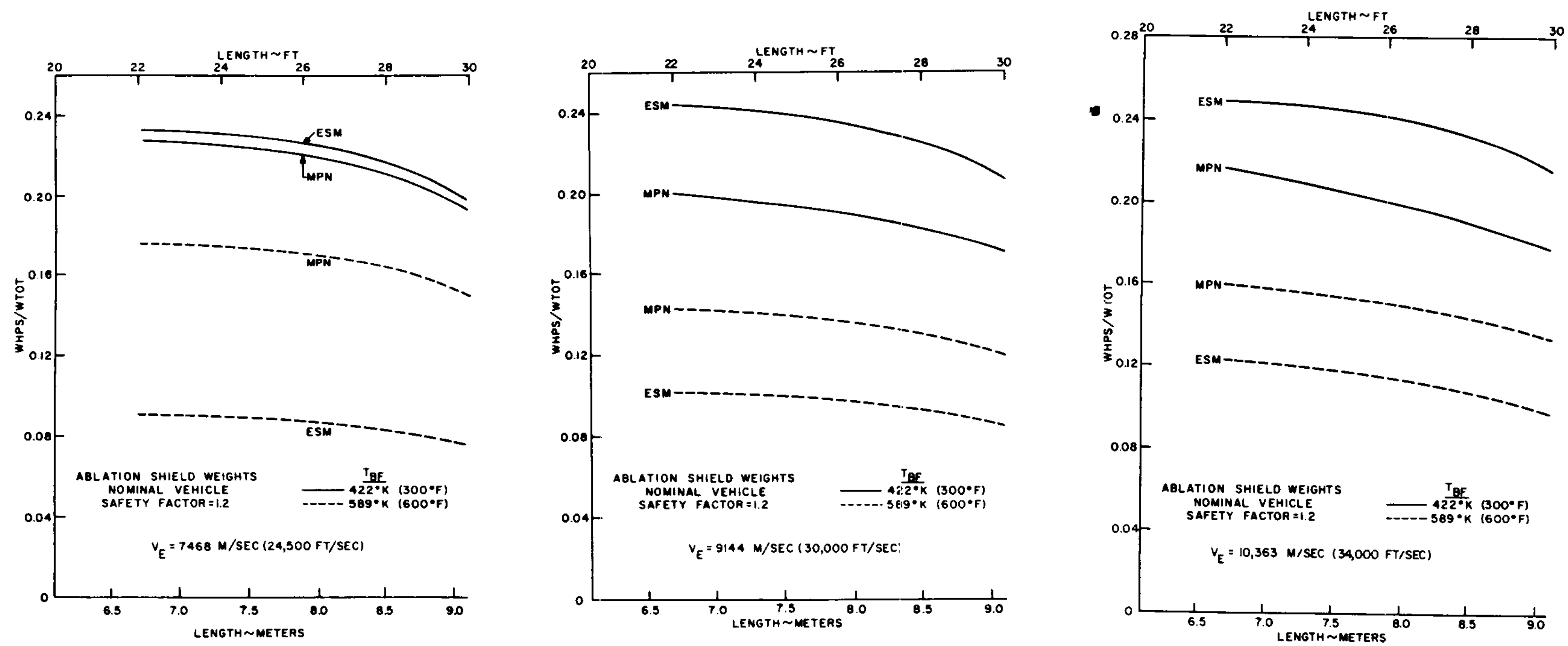


Figure 4. Heat Shield Weight for the Ablation - Type Heat Protection System

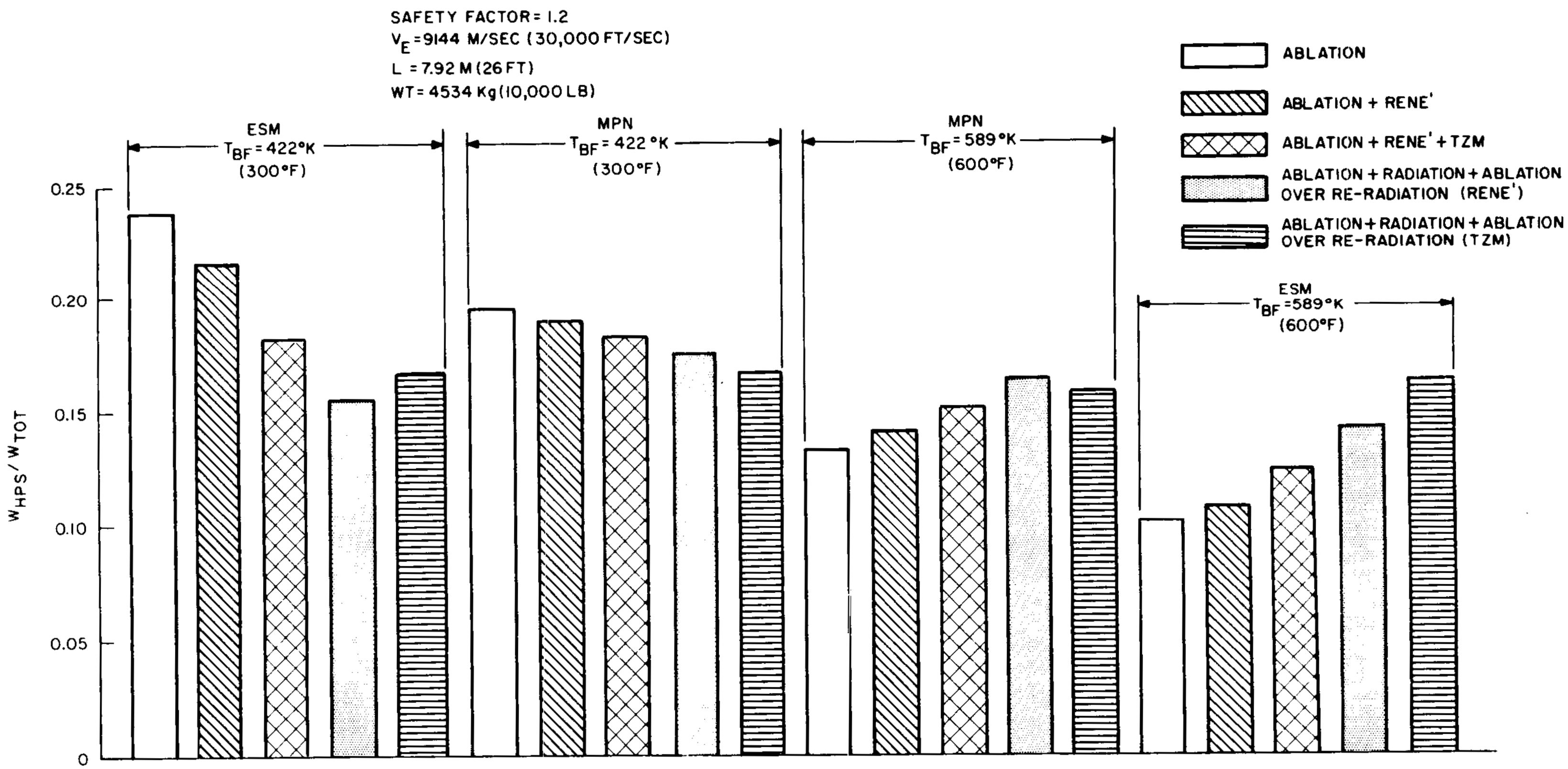


Figure 5. Comparison of Heat Shield Weight for the Various Systems for A Nominal Vehicle Size and Re-entry Condition