Lifting Entry Vehicle Mass Reduction Through Integrated Thermostructural/Trajectory Design

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The study described in this paper examines the impact of thermostructural/trajectory design integration on advanced-winged entry vehicle mass. A variety of thermal protection system (TPS) concepts are considered, and entry trajectories tailored specifically to each concept in terms of peak heat rate and total heat load are used in conjunction with an aerodynamic heating/thermal analysis program to determine the TPS requirements. Results indicate that for an aluminum structure, either the reusable surface insulation (RSI) or the hybrid TPS (RSI forward, René 41 metallic standoff aft) has the potential to yield the lowest mass system. The metallic standoff system is, however, quite competitive and, with the 25% reduction in the panel mass anticipated, could surpass the RSI system. Results also indicate that significant improvements in hot-structure design are necessary before such a system can become competitive. An assessment is made of the potential impact of higher temperature structure materials on combined TPS/structure mass. Results indicate that the greatest reduction in mass is obtained with the first 200K increase in temperature capability over that of aluminum and, thus, the potential for the lowest mass system appears to lie with either a graphite/polyimide or a titanium structure.

Nomenclature

C_L	= lift coefficient
c_p	= specific heat at constant pressure, J/kg·K
g	= acceleration due to gravity, m/s^2
H	= altitude, km
k	= thermal conductivity, W/m·K
L	= vehicle length, m
L/D	= lift-to-drag ratio
$\dot{q}_{REF}$	= reference heat rate, kW/m^2
Q_{REF}	= reference heat load, MJ/m^2
t	= thickness, cm
T	= temperature, K
V	= Earth-relative velocity, m/s
x	= body centerline location, m
α	= angle of attack, deg
ρ	= density, kg/m^3
σ	= ultimate tensile strength, kN/m^2

Introduction

IN order to maintain a long-range, aggressive national program that exploits the potential benefits of space, improvements and new capabilities will have to be introduced into the space transportation system as needs, technology, and economics dictate. The desire for reduced operations costs could lead to a new fully reusable launch/entry vehicle some time in the 1990s. In addition to full reuse, a new vehicle should incorporate low-maintenance features in the areas of propulsion and thermal protection systems (TPS). Reliability and durability must approach those of commercial aircraft. Because of the fragile nature of the current reusable surface insulation (RSI) TPS on the Shuttle Orbiter, other potentially more rugged systems are being studied for application to future reusable launch/entry systems.

The TPS of the entry vehicle, as much as any other vehicle component, requires integrated design at the vehicle system level. The importance of integrated aerothermostructure design for entry vehicles has long been recognized. However, in the past this integration has generally proceeded mainly in one direction (i.e., the entry trajectory is defined and the TPS is designed to the heating considerations of that trajectory within the constraints of cost and normal developments in TPS technology). Winged entry vehicles typically have the aerodynamic capability to fly entry trajectories within a broad altitude/velocity envelope. This allows considerable latitude in shaping the entry trajectory to the characteristics of the TPS, as well as the TPS to the characteristics of the entry trajectory. Recent results show metallic TPS to be an option worth considering for advanced vehicles, with proper tailoring of the entry trajectory.[1] Figure 1 shows that the typical entry planform loadings associated with advanced vehicle concepts are considerably lower than that of the Shuttle. These reduced planform loadings simplify the task of achieving the lower heat rate entries required for a metallic TPS.

The purpose of this study is to demonstrate the impact that aerothermostructure design integration can have on TPS mass. Four basic categories of TPS are considered: external insulation, metallic hot structures, metallic standoff, and hybrid (high-temperature surface insulation in the stagnation region and a metallic system over the remainder). A variety of concepts in these basic categories are examined. Entry trajectories tailored to the characteristics of each TPS concept are generated. An aerodynamic heating program is used with the appropriately tailored trajectories to determine the centerline TPS requirements for each concept under consideration. Heating calculations are made under the assumption of strictly laminar flow. The Space Shuttle will test the validity of this very important assumption. Entry isotherms determined in previous studies are used to extrapolate qualitatively the centerline results to the remainder of the vehicle's lower surface. Initially, a backface temperature limit of 450K (350°F), the maximum allowable aluminum structural temperature, is used to size each of the candidate TPS concepts (except metallic hot structures). The relative merits of each of the TPS/trajectory combinations considered in this study are assessed. The impact of sizing one type of TPS for a trajectory initially designed for another type is investigated.

The study also examines the impact of structural temperature capabilities on TPS mass. Representative TPS concepts are sized for a series of backface temperature limits

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associated with candidate structural materials other than aluminum. The impact of structural materials that maintain their integrity to higher temperatures on the combined TPS/structure mass is examined, and the relative merits of the TPS/structural mass/trajectory combinations investigated are assessed.

Vehicle Description

A control-configured vehicle (CCV) concept[2] was used as a representative advanced entry vehicle in the present study. The reference vehicle, shown in Fig. 2, was a fully reusable, delta-wing, vertical takeoff/horizontal landing, single-stage-to-orbit (SSTO) vehicle. The followng vehicle characteristics at entry were used: weight 1.911 MN (429,613 lb), reference wing area 557.4 m^2 (6000 ft^2), vehicle length 66.8 m (219 ft), and planform loading 1.7 kPa (35.5 psf). The experimental aerodynamic characteristics of the reference vehicle were used. The hypersonic L/D and C_L at 40 deg angle of attack were 1.267 and 1.28, respectively. At 32 deg α (used for the hybrid TPS), the corresponding values were 1.390 and 0.912.

Trajectory Development

Optimized entry trajectories were generated using the POST (program to optimize simulated trajectories) computer program.[3] The key considerations for the TPS design are the external surface temperatures associated with the peak heat rate and the total heat load. Shown in Fig. 3 is a qualitative comparison of the peak heat rate, total-heat-load characteristics associated with each of the four basic TPS types. The high-temperature capabilities and heat sink nature of the external insulation systems favor shorter, deeper entry trajectories with high heat rates and minimum heat loads. Hot metallic strucures have no TPS per se: rather, the structure itself is designed to radiate most of the heat encountered to the atmosphere. Since fairly large mass penalties are associated with the material changes required for increased temperature capability and since the total heat load does not impact the structural mass significantly, longer, higher entry trajectories with relatively low heat rates and high heat loads are favored.

A system incorporating a radiative metallic outer surface, insulated from and attached to the main structure of the vehicle, is termed a metallic standoff heat shield. This type of system operates by radiating some of the heat away and absorbing the remainder into the heat sink provided by the insulation. Entry trajectories tailored to metallic standoff systems must conform to the heat rate/temperature constraints of the metallic outer surface and must minimize the heat load to reduce the insulation mass required. These trajectories are similar to those required for metallic hot structures, but must be shorter in duration to minimize the heat load. The hybrid system is one that employs high-temperature external insulation in the stagnation regions of the vehicle and a metallic system over the remainder of the vehicle's lower surface. This type of system is designed to take advantage of the vehicle's heating characteristics for low angle-of-attack entries. Reduced angle of attack ($\approx$30 deg) leads to somewhat increased temperatures in the stagnation regions and over the upper surface. Over the remainder of the lower surface the temperature decreases, allowing use of a lower temperature TPS in that region. Low α entry trajectories yielding peak reference heat rates that fall between those for externally insulated structures and those for metallic hot structures are thus required for the hybrid TPS. Heat load must also be minimized in order to reduce the mass of RSI required on the fore region, as well as the mass of the metallic standoff internal insulation required on the aft region of the lower surface.

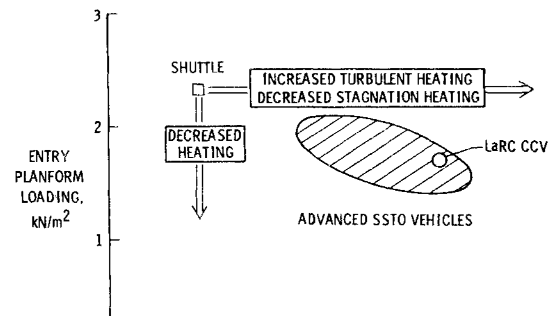

Fig. 1 Planform loading, body length comparisons for advanced entry vehicles.

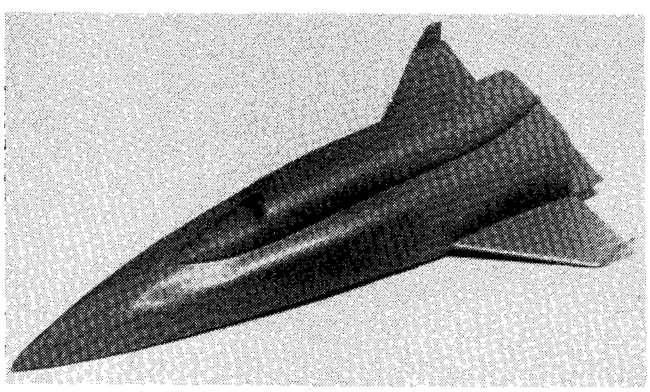

Fig. 2 Model of the LaRC control-configured vehicle.

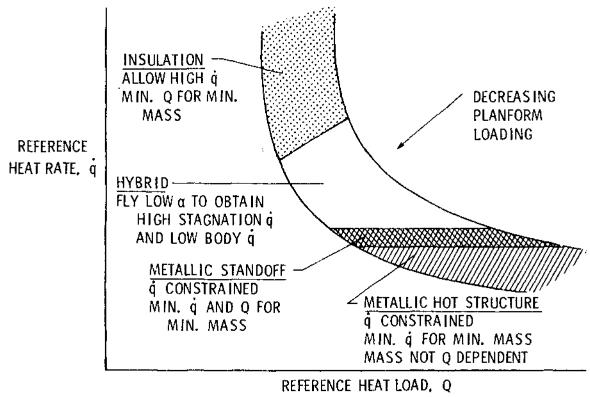

Fig. 3 Typical SSTO entry trajectory heating characteristics for four classes of TPS.

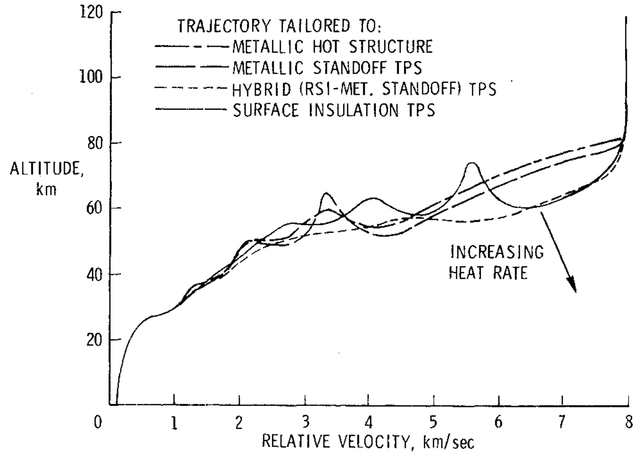

Fig. 4 Entry trajectories tailored to thermal protection system characteristics.

A number of entry trajectories were developed for each of the four categories of TPS concepts, each with different peak heating constraints. The planet model employed in POST was a spherical, rotating Earth. The 1962 standard atmosphere with no winds was used in the analysis. All trajectories had a minimum cross-range constraint of 2037 km (1100 n.mi.) for a once-around return capability. Acceleration values were also monitored in order to be certain that they were maintained within acceptable limits (3.3 *g*). Initial entry conditions at 122 km (400,000 ft) were obtained by deorbit from a 185.2 km (100 n.mi.) orbit with a slightly retrograde inclination. The corresponding initial latitude and longitude were 47.84° N and 17.2°E, respectively. The inertial velocity, heading, and flight-path angle were 7818.7 m/s (25,652 ft/s), 338.86 deg, and −0.84 deg, respectively. Each trajectory employed a two-step angle-of-attack profile with a constant hypersonic angle of attack held to 2440 m/s (8000 ft/s) followed by a pitch down to 12 deg α at 1070 m/s (3500 ft/s). A hypersonic angle of attack of 40 deg was utilized for all trajectories except those developed for the hybrid system, where an α of 32 deg was utilized. Heating rates in POST are determined by a simplified heating analysis based on Chapman's equation for stagnation heating to a sphere.[4] Reference values based upon a 0.305 m (1 ft) radius sphere were used for comparison purposes. Heat load in POST is simply calculated as the stagnation heat rate integrated over the time of the entry trajectory. Throughout the peak heating phase of each entry, the bank angle was modulated, increasing and decreasing lift as necessary to maintain the desired peak reference heat rate limit. The length of time that the heat rate was held was allowed to vary in order to minimize the total heat load. Heat load was minimized for all except the metallic hot-structure trajectories. After the high heating phase of each entry, the bank angle was decreased to 0 deg.

The altitude/velocity profiles for the trajectories chosen for more detailed heating analyses and use in the TPS sizing portion of this study are shown in Fig. 4. Further refinement to reduce or eliminate the trajectory oscillations is anticipated. Unreasonable *g* loads and dynamic pressures were not imposed on the vehicle in this region and the oscillations should not affect the results of this study. A somewhat higher peak heat rate trajectory was chosen for the metallic standoff system than for the metallic hot structure because of the significant decrease in heat load (and consequently TPS mass) that could be realized. A relatively high stagnation heat rate trajectory was chosen for the hybrid system for the same reason. The low angle of attack (32 deg) helped to alleviate heating over the lower surface of the body. Shown in Fig. 5 are the heat rate profiles associated with the entry trajectories chosen for further analyses. As this figure illustrates, the duration of peak heating varies directly with the total heat load that must be accommodated by the vehicle and inversely with the peak heat rate.

TPS Sizing

Method of Analysis

Detailed heating analyses were performed using the MINIVER aerodynamic heating program.[5] The four trajectories chosen in the first portion of the study were input by means of altitude, velocity, and angle-of-attack time histories. The 1962 standard atmosphere properties were used throughout the study. The vehicle was modeled using a delta wing configuration with a cross-flow technique accounting for the effects of local flow divergence at angle of attack.[6] A thick-skin conduction model was used to represent the surface. The surface thickness was divided into a number of layers (nodes), each with the appropriate temperature-dependent material properties. For all but the hot metallic structures, the innermost node in the MINIVER material model was used to represent the structure of the vehicle. Initially an aluminum structure with an equivalent thickness of 0.476 cm (0.188 in.) was used to represent the heat sink capacity of the vehicle structure.[7] The back surface of the structure was in all cases assumed to be adiabatic (no active cooling was considered). The initial temperature throughout the surface was assumed to be 311K (100°F), a value shown in previous studies to be consistent with typical vehicle attitude, orbital inclinations, and thermal control on orbit.[8] An external emissivity of 0.8 was used for all surface materials. This value was considered to be consistent with the materials studied in this investigation, although some degradation in emissivity would generally be expected to occur after numerous thermal cycles. The potential for the development of various high-emittance coatings prior to the production of such a vehicle suggests that this value may perhaps even be conservative for the time frame of interest here.

Laminar heating along the windward centerline was calculated using the Eckert reference enthalpy flat-plate method.[9] For the purposes of this study, only laminar heating was considered. The effect of turbulent heating would be to increase TPS masses over the aft portion of the lower surface of the vehicle for all of the systems studied. Turbulent heating would tend to increase the heat rate as well as the heat load in each case. Differences in TPS masses over this portion of the vehicle would thus be accentuated even more than for the laminar flow cases. A strategy by which entries may be tailored so that turbulent heating can be avoided, at least through the high heating phase of the entry, has been proposed in a previous study.[1] A need exists for further investigation into this type of approach.

Using the appropriate material model of the TPS and structure with the trajectories generated previously, the peak laminar windward centerline temperature distributions (but not radiation equilibrium temperatures) were determined for each of the four basic TPS concepts under consideration. These temperature distributions are shown in Fig. 6 along with the temperature capabilities of some of the TPS materials considered in this study. The peak centerline temperature distribution increases from the metallic hot

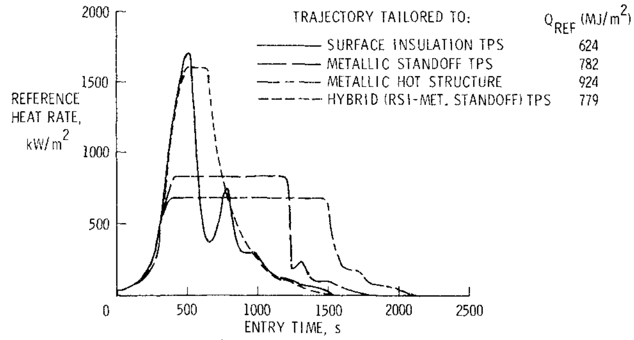

Fig. 5 Entry trajectory reference heating profile comparison: Chapman's equation, reference sphere radius = 0.3048 m, LaRC CCV.

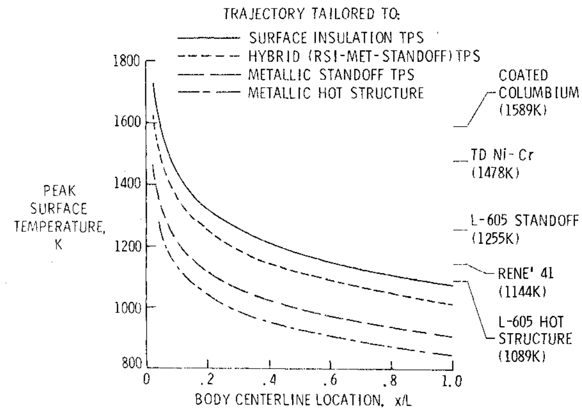

Fig. 6 Entry trajectory effects on windward centerline peak heating distribution: laminar heating, LaRC CCV.

structure to the metallic standoff, to the hybrid, to the surface insulation trajectory, as is appropriate for the corresponding TPS type. These curves were used to determine the particular TPS concept applicable over each region of the vehicle centerline, depending upon the maximum temperature capabilities of each concept.

Material Considerations

Carbon-carbon is the TPS material in the very high-temperature stagnation regions for all concepts under consideration. The main limitations of carbon-carbon are poor oxidation behavior, high cost, high mass, and the need for replacement prior to the 100 mission durability requirement. Consequently, the area over which this must be applied should be kept to a minimum. RSI LI900, the high-temperature surface insulation used in the Shuttle, was assumed to be applicable to 1728K (2650°F). Its density, 144 kg/m^3 (9 lb/ft^3), was used in subsequent TPS mass determinations. This material was considered with the assumption that a material of significantly improved durability and reliability with roughly the same thermal properties and density will be developed soon enough to find application on a vehicle such as the study configuration. The fibrous refractory composite insulation[10] (FRCI), presently under development, may meet this need. The effect of heat conduction through the material bonding the RSI to the main structure was assumed to be negligible.

A number of different metals was considered for the outer surface in a metallic standoff system over a range of temperatures at 1922K (3000°F) and below. The L-605 (a cobalt-based superalloy similar to Haynes 188) outer surface thickness was determined from an L-605 metallic standoff TPS previously fabricated and studied for application at 1255K (1800°F).[11] The outer metallic surface thickness and mass per unit area for the other metallic standoff concepts were determined relative to the L-605 value using the strength-to-density ratio (σ/ρ) at the maximum-use temperature for each material. The appropriate strength-to-density ratios were determined from a number of previous studies. Each metallic standoff concept was insulated with microquartz felt insulation at 56.1 kg/m^3 (3.5 lb/ft^3) with a maximum-use temperature of 1811K (2800°F). The heat conducted to the structure through the standoffs was neglected in this analysis. Tantalum, a high-temperature, high-density refractory metal, was assumed to be applicable to 1922K (3000°F), and an equivalent thickness of 0.102 cm was used. Coated columbium (Cb), one of the most easily obtained and fabricated of the refractory metals, was considered for use to 1589K (2400°F). An equivalent thickness of 0.053 cm was assumed for this material. TD NiCr, a nonrefractory metal, was considered for use to 1478K (2200°F). However, its lower strength-to-density ratio relative to coated Cb results in a greater mass system than the coated Cb, even at temperatures below 1478K (2200°F). Therefore, coated Cb was generally used for this range of application. L-605 was considered for applications to 1255K (1800°F). Its equivalent thickness was chosen to be 0.058 cm as determined from previous studies.[11]

Finally, René 41, a nickel-based superalloy was considered for use at temperatures up to 1144K (1600°F). An equivalent thickness of 0.024 cm was used for this material. More recent results indicate that a reduction of approximately 25% in metallic standoff panel masses can be achieved through advanced design.[10] This reduction would carry over to each of the metallic standoff systems studied here.

The same maximum-use temperatures were assumed for the metallic hot structure as for the metallic standoff except in the case of L-605. For use as a primary structure, L-605 was assumed to have a maximum temperature capability of 1089K (1500°F), corresponding to the temperature at which the material retains about 40% of its room-temperature mechanical properties. The René 41 honeycomb mass per unit area was determined from previous studies,[7] and the values for other metallic systems were again related to this value based upon their strength-to-density ratios at operating temperature. The sizing criteria for the René 41 hot structure and the aluminum cold structure should be consistent as they were derived from the same study. The honeycomb surface model in MINIVER consisted of inner and outer face plates of the appropriate metallic material and a honeycomb core model using the effective thermal properties of the core.

Minimum TPS Requirements—Aluminum Structure

The surface insulation, metallic standoff, and hybrid systems were each sized by using the appropriately tailored trajectory and determining the insulation thickness required to limit the backface to 450K (350°F) as required for the aluminum structure. Locations where material changes were necessary for the metallic and the hybrid systems were determined from the temperature distributions in Fig. 6 in combination with the material temperature limits described previously. When more than one system was applicable at a given temperature, the lowest mass system was chosen. The metallic systems were selected strictly according to the temperature limits of the metals. The results for each of the four basic TPS systems using appropriately tailored trajectories are shown in Fig. 7. It is important to recognize that in this and subsequent figures, the absolute values of the TPS and combined TPS/structure masses should be viewed as indicators with the relative values reflecting the proper trends. The masses given include the TPS as well as the average mass of the aluminum structure. The metallic hot structure includes only the hot-structure mass. However, internal systems and payloads will require added insulation if this type of system is used, further increasing the impact on the overall vehicle mass. The metallic hot structure utilizes coated Cb to a body centerline station of 0.08L and René 41 along the remainder of the lower centerline. The metallic standoff employs a coated Cb standoff to 0.08L, L-605 standoff to 0.157L, and René 41 standoff along the remainder of the vehicle centerline. The hybrid system employs RSI to 0.41L and René 41 standoff along the remainder of the centerline. Entry surface isotherms are assumed to represent lines of constant TPS mass per unit area. Consequently, differences along the centerline in the region aft of approximately 0.4L have the greatest impact since beyond this point the isotherms and corresponding lines of constant TPS mass encompass the wings.

It is evident from Fig. 7 that the metallic hot structure is not yet competitive with the other systems. The metallic standoff system is competitive with the surface insulation and hybrid systems, but still appears to result in a small mass penalty (less than 10%) forward of 0.157L. The use of TG-15000 insulation at 16 kg/m^3 (1 lb/ft^3) in regions where the tem-

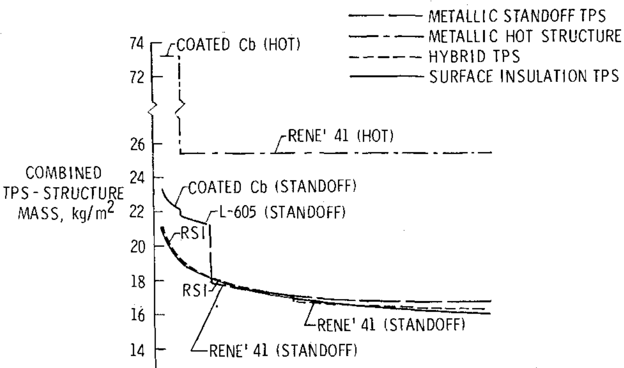

Fig. 7 Combined TPS/structure centerline mass requirements for four representative systems: appropriately tailored trajectories, aluminum structure, LaRC CCV.

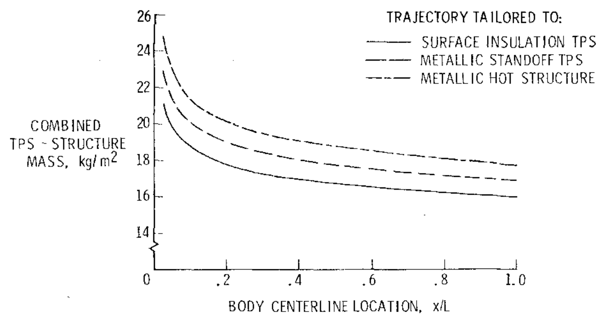

Fig. 8 Impact of inappropriately tailored trajectory on centerline mass requirements: surface insulation systems, RSI LI900, aluminum structure, LaRC CCV.

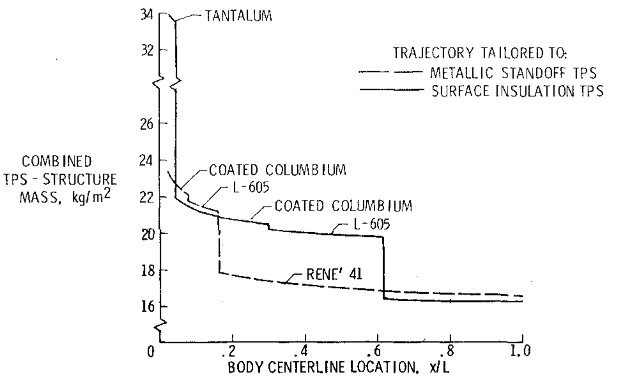

Fig. 9 Impact of inappropriately tailored trajectory on centerline mass requirements: metallic standoff system, aluminum structure, LaRC CCV.

perature does not exceed 700 K (800°F) would reduce the metallic standoff mass somewhat, but not significantly. The surface insulation system utilizing the RSI coupled with a high angle-of-attack, low total-heat-load trajectory yields essentially the same system mass as the hybrid TPS with the RSI and René 41 metallic standoff coupled with a lower angle-of-attack, low total-heat-load trajectory. Strictly from a minimum-mass viewpoint, either of these systems could be chosen; however, if the durability of the RSI cannot be improved, it may be necessary to pay the apparently slight mass penalty and utilize a metallic standoff system that would offer much greater durability. The hybrid system seems to represent a viable compromise between the all-surface-insulation system and the all-metallic-standoff system. If the mechanical properties of the RSI cannot be improved, only a relatively small portion of the vehicle would require refurbishment. If the 25% reduction in metallic standoff panel mass mentioned previously could be realized, the metallic standoff and the hybrid systems would have the potential to yield the lowest mass.

Nonoptimum Trajectory Impact on TPS Requirements

Perhaps the importance of integrated aerothermostructure design for entry vehicles can best be demonstrated by showing the impact of inappropriately tailored trajectories on TPS mass requirements. Figure 8 illustrates the centerline mass distribution for a surface insulation system sized for three different trajectories. A mass penalty of approximately 5% would be incurred with the utilization of a trajectory tailored to a metallic standoff system rather than to the surface insulation system. An additional 5% would be sacrificed if a trajectory tailored to a metallic hot structure were to be utilized. The increased RSI mass is due primarily to the increased heat loads associated with the nonoptimum (for the surface insulation system) trajectories. If these results can be

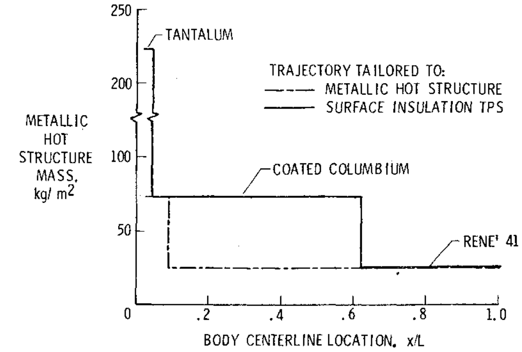

Fig. 10 Impact of inappropriately tailored entry trajectory on centerline mass requirements: metallic hot structure, LaRC CCV.

extrapolated to the remainder of the lower surface of the vehicle, the total mass penalties would be quite significant.

Studies have often compared TPS mass based upon a single trajectory that was more suited to a surface insulation system. This type of approach in the past has led to a lack of consideration of metallic systems as a viable alternative to a reusable surface insulation system. Advanced entry vehicles, however, allow considerable latitude in shaping the entry trajectories to the characteristics of metallic systems. Figure 9 shows a comparison between a metallic standoff TPS sized for a trajectory tailored to a standoff system and one sized for a trajectory tailored to a surface insulation system. Between stations 0.046L and 0.157L and beyond 0.615L, the mass differences are relatively insignificant. However, very near the stagnation region and between 0.157L and 0.615L the increased temperatures associated with the surface insulation trajectory necessitate the use of heavier, higher temperature materials for the standoff system. Again, a significant mass penalty would be incurred by sizing the metallic standoff TPS to an inappropriately tailored trajectory.

Figure 10 shows that an even more substantial mass penalty would be incurred if a metallic hot structure were to be sized utilizing a trajectory tailored to a surface insulation system. This penalty is due primarily to the high density of the high-temperature materials which would be necessary: tantalum and coated Cb over 60% of the lower surface centerline for the surface insulation trajectory as opposed to René 41 over 90% for the optimum trajectory.

Structural Material Effects on TPS Requirements

The final portion of this study examined the impact of increased structural-temperature capability on TPS mass and on combined TPS/structure mass. The structural materials, maximum operating temperatures, and equivalent thicknesses used in this analysis were: aluminum, 450K (350°F), 0.476 cm; graphite/polyimide (GR/PI, a lightweight composite material), 644K (700°F), 0.457 cm; titanium, 672K (750°F), 0.251 cm; Lockalloy (a beryllium-aluminum alloy), 700K (800°F), 0.762 cm; Inconel (a nickel-based superalloy), 978K (1300°F), 0.176 cm; L-605, 1089K (1500°F), 0.382 cm; and René 41, 1144K (1600°F), 0.408 cm. The strength-to-density ratio of each structural material at maximum operating temperature was again used to determine the equivalent thickness and mass per unit area relative to the aluminum values. Strength-to-density ratios were obtained from a number of previous studies. The values used were: aluminum, 12,200 m; GR/PI, 22,700 m; titanium, 14,500 m; Lockalloy, 10,100 m; Inconel, 11,100 m; L-605, 4600 m; and René 41, 4800 m. The appropriate thermal properties coupled with the appropriate thickness were used for the innermost node in the MINIVER material model to represent the heat sink capacity of the vehicle structure. Again the RSI TPS was sized so that the structural temperature limit of the backface material was not exceeded.

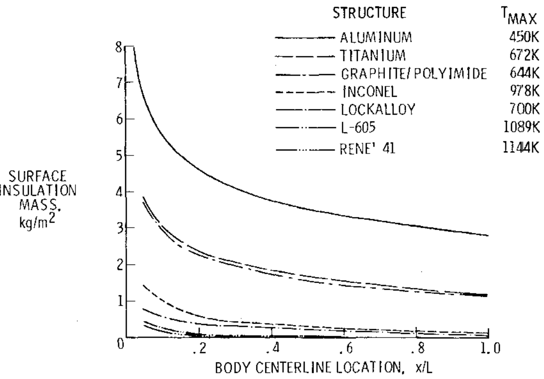

Fig. 11 Structural material effects on centerline TPS mass requirements: surface insulation system, RSI LI900, insulative TPS trajectory, LaRC CCV.

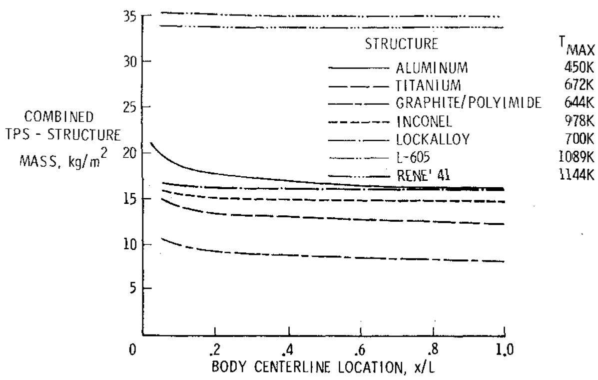

Fig. 12 Structural material effects on centerline combined TPS mass requirements: surface insulation system, RSI LI900, insulative TPS trajectory, LaRC CCV.

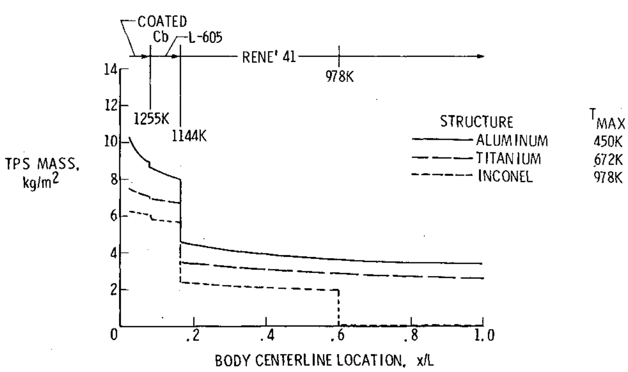

Fig. 13 Structural material effects on centerline TPS mass requirements: metallic standoff system, microquartz insulation, standoff TPS trajectory, LaRC CCV.

Figure 11 shows the reduction in RSI mass alone with the increased temperature capability of the structure. The RSI mass required for the Lockalloy structure does not quite follow this trend because of the greater heat sink capacity of the Lockalloy. The major reduction in the required RSI mass occurs over the first 200K (360F°) increment above the maximum operating temperature of aluminum. As the allowable temperature of the structure approaches the external surface temperature, the thermal mass of the RSI for a given thickness decreases due to the reduced temperature gradient across the insulation. Thus, the reduction in RSI mass for the approximately 200K (360F°) temperature increase between Inconel and René 41 is small compared to the reduction in RSI mass for the approximately 200K (360F°) increase between aluminum and graphite/polyimide.

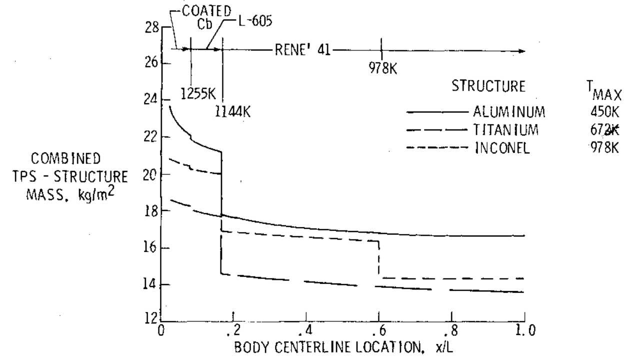

Fig. 14 Structural material effects on centerline combined TPS/structure mass requirements: metallic standoff system, microquartz insulation, standoff TPS trajectory, LaRC CCV.

The combined effect of the structural mass plus the insulation mass must also be examined. Figure 12 shows that, whereas the increased temperature capabilities of the L-605 and René 41 structural mass for these systems over that of aluminum is so great that the benefits of the reduced TPS mass are entirely outweighed. The greatest reduction in combined structure/TPS mass, nearly 50%, is obtained with the graphite/polyimide structure followed in order by the titanium, Inconel, and Lockalloy structures. In this portion of the study an RSI bonding capability was assumed to exist up to 1144K (1600°F). In reality the highest temprature RSI bond available today is for RA59 with a capability of up to 644K (700°F).[12] If a higher temperature bonding capability cannot be developed, the highest structural temperature that can be allowed is 644K (700°F), regardless of the structural material capabilities. Nevertheless, the graphite/polyimide structure appears to have the potential to yield the lowest mass system (RSI TPS) assuming the composite technology is mature enough to allow fabrication of an entry vehicle with a primary structure of GR/PI. Titanium would represent the next choice for a low-mass RSI/structure combination. The development of higher temperature aluminum alloys [to 750K/(890°F)][10] and lower mass aluminum honeycomb structures[7] may eventually offset these benefits. The increased insulation requirements for internal systems and payloads necessary for these warm structures would also reduce the benefits somewhat.

TPS mass and combined TPS/structure mass were compared for the metallic standoff system for three different structural materials as shown in Figs. 13 and 14. The trends are similar to those obtained previously. Only aluminum, Inconel, and titanium structures were examined in depth. These, however, show similar trends to those seen for the surface insulation system and the same would be expected of the other structural materials under consideration. As observed previously for the RSI system, increased temperature capability of the structure reduces the TPS mass required (Fig. 13). However, a consideration of the combined effect of the structure plus the TPS mass is still necessary. Apparently, the increased structural temperature capability does not benefit the metallic standoff system quite as much as the surface insulation system. This is due to the lower density of the internal insulation compared to that of the RSI. The combined effect of the reduced TPS mass because of the increased temperature capability, and the reduced structural mass of the GR/PI structure, is anticipated to give this system the potential for the lowest mass. The potential for reduction in aluminum structural mass through the use of aluminum honeycomb and aluminum alloys with increased temperature capabilities must again be considered, however. The combined effect could make the aluminum structure quite competitive with the GR/PI.

Finally, the impact of structural materials that maintain their integrity to higher temperatures on the hybrid

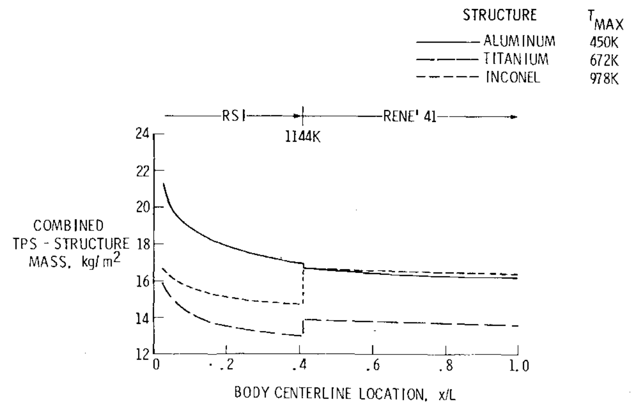

Fig. 15 Structural material effects on centerline combined TPS/structure mass requirements: hybrid TPS, RSI metallic standoff, hybrid TPS trajectory, LaRC CCV.

TPS/structure mass was investigated. As can be seen in Fig. 15, results similar to those obtained previously are evident. The increased structural temperature limits are again shown to benefit the surface insulation system somewhat more than the metallic standoff. Once again the GR/PI structure would be chosen, but possible improvements in aluminum structural masses and temperatures must be considered.

This study has shown that the total thermostructural mass can be reduced significantly through this type of design integration. Both the TPS and the structural mass reductions represent significant portions of the total reduction obtained in this study.

Study Limitations

A number of limitations should be kept in mind when considering the results of this study. As mentioned previously, the absolute values of the TPS/structure masses given in this study could vary due to differences in design criteria. However, the relative values and the trends indicated should be valid. RSI bonding temperatures to 1144K (1600°F) have been allowed for the purpose of this study. In reality, backface temperature limits higher than 644K (700°F) should not be considered for RSI unless the potential for an RSI bonding material with higher temperature capability exists. This should not affect the results of this study, however, as the maximum use temperatures of the two most favorable structural materials, GR/PI and titanium, were both assumed to be approximately 644K (700°F). It has also been assumed for this study that the durability of RSI can be improved without degradation of thermal properties or increase in density. This assumption is supported by the development of FRCI.[10] If not, however, it may be necessary to pay the mass penalty associated with the more durable metallic standoff systems. The ability to fabricate curved and intersecting surfaces and the effect of local hot spots because of shock impingement must be assessed before this option can be chosen. It has also been assumed that a minimum mass system results when the TPS is sized so that the structure operates at the maximum allowable temperature for the material. However, this may not necessarily be the case. Mechanical property degradation of the structural material at elevated temperatures may lead to a higher structural mass requirement and perhaps a higher combined TPS/structure mass than might be attainable if the structures were operated at somewhat lower temperatures where less degradation in mechanical properties occurs. Investigations into this possibility are currently being conducted.[13] Finally, turbulent heating has not been considered in this study. The possibility of tailoring entry trajectories to limit turbulent heating and the resulting impact on the TPS/structure mass requires further investigation.

Conclusions

This study has shown that integrated aerothermostructure design is highly important for advanced winged entry vehicles. Substantial mass penalties may be incurred when a TPS of one type is sized for a trajectory tailored to another type of TPS. Tailoring the entry trajectory to the characteristics of the TPS is very important, even for preliminary design. Significant mass reduction can be realized through utilization of structural materials with higher allowable temperature limits than aluminum. The major portion of this mass reduction occurs with the initial increase in allowable structural temperature. Beyond that, the loss in thermal mass because of the reduced temperature gradient across the insulation becomes increasingly important. The mass reduction associated with utilization of higher temperature structural materials results from reduced insulation requirements, as well as reduced structural mass. Higher temperature structural materials benefit surface insulation systems somewhat more than metallic standoff systems because of the higher density of the external insulation material. For an aluminum structure, either the RSI TPS coupled with the trajectory tailored to a surface insulation system or the hybrid TPS (RSI-René 41 metallic standoff) coupled with the trajectory tailored to the hybrid TPS appear to represent the minimum mass systems. If the RSI durability cannot be improved, a metallic standoff system consisting of coated columbium, L-605, and René 41 standoffs used with the appropriately tailored trajectory might represent the best choice. A slight mass penalty would result. Advanced metallic standoff panel designs, however, may result in a metallic standoff system lower in mass than either the RSI or hybrid systems. If structural material changes are to be considered, the graphite/polyimide structure with either a RSI TPS or a hybrid TPS and the appropriate entry trajectory appears to have the potential to yield the minimum mass system. A titanium structure would be the next choice if composite technology was not mature enough to allow fabrication of a primary structure of this size from GR/PI. However, development of higher temperature capability aluminum alloys and lower mass aluminum honeycombs may make the aluminum structure much more competitive. If the durability of the RSI could not be improved sufficiently, the metallic standoff system (coated Cb, L-605, René 41) would be recommended as before.

The planform loading of the vehicle used in this investigation is considered typical of potential advanced-winged entry vehicles, but vehicles with very different planform loadings are apt to favor different TPS concepts and TPS/structure combinations. Metallic systems will be more favorable for low planform loadings than for high, because of resultant lower peak temperatures. For this study the TPS/structure mass alone has primarily been assumed to represent the performance of candidate systems. However, in the final choice of a TPS/structure/trajectory combination, many other factors would be involved. Production costs, durability, operations costs, etc., all play an important part in this decision. Differences in these factors for the candidate systems could swing the TPS/structure choice to an off-optimum mass system. Continuing development of materials and TPS concepts such as multiwall[7] may lead to more durable and lower mass systems and may require different strategies in the tailoring of entry trajectories.

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