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STRUCTURES AND MATERIALS ASSESSMENT FOR HYPERSONIC VEHICLE TECHNOLOGY

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TECHNICAL REPORT AFFDL-TR-69-83

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FOREWORD

This report covers work performed under the second portion of Task II, Contract F33615-68-C-1462, during the period November 1968 through March 1969. The contract was initiated under Project 1368, Task 136804, "Thermantic Structures," and was administered under the direction of the Applied Mechanics Branch, Structures Division of the Air Force Flight Dynamics Laboratory with James F. Nicholson being the Project Engineer.

This report is concerned with an "Assessment of Materials and Structures for Hypersonic Vehicle Technology" and contains a review of high L/D vehicle design-structural concept considerations. A separate report (AFFDL-TR-69-12) was prepared on protective coatings for tantalum structures and is discussed only briefly in this report.

This task at Universal Technology Corporation was managed by Robert J. Gran with Robert D. Guyton and Jesse C. Ingram, Jr., being principal investigators. Acknowledgement is extended to Mr. J. F. Nicholson for his review and constructive input to this document.

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ABSTRACT

An analysis and assessment program was conducted to evaluate the relative merits of candidate radiative thermostructural configurations for a hypersonic L/D=3 reentry vehicle having a useful payload capacity. The report discusses the effects of vehicle configuration on overall structural design and attempts to assign the refractory metallic alloys to their most efficient range of design utilization expressed in terms of time-temperature-loads environmental inputs. One section of the report is devoted to the conceptual design and integration of variable geometry structure to a high L/D vehicle, with an assessment of the design penalities and problem areas incurred due to the use of variable geometry surfaces.

The report identifies the analysis rationale employed in the derivation of the findings and conclusions offered in this report. The study considered the elements of design efficiency, construction techniques and processes, cost-availability considerations, and reliability in the overall investigation of the several candidate thermostructural systems.

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SECTION I

INTRODUCTION

A current assessment is presented to provide structural design efficiency values for radiative thermostructural configurations and to suggest probable advanced design and construction concepts which could be used in the development of a hypersonic L/D = 3 reentry vehicle. A vehicle with this performance capability and typical of the general aerodynamic shape under consideration by the Air Force is shown in Figure 1. The findings reported herein offer some newer and interesting thermostructural systems candidates for the hypersonic flight vehicle type of Figure 1 as well as other future hypersonic vehicles being analyzed by the Air Force.

The report attempts to review the critical problem areas confronting the designer of a thermal protection system which will provide high design efficiency, reliability, and safety of flight. The study makes an assessment of the compromises that seem justifiable in order to achieve overall structural integrity.

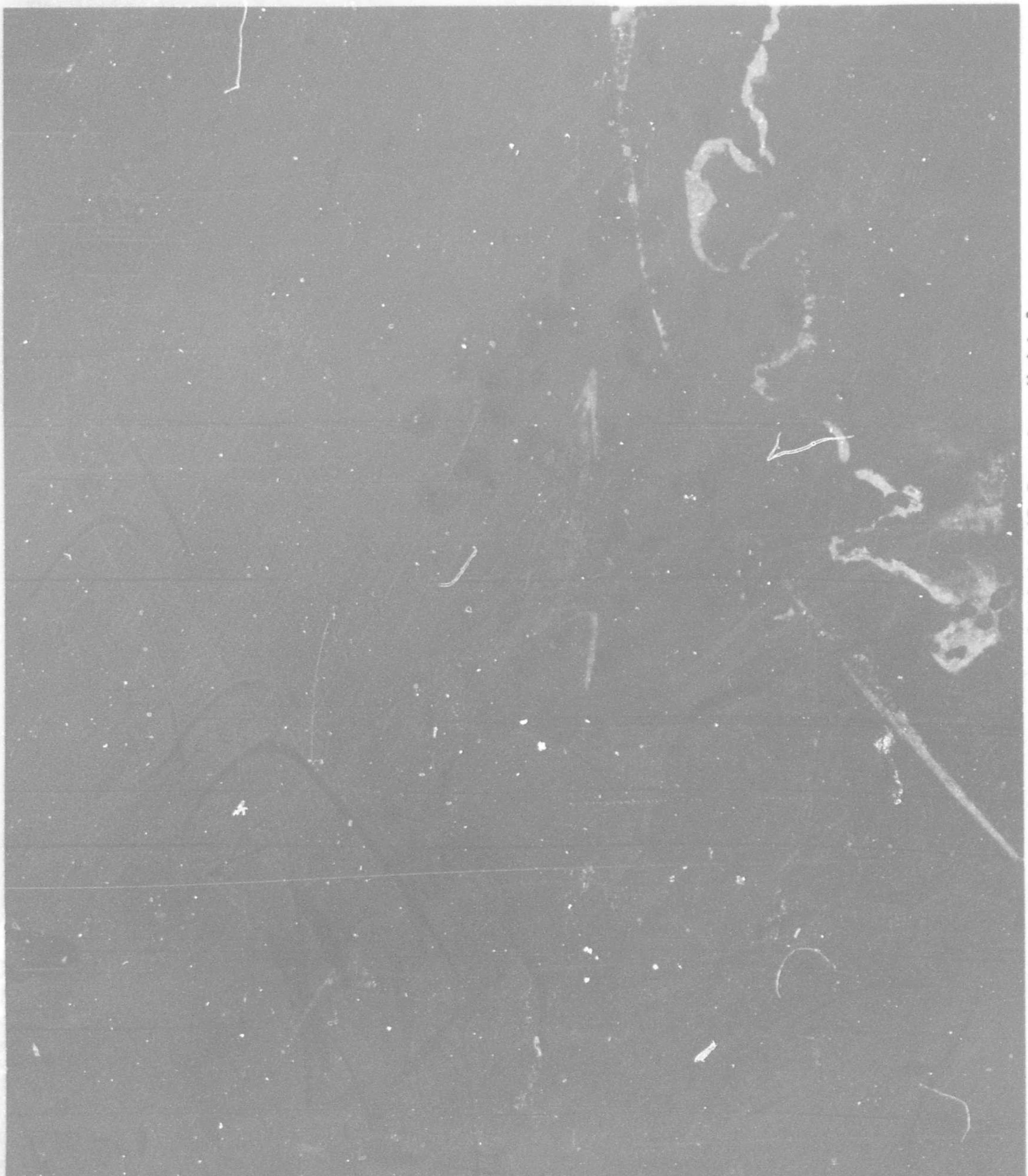

Figure 1. Artist Concept of High L/D Reentry Vehicle

SECTION II

VEHICLE STRUCTURAL INFLUENCES

A. Vehicle Configuration Effect on Structural Design

With the hypersonic vehicle configurations under consideration to achieve a hypersonic L/D ratio of the order of 2.5 to 3, the interrelationship of volumetric efficiency and structural weight control is a dominant factor in the successful development of these vehicles. Not only is the overall vehicle weight control of prime importance, but the factor of structural weight distribution can become a problem in terms of c.g. shifts, ballast requirements, internal compartments, and equipment arrangement. Moreover, this study will focus on vehicle sizes greater than 35 feet in length, medium wing loadings of the order of 40 to 65 psf, and a payload capability which includes crewmembers in orbit or high-altitude cruise for extended time periods.

Since the late 1950's, many and varied thermal protection systems have been studied for hypersonic reentry vehicles in terms of temperature limits, time at temperature, heating rates and total thermal capacity. A review of the engineering data and analysis information from these studies indicates that there is no clear-cut choice among the hot structure, insulated concept, cooled system, or combination design for these thermal protection-structural systems. The relative merits of these systems continue to be evaluated for future flight vehicle applications in light of aerodynamic configuration requirements, internal component temperature allowables, and weight restrictions.

The absorptive thermal protection systems have received primary consideration in the civilian space vehicle program where the emphasis is directed toward the modified ballistic or low L/D reentry vehicles with total reentry times of only a few minutes. These thermal protection systems have consisted of an ablative heat shield bonded to a conventional metallic alloy load bearing structure, wherein all of the incoming heat was absorbed by the ablative shield with no heat being transferred to the internal vehicle compartments housing the crew, subsystems, and other payload. Peak heating periods during reentry for these modified ballistic vehicles are measured in terms of five to eight minutes, with heat fluxes in the order of 300 to 600 Btu/ft^2-sec. Thus, the total heating for the modified ballistic or low L/D reentry vehicle is in the range of 150,000 Btu/ft^2 of surface area.

The total thermal input in the stagnation region for the L/D = 3 reentry vehicle can be three to four times the 150,000 Btu/ft^2 total heat load for the modified ballistic reentry vehicles. The duration of the heat pulse in a high lift mode will be measured in hours instead of minutes (as in the drag mode), with heat fluxes of 60 to 120 Btu/ft^2-sec at the stagnation region. Ablative materials and the mechanics of ablation have been developed and integrally "tailored" to challenge and withstand the shorter time, higher heating rates but their use in a long duration reentry cycle becomes impractical. It is practical to consider only a radiative metallic thermal shielding-structural concept for these high L/D vehicles being investigated in this study.

From the standpoint of design efficiency versus construction practicality, the past work to develop a L/D = 2 wing glider configuration will be reviewed. If structural efficiency solely dictated the selection of an airframe for the winged glider vehicle, the choice would be a hot wing and lifting surfaces mated to an insulated and cooled fuselage area. With this design approach, the lower surface areas of maximum heating can reradiate the heat through the small wing depth to the lower temperature upper surfaces. Since the wings and lifting surfaces account for some 60-80% of the total vehicle planform area and since these surfaces must withstand a major portion of the total thermal loading, the importance of reradiation is quite significant. The active structural cooling concept is most effectively utilized in those areas of maximum heat absorption where protection of men and equipment is needed and in the thicker vehicle sections where internal radiation or conduction must be prevented.

From a practical standpoint, the joining of a hot wing to a cool body presents numerous problems, including expansion mismatch, distortion, dissimilar material contact and severe thermal stresses. Also, it would be speculative to derive a maximum strength limit (load factor) for the vehicle since the cold structure could be designed for high structural strength and rigidity while the hot structure would be designed on the basis of its high temperature, lower strength values. This hybrid structural approach is worthy of future consideration, but must be considered for man rated flight only when more vehicle and component test programs are completed and a higher design confidence is achieved with the high temperature materials.

Extensive testing has confirmed that an active regenerative cooling system, utilizing water as the coolant, can perform satisfactorily under heat fluxes and total thermal inputs representative of hypersonic reentry flight. However, the reliability of such a system needs to be established and the question remains as to overall integrity of an active cooling system in operational performance, and more specifically, in the use of a regenerative system to maintain the load carrying structure within its useful temperature range. Active cooling designs should be applied only when safety can be assured against cooling system failure and could include an acceptable structural redundancy as well as auxiliary media.

B. Trade Study Analysis

The designer of these future hypersonic vehicles must direct his thinking, and apply his talent, toward the solution of a reliable, minimum weight, thermal protection-structural system that is designed for considerations other than only basic yield strength. These include the aspect of thermal stress, thermal expansion, warpage, creep, and structural deflections which are beyond the tolerances of nominal aerodynamic design and become critical design constraints. Therefore, in a structural trade-study for hypersonic flight vehicles, it is no longer accurate to assign structural efficiency factors solely on the basis of strength to density ratios, stiffness to weight characteristics, or combinations of these values. The operational environmental influences are different and also, much more severe than even the supersonic aircraft.

Other vehicle design and systems integration influences must be analyzed as a part of the selection process for the structural-thermal protection concept. Since the hypersonic vehicle is to accommodate a crew and attendant equipment needs for significant time periods, it is necessary to achieve the highest volumetric efficiency possible for containing this payload. The term "volumetric efficiency" presents the concept of achieving maximum payload with minimum structural weight and is mathematically represented by the dimensionless ratio of vehicle volume to wetted surface area in comparison to that of a sphere. Also, the retention of a high percentage of the total volume as available and useful space becomes progressively more difficult as the higher L/D ratios are attained. Reported values of volumetric efficiency for several vehicle configurations evaluated under Government sponsorship reflect this fact and are shown below in Table I.

Table I. Vehicle Volumetric Efficiency Relationships

Configuration	Hypersonic L/D	Volumetric Efficiency
X-20	1.8	0.22-0.35
Asset	1.2	0.52
Gemini	0.4	0.85

It is obvious that as the aerodynamic design leads to a thinner wing and higher slenderness ratio configuration to gain higher L/D, a larger percent of the internal vehicle sections become unusable in terms of payload carrying potential. This relationship between volumetric efficiency and aerodynamic performance is shown further in Figure 2. The plot identifies regions in which various vehicle types might be expected to fall in terms of volumetric efficiency versus L/D. Specific vehicles are identified to indicate their relative efficiency, although, the wide range of vehicle sizes do not permit a true comparison. As can be

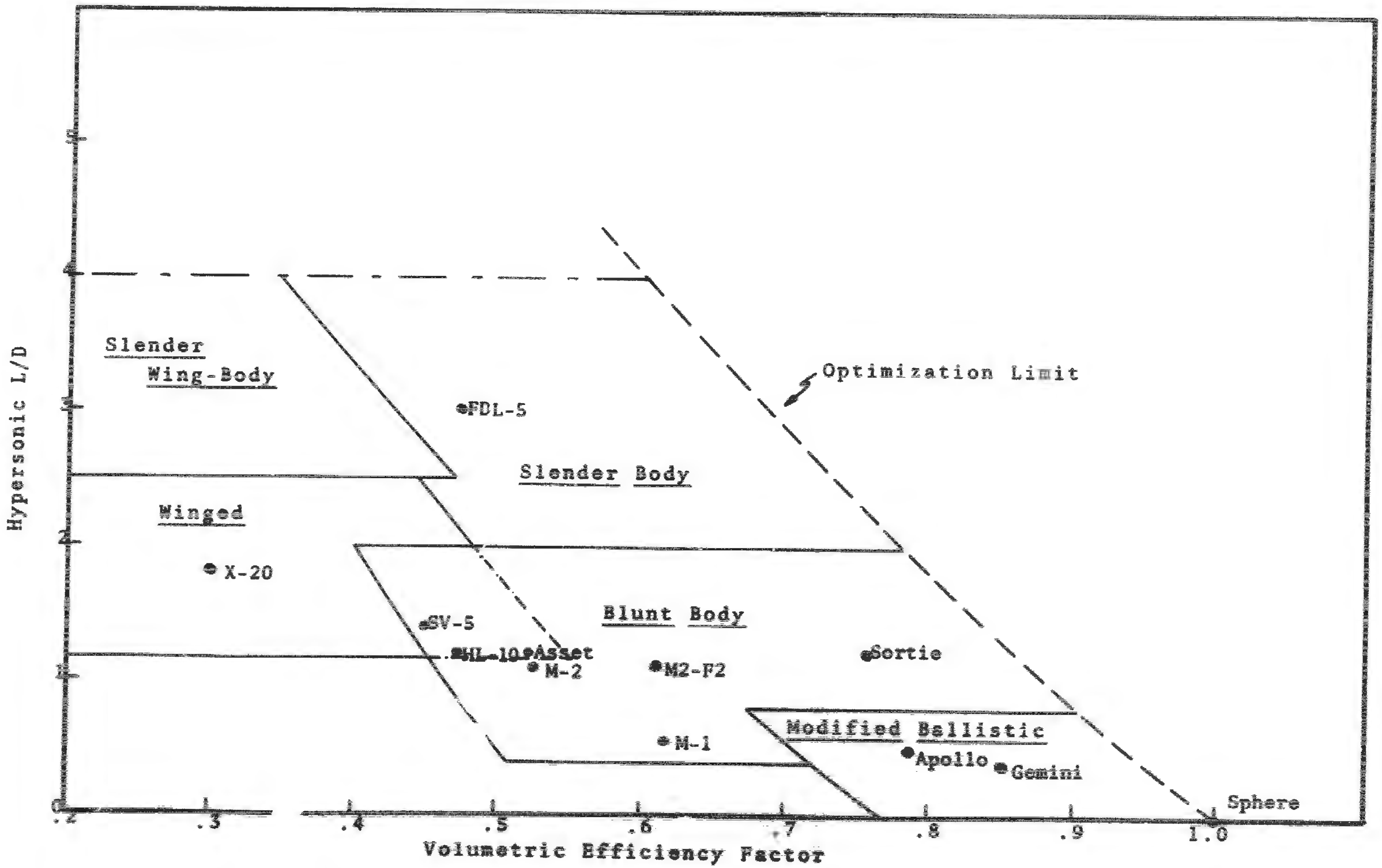

Figure 2. Reentry Vehicle Efficiency - Performance Relationship

seen in Figure 2, two hypersonic vehicle design trends can be identified. The first represents the Modified Ballistic-Blunt Body-Winged design approach with considerable reduction in volumetric efficiency with increasing L/D. The second trend represents the compact Blunt Body-Slender Body configurations which achieve high L/D with less reduction in volumetric efficiency. These Volumetric Efficiency values represent "total vehicle volume" and do not necessarily indicate "actual usable volume" within the reentry vehicle. Hence, every effort must be exerted to assure that the usable volumes in the high L/D vehicles remain compact as working and equipment placement areas. It follows then, that the design and integration of the thermal protection system must be developed to preclude undue penalties on crew station and equipment compartments.

In vehicles characterized by high fineness ratio and small diameter stagnation areas, the problems of localized structural weight control become more severe. A recent summary report on an Air Force sponsored program concluded that the total weight of the forebody section was comprised of 87% ballast and 13% structural weight. Although, some limited amount of ballast weight for balance and c.g. control may be unavoidable, the foregoing design approach should be critically examined to assure effective utilization of vehicle weight requirements. Stagnation region structural development continues to be a very critical element of design in hypersonic vehicle fabrication, and in the frontal areas a certain amount of overdesign and added costs can be justified. This overdesign is certainly warranted if it removes ballast or other vehicle weight which does not add to the integrity of the airframe.

C. Off-Design Conditions

One off-design condition which can influence the vehicle structural design is that for an abort. The specification for abort capability during exit presents unusual demands on the structure of the medium wing loading class of hypersonic vehicles. Certain structure is inherently lightweight, even minimum gage in various locations, and is therefore design-critical as to stability and/or panel flutter considerations. It becomes apparent that any unusual maneuvers (pitch-up, accelerations, etc.) which would be performed to separate the vehicle during boost could result in high dynamic pressures during a period of transient high heating and structural loading conditions. Moreover, a vehicle of greater than 35 feet length, which is under consideration in this study, could experience large bending loads in the fuselage area.

Another off-design condition which can greatly influence the thermal-structural design is the deviation or excursion from the planned or desired reentry flight profile. This may occur as the result of vehicle control inaccuracies, equipment malfunction, mission termination or crew problems; and could cause severe or excessive thermal-structural loadings on vehicle heat shield and load-carrying components.

Primarily, it is important to review and analyze the off-design parameters in order to determine the added structural weight necessary for vehicle survival and to define the impact on overall structural reliability. Then, it is necessary to establish test evaluations of these off-design conditions so that maximum capabilities can be reasonably well defined. Only after such evaluations can decisions be made regarding the amount of tolerance, or deviation from the nominal design, that can be permitted. The conclusion may be quite similar to the approach for the number of occurrences for gust loads in the design of conventional aircraft structure. In any event, somewhere in the design, one or more correction factors will be introduced to assure "safety of flight"; and regardless of the concept or material involved, these will add weight.

SECTION III

VARIABLE GEOMETRY STRUCTURE CONSIDERATIONS

Several structural design concepts have been investigated and analyzed for variable geometry lifting surfaces to be used with reentry vehicle configurations. Inflatable structures, expandable and unfurlable devices and various rigid structural designs have evolved. While there are advantages and disadvantages associated with each of these designs, there are common problem areas centered around the design of the variable geometry surfaces, the stowage of the total system, and the equipments required to achieve deployment and retraction.

The primary advantage of the inflatable and/or expandable assemblies is the ability to package the structure in a minimum volume, therein requiring a relatively small amount of the critical usable volume that exists in the high L/D vehicle. The advantage of this type packaging becomes significant when compared with other designs which result in severe volume penalties of up to 15% with rigid variable geometry structures. The principal disadvantages with the semirigid inflatable or expandable structures are the possible thermal deterioration during reentry and lack of stiffness or questionable performance of the structure during high dynamic load environments in the low speed and landing phase. As the larger flight vehicles seem to be of primary interest to the Air Force, the effects of variable geometry wing size and the amount of permissible deflection over the span are further unknowns.

Integrating rigid variable geometry structure into the hypersonic L/D = 3 vehicle configurations results in both weight and volume penalties, with the volume penalty being more critical. In a recent Air Force study it was reported that a variable geometry concept for a 32.5 foot vehicle, weighing 7700 pounds incurred a weight penalty of 11% and a volume loss of 38 ft^3. The hypothetical vehicle was reported to have hypersonic performance characteristics approaching L/D = 3.

In the normal deployed performance range, the rigid variable geometry structure can be safely and reliably designed to withstand the aerodynamic and structural loads. The problem of design is the formulation of the total structural system, including the necessary cutouts, built-up structure in the cutout area, pivot structure, deployment equipment and support structure. The weight of the total variable geometry system, assuming a hot structure vehicle with compartment insulation and cooling, could be broken down as follows:

Wing Weight...........................	21%
Pivot Structure Weight................	31%
Support/Coolant/Insulation Weight......	48%

The case is presented herein for certain inherent advantages for the use of variable geometry lifting surfaces with a cooled vehicle design. It must be conceded that there is no simple, single or general solution for the problems of cutouts. However, problems incurred with blow-away closeouts that are proposed with most design approaches, high temperature pivot (deployment) structures and mechanisms, or additional cooling required to absorb the heat, can be solved. Moreover, with a total usable internal compartment, the integration of the variable geometry system can become a matter of more selective orientation and placement with other equipments. Obviously, structural weight may be saved through this approach provided the design of closeouts and the coolant distribution system takes into account the total deployment system/procedures for the variable geometry surfaces.

SECTION IV

STRUCTURAL COMPONENT DESIGN FACTORS

A. Materials Technology

The DynaSoar systems development program created the need to investigate the structural capabilities of alloys of the refractory metals: molybdenum, niobium, tantalum, and tungsten. Until the initiation of the DynaSoar program, principles of design that had been in existence for many years were being used for the application of materials in structures. The use of the refractory metals in structural design changed this basic philosophy since new structural concepts had to be developed to "fit" the emerging refractory metal alloys and their related unusual characteristics which resulted from coatings problems and fabrication difficulties.

The demand for the refractory metals has declined markedly and the Industry must now respond on a small, specialized order basis that precludes the attainment of an experienced and efficient production operation. The operational cost of the Navy funded Inert Fabrication (InFab) Facility caused the early termination of operations in this facility which was designed for high temperature processing of refractory metals under inert atmosphere conditions wherein the contamination could be maintained at a very low level.

Other materials receiving consideration in hypersonic vehicle structural design have included the nickel/cobalt alloys, beryllium and titanium alloys.

Molybdenum Alloys

Three molybdenum alloys were investigated during the DynaSoar era with the TZM alloy continuing to be the workhorse and most versatile of the molybdenum materials. The Mo-0.5% titanium alloy and the TZC alloy are available but neither of these alloys has attractive qualities equal to the TZM alloy. Actually, much unalloyed molybdenum has been and still is being used; particularly in massive forgings and powder slipcast or sintered parts. These can be obtained in almost any size or dimension desired.

The rolling of thin gage molybdenum materials has been a significant problem area. Rolling of foil for use in honeycomb and/or other lightweight structure is very questionable even at the present time and certainly entails a premium price per pound.

Only in the past three years has quality molybdenum materials been produced to a rigid specification. Sheet products of molybdenum to a gage size of 0.010 inch can be produced to very close tolerances. In the heavier gage sizes of 0.040 inch and up, sheet sizes to 96 inches by 240 inches have been rolled with close tolerances held for premium prices. In foil gage thicknesses, widths to two feet can be produced.

Niobium Alloys

The niobium Cb-752 alloy in sheet form has become the most widely used refractory metal structural alloy for hypersonic vehicle design and structural component fabrication and evaluation. It is available in bar, sheet, rod, and small diameter wire by a number of producers. The rod and wire are used for mechanical fasteners and welding.

Sheet can be obtained in almost any size desired up to 60 inches wide by 240 inches long in gages down to 0.060 inch. Smaller sheet sizes are available in gages down to 0.006 inch and to almost any tolerance desired. Foils from 0.006 inch down can be obtained up to 24 inches wide and in coil lengths with tolerances specified as desired and at a premium price.

Other alloys such as Nb-1Zr and Nb-10Ti-5Zr (D-36) and Nb-5Mo-5V-1Zr (B-66) are also available, with some being produced in other product forms such as forging stock and tubing. All of the alloys used are amenable to the same working, fabrication, joining, and coating processes to some reasonable degree. Quality and surface finish can be assured in most cases and purity closely controlled.

Tantalum Alloys

The Tantalum T-222 alloy in sheet form enjoys the same "workhorse" status in the tantalum alloys as does the Cb-752 alloy in the niobium alloys. The T-222 alloy can be produced and is available in structural quality within the following limits:

Sheet sizes to 15 inches wide by 50 inches long.

Gage tolerances of about ±0.001 inch in sheet thicknesses from 0.007 to 0.020 inch.

Gage tolerances of about ±0.002 inch in sheet thicknesses from 0.025 to 0.040 inch.

Gage tolerances of about ±0.003 inch in sheet thicknesses up to 0.093 inch.

Gage tolerances of about ±0.0005 inch in thicknesses from 0.002 inch to 0.006 inch in foil sizes or 6-8 inch wide strip in long lengths.

The tantalum T-111 alloy is available in the same range of dimensions as stated above for T-222. In the Ta-10W alloy almost any usable size up to 36 inches x 120 inches and the complete range of gages can be produced. For the unalloyed tantalum metal in capacitor grade, sheet products up to 12 inches wide in coil lengths can be produced at some increase in cost.

Tungsten and Its Alloys

Essentially all tungsten sheet made to date has been unalloyed and until a few years ago was processed almost exclusively by the powder-metallurgy process. Some sheet was sintered/pressed and rolled, while other sheet was rolled directly from powder which was held together with a binder, however, in both cases contamination remained a processing problem. Direct rolling of the arc-cast ingot product was nearly impossible due to the large, preferentially oriented grains and interstitial contamination. Recently, however, newer processing innovations, including the ability to reduce contamination, and control grain size and orientation, appear to offer much greater possibilities in future tungsten sheet production.

Much of the tungsten metal usage to date has been in thoria dispersed tungsten, mostly for filaments and electrodes. This material can be processed with a high degree of reproducibility and purity. Even though tungsten will accept many other elements as alloying constituents, none strengthen it very much. From one viewpoint, some elements (Nb and Re) are quite beneficial for grain refinement, since a finer grained material is usually less brittle.

The tungsten-rhenium alloys (up to 25% Re) are produced in sheet, wire and rod forms and in fairly large sizes and quantities. The tungsten-Re alloy products are fairly ductile in comparison to unalloyed tungsten but the major use of these alloys has been for various sizes of thermocouple wire fabricated to close tolerances. Tungsten can also be alloyed with niobium and molybdenum, either individually or in combination. In this use, niobium serves as a grain refiner and apparently imparts ductility while molybdenum, also a grain refiner, imparts workability. It is possible that the 88W-6Nb-6Mo or the 93W-5Re-$2ThO_2$ alloys could offer some useful structural properties and beneficial fabrication characteristics (Reference 12).

Close tolerance control of tungsten sheet has not been achieved with the small sizes produced to date. However, a surface grinding and pickling operation could be performed to achieve the tolerance controls desired in hypersonic vehicle applications. To date, the demand for this degree of tolerance control has not evolved but as added requirements for hypersonic vehicles are developed, the demand will be created.

Tungsten shaped assemblies and contours can be achieved by spinning or shear-forming, with good tolerance control. The material can be arc fusion spotwelded, plasma spray welded and electron beam welded. It has also been demonstrated that plasma sprayed tungsten shapes can be built up on a mandrel.

Porous products have been sintered to form fairly large sizes, such as rocket nozzle throats, with good control over the porosity and subsequent infiltration of the pores with a transpiring medium. Large rocket nozzle throats have also been forged from unalloyed tungsten.

Thoriated tungsten (1-2% ThO_2) has been widely used in industry for many decades. It is produced primarily as electrode material for the welding industry, filaments for incandescent and radiant lamps and some for heating elements in special furnaces. The larger product sizes are processed by being compacted, extruded, and sintered while the smaller diameters are drawn. Limited experimentation has shown that larger percentages of ThO_2 can be introduced and that properly sized and dispersed ThO_2 can inhibit oxidation significantly.

The past work of the Air Force which resulted in a composite tungsten-thoria frontal section for use to 5000°F indicates that this concept can provide the overdesign philosophy that will yield a reliable thermostructural component. Although thoria is expensive and tungsten is difficult to fabricate, the thermostructural capabilities of the tungsten-thoria system are outstanding in frontal section applications. A design goal of 4000°F and heating rates of 100-200 Btu/ft^2-sec, may open up the corridor of performance for the higher L/D vehicles to the extent that growth potential and off-design performance can be obtained. It is not wise to design the refractory metal systems on the basis of pushing near the limit of their capabilities, if flight safety is to be assured.

Using tungsten as a direct substitute for tantalum in frontal areas for the L/D = 3 vehicle, a weight penalty of 15% would be incurred. Since emissivity and coefficient of expansion values at elevated temperatures are quite similar for coated tantalum and the tungsten-thoria system, the reradiation and deflection features should not be altered significantly. Also the strength requirements and increased oxidation protection may permit designing without a weight penalty. It would remain to conduct the sizing, the attachment concept, the mating of frontal sections and the detail design in order to use the tungsten-thoria system in the high L/D vehicle configuration. Considering today's technology, this then, is assessed as a primary role for tungsten in forthcoming hypersonic vehicles.

Refractory Metals Summary

Table II presents a summary of the technology status for the four refractory metal alloy groups being considered in this assessment. As will be noted from this summary, certain distinguishing characteristics have an impact on the structural trade studies for hypersonic vehicles and

Table II. Refractory Metals Technology Status

Material	Product Form Availability	Tolerance Control	Fabricability
Molybdenum TZM TZC Mo-.5Ti	1)Sheet of inconsistent quality 2)Special order only 3)Thin gage material questionable	Questionable, and costly to achieve	Marginal
Niobium Cb-752 D-36 B-66	1)Useful sheet sizes 2)Reasonable order/ delivery basis	Good	Good
Tantalum T-222 T-111 Ta-10W	1)Larger sheet sizes could be useful 2)Delivery is marginal	Fairly Good	Under investigation and is deemed to be acceptable for future vehicle construction
Tungsten 88W-6Nb-6Mo 93W-5Re-2ThO$_2$ W-25Re W-0.6Nb	1)Limited sheet materials 2)Forged components 3)Shaped assemblies	Unknown, and would necessitate additional post manufacturing operation	Amenable to alloying for improved workability

will be entered into the analysis accordingly. One such example would be the improbable status of thin gage molybdenum materials for honeycomb or sandwich structure in thermal shielding configurations. This would restrict or even prevent the design of such a structural concept.

Beryllium

There are no true alloys of beryllium available today. That is to say there are no beryllium base materials having controlled amounts of elements introduced to form solid solution matrices or to offer a controlled thermo-mechanical response. Beryllium, however, is available in several forms which generally contain 1-2% residual beryllium oxide. Forgings, extrusions and sheet are available as well as wire, rod, and bar stock with current products considered to be of reasonable purity and quality.

Beryllium cannot yet be welded satisfactorily, however, some recent brazing developments appear quite promising. Mechanical fasteners made from beryllium have not proven successful, except for specialized applications, due to the notch-sensitivity and low impact resistance. Therefore, most beryllium assembly has been accomplished through mechanical fastening with K-Monel rivets or bolts.

The inherently formed, tightly adherent, beryllium oxide film is somewhat selfprotecting up to 1200°F, however, any extended or cyclic use above 600°F-800°F would require a coating. Also, since beryllium does react with a large number of other metals and chemical compounds, it is well to consider a protective coating for most applications. Beryllium can be readily coated and is reasonably protected up to 1300°F by anodizing with chromates and up to 1550°F by a fused slurry coating of beryllium-silicon.

B. Refractory Metal Coating Capabilities

In all hypersonic vehicle designs the refractory metals must be coated for protection against environmental influences. For hypersonic vehicle applications, refractory metals are being considered where other materials such as conventional metals and superalloys cannot withstand the extreme and sustained thermal inputs. These high heat fluxes would reduce better known metals to virtually no structural value or would actually melt many of these alloys. The high temperatures involved along with the high shear forces, presence of oxygen, ionization effects and reduced pressures render the coating indispensable. For the present however, only the paramount factors of coating degradation by oxidation and loss by vaporization will be considered even though, in designing a vehicle, all aspects of coating degradation must be assessed. Therefore, in attempting to present useful life data, it must be remembered that only a part of the environmental spectrum is being applied and other specific test methods could be employed to invalidate any data results presented. Thus, it is possible to conduct a test, or control the influencing factors, to such an extent that the evaluation results will represent the applied environment which may be very different from the true environment.

The average life expectancy of several coatings for these refractory metals at various test temperatures is summarized in Table III. These refractory metal coatings are discussed further in the following paragraphs.

Niobium Coatings

The Cr-Ti-Si two-step coating is still probably the best known of all coatings for niobium alloys. The protection this coating offers is very nearly the same for all niobium alloys with the principal variation in oxidation life due to differences in substrate alloying constituents. The more recent fused slurry silicides offer greater protection at higher temperatures. These coatings are much less sensitive to handling procedures and surface contamination; and also, due to greater cohesiveness and better capillary action they are much more effective in edge coverage and penetration of faying-surfaces.

Niobium can experience significant and rapid volume loss providing a given combination of factors are present.

Table III. Life Expectancy for Various Coating-Substrate Systems

Substrate Alloy	Type Coating	Average Coating Life (Hrs) at Various Temperatures (°F)										
		2400	2500	2600	2700	2800	2900	3000	3100	3350	3500	4000
Nb	Cr-Ti-Si	150	100	50	5							
	Fused Slurry Silicide		100		50			5				
Mo	$MoSi_2$				40-50		10-12		3-5			
	Fused Slurry Silicide				50+		12+	10+	5+			
Ta	Fused Slurry Silicide					50		5+	1+			
	WSi_2					40		20	10			
	W plus WSi			50+				20-30	12-15	7-9	3-5	
W	Si_2							20-30	16-20	10-12	5-7	
	WSi (Modified)							30-40	25-30	16-20	9-12	~1

First, the coating must be damaged or removed by either mechanical or thermal means. Secondly, the temperature must be sufficient to form oxide of the substrate. Third, the air velocity over the surface must be such that the shear forces will wipe away the oxide and expose fresh metal. This could easily happen where a projection or protuberance (e.g., joint mismatch) into the flow caused a local turbulent condition resulting in an excessive temperature increase and high shear force. The possibility of this occurring along with the fact that most niobium alloys become less competitive, in the higher temperature ranges, on a strength/density basis may be a deterrent to their use above 2700°F.

Molybdenum Coatings

The coating failure mechanism for molybdenum is different from that of niobium. With molybdenum, the oxygen does not penetrate the substrate, rather, the molybdenum surface-coating interface is converted to different compounds, and in effect, migrates outwardly and eventually comes in contact with oxygen. If thermal cracking is experienced in the coating and "healing" is not accomplished, oxygen can find access directly through the cracks to the substrate. This is usually experienced with a thick $MoSi_2$ coating under cyclic conditions. Eventually MoO_3 is formed which is inherently volatile and literally vaporizes, and can be catastrophic. This fact could be a deterrent to the use of molybdenum even though its load carrying capability at temperature is considerably above that of niobium. The useful structural strength of molybdenum extends well beyond 3000°F, however, the most attractive coatings again, are the fused slurry silicides which are rendered somewhat useless above 3100°F.

Tantalum Coatings

Tantalum has a measurable structural load-carrying capability up to 4000°F, however, no currently available coating will survive that temperature level. The fused slurry silicides can protect tantalum up to 3100°F-3150°F for brief periods, however, this is not the temperature range of primary interest. Available information on current technology indicates that a W barrier/WSi coating has the potential of achieving utilization of tantalum alloys up to or slightly over 3500°F. A more detailed discussion of this topic is contained in a separate report (UT Report 337-2) prepared under this contract.

Tungsten Coatings

Tungsten can be considered as having load-carrying capability up to 4700°F but no known coating will offer protection at temperatures approaching that magnitude. In the future it is possible that tungsten plus dispersoids may offer the ultimate in high temperature utilization, however, at present it appears that tungsten coated with silicon plus modifiers is the best available and can provide reliable protection up to 4000°F.

C. Integrated Thermostructural Design

The design of thermal protection-structural systems for reentry vehicle applications has been centered around a double-wall concept, using the basic elements of construction as shown in Figure 3. These elements consist of an aerothermal protective external shield, a layer of high temperature insulation, a load bearing vehicle structure with or without liquid coolants and additional insulation to absorb the heat leakage and restrict the temperature rise in vehicle compartments. The integration of these basic elements into the most efficient thermostructural concept has been the topic of several specific component development programs sponsored by the Air Force, as well as the primary development efforts in the X-20 and ASSET programs. Not shown in Figure 3 are the attachments, fasteners, and local fittings for panel assembly which comprise about 15% of the total panel assembly weight.

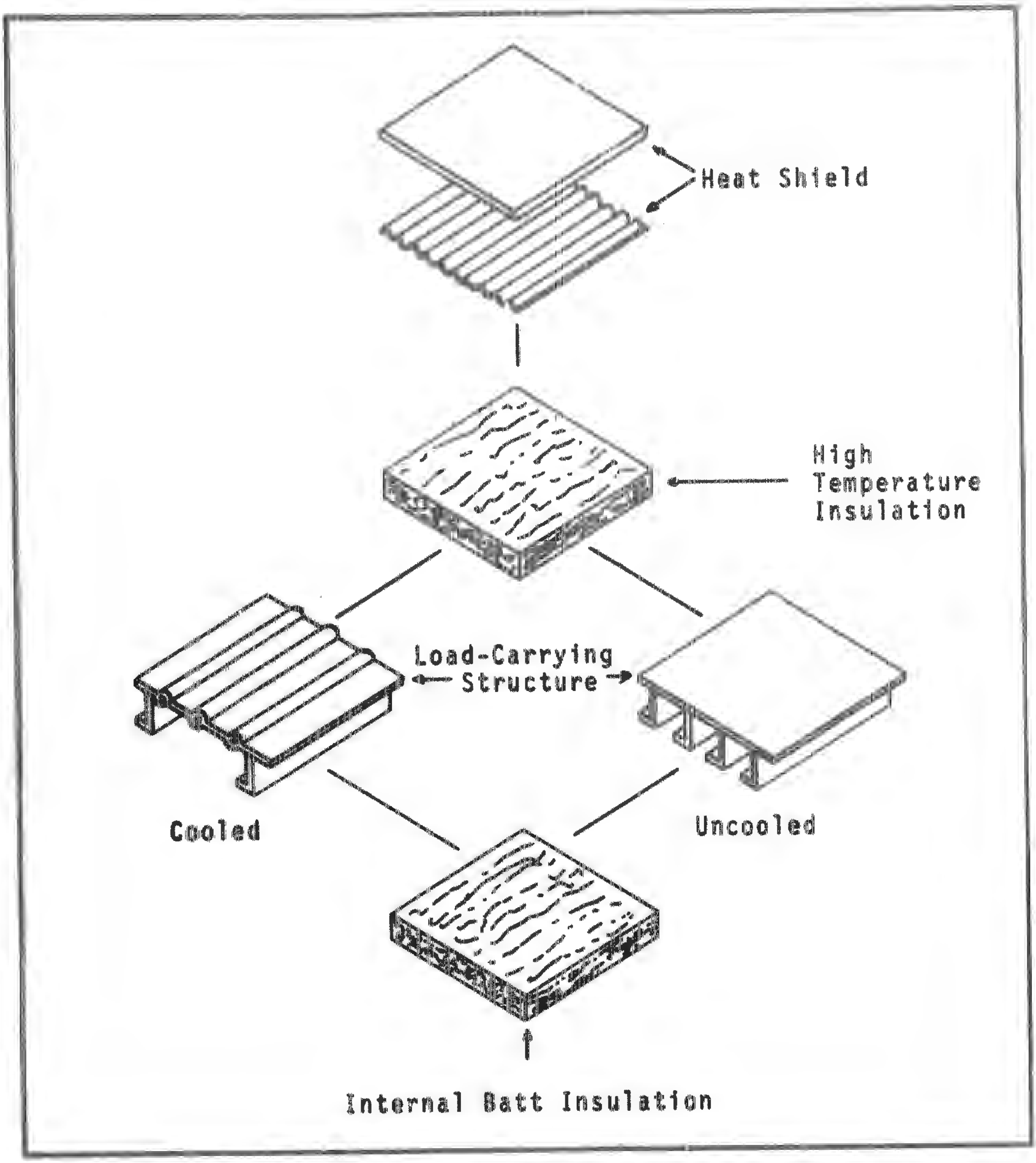

Figure 3. Basic Heat Protection
and Structural Elements for Hypersonic Vehicles

In this construction, the outer surface panel is used to contain the insulation and to serve as a thermal radiator, transferring the small local airloads to the internal structural members. In order to obtain a confidence of design with the coated refractory metals, the hot exterior skin does not support major structural loads, but may consist of segmented panel assemblies sized to allow for thermal expansion with minimal thermal stress levels. A further effect on outer surface size and configuration are the dynamic influences which would contribute to panel flutter and localized instability. The work which has been conducted to date shows that outer surface panels up to one square foot at high heating regions can perform satisfactorily with larger sizes being acceptable on the upper portion of the vehicle and areas away from the high heating regions.

The designer of hypersonic reentry thermostructural concepts has the formidable task of selecting the combinations of heat shield structure, insulation, sub-structure and coolant which have the least weight under various heating conditions. A number of studies have been made in this technical field, and all of the studies generally conclude that the hot structures and the insulated and cooled structures are quite competitive, the favored approach being selected on the basis of compartmental cooling requirements, integration with other subsystems, and other factors related to overall vehicle design. Work reported by NASA in the early 1960 time period concluded that hot structures should be used when the loading intensity is low, or with the lower wing loading type of vehicles. This work considered a maximum temperature limit of 2600°F, and it further concluded that as more efficient insulators are developed the range of usefulness of insulated and cooled structures increases.

As suggested earlier in this report, the hot structure concept finds its most effective use in vehicles characterized by large lifting surface areas where reradiation of incoming thermal loads through the depth of the structure and across the external surfaces can be attained. A vehicle which closely conforms with these characteristics is the X-20, having a basic fuselage shell and relatively large, low wing areas. The X-20, as stated earlier, had small payload carrying provisions, hence there were no reasons to design a total cooled compartment area. Since the vehicle configuration under evaluation in this study is more like a lift body shape and different from the X-20 configuration, it would appear that internal cooled structures will be the minimal weight design approach. In light of the vehicle size, length and payload carrying potential, it is apparent that the bending loads will be higher, creating a need for high strength/density structural materials and also dictating the design selection of these materials on the bases of creep resistance and stiffness considerations.

An approximate weight of 4 pounds per square foot for a 2600°F thermostructural panel assembly as shown in Table IV is a reasonable estimate, using the basic elements of construction presented previously in Figure 3.

Table IV. Thermostructural Panel Unit Weight Summary

Panel Component	Unit Weight (lb/ft^2)
Thermal Protection Surface An 0.012 gage niobium alloy stiffened by an 0.015 gage continuous corrugation, plus local support structure.	1.40
Insulation	0.50
Coolant	0.80
Load Bearing Structure	1.30
Total Weight	4.00

This external temperature of 2600°F is representative of an average lower surface panel for the vehicle under study, and corresponds to a reentry total heat flux of about 100,000 Btu/ft^2. The weight estimate has been derived on the basis of present day technology for quality refractory metal alloys. On a minimum weight design basis, the gage sizes of the refractory metals could be reduced or a honeycomb sandwich panel construction developed which could provide adequate heat shield integrity. However, some measure of off-design capability or perturbation from the nominal mission should be built into the vehicle in all cases where the added weight can be justified.

As previously shown in Table II on Refractory Metals Technology Status, the molybdenum and tantalum products can be made available on about the same basis as the niobium alloy product forms, with minor differences in processing practices and delivery schedules. Also, Table III on coating performance results shows the range of usefulness for the coated alloy systems. Using this information as baseline data, weight estimates can be derived for the molybdenum and tantalum heat shield configurations, with only minor weight increases for the molybdenum assemblies and some fairly large weight increases being incurred with the tantalum panel assemblies used in the 3000°F temperature range. Molybdenum panel assemblies would be designed primarily in those areas where stiffness criteria dictates the need for higher modulus at the temperatures of interest. The need for tantalum heat shield assemblies is, of course, related directly to its higher temperature capabilities and therefore, its ability to be used in or adjacent to the critical stagnation regions of the vehicle.

D. Advanced Design Concepts

The high L/D hypersonic vehicle is intended to be a useful manned operational system with the capability for landing at pre-selected or alternate sites, high maneuverability, and long-time reentry periods. For effective vehicle performance the crewmember functions will require interface with the onboard equipment. It will have a conventional landing gear but will require other sophisticated equipments in order to meet the mission requirements. In summary, it can be concluded that provisions for a completely useful internal working area is essential to the success of the mission.

Of the total vehicle structural surface area, a primary interest in structural trade-off concepts lie in the mid and aft sections of these vehicles. Specifically, the trade study in these sections must focus on the integration of overall internal compartmented areas with individual optimization procedures for specific subsystems such as the alighting gear, variable geometry surfaces and avionics packages. In the past, the thermostructural optimization procedures have been aimed toward the specific subsystem approach, with too little emphasis on the overall airframe optimization. It is believed that the isolated optimization of specific subsystem components and separate compartment areas cannot lead to an optimum airframe.

As has been earlier discussed, tungsten structural assemblies can be effectively utilized in the stagnation region and forebody areas of the vehicle. This is a trade-off wherein useful structure replaces ballast weight. It is realized that adequate 4000°F thermostructural concepts could be provided by using nonmetallics, ablators or combination ablative-nonmetallic configurations at about 60% of the tungsten-thoria system weight. However, the metallic materials provide the versatility of construction, reuse and repair that cannot be achieved with the ablator or ceramic materials. As the hypersonic vehicle tends to grow in size, performance, reuse, and operational deployment status, the tungsten alloys and tungsten-thoria systems can provide this growth capability.

Aluminum is quite satisfactory as an internal structure for withstanding the loads encountered during hypersonic flight and reentry provided that this substructure is protected from the hot exterior surfaces. However, aluminum structure offers little "flight safety" in the event of excessive heatload or cooling system failure, since the aluminum structure maintains its load carrying capability only at reasonably low temperatures. Obviously, weight limitations preclude dual systems, excessive redundancy, and backup in hypersonic vehicle structure, but the critical sections of the airframe must be carefully examined to determine where added safety features merit increased weight.

The potential advantages of an internal cold-wall titanium load carrying structure are worthy of exploitation. In addition to its high strength, titanium can be more readily diffusion bonded, and this process could be employed to produce integral cooling passages in a titanium load bearing substructure. An integral design of this type could be very efficient in that the attachment weight for cooling tubes could be eliminated. Certain of the emerging titanium alloys, such as Beta III (See Tables V and VI), possess good fracture toughness, high strength and appear to have good fabrication characteristics.

With the use of titanium, strength and integrity to temperatures of 800°F could be attained, for a cooled structure. Strength considerations would create no added weight penalties, when titanium is compared at this elevated temperature with aluminum structure at room temperature. It is not expected that long time exposure will have an adverse effect, such as continued aging, providing optimum materials are selected. It is reported that once the Beta III alloy

Table V. Room Temperature Tensile Properties of Beta III .063" Sheet After Various Solution and Aging Treatments

Heat Treatment	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 inches (%)	Reduction in area (%)	Minimum Bend Ratio (R/t)
ST@1325°F,AC	141	128	17	45	2.0
WQ	122	107	20	52	2.4
ST+900°F,8hr,AC	205	191	7	29	-
ST+1000°F,8hr,AC	168	158	8	45	-
ST@1425°F,AC	130	121	18	45	1.3
WQ	120	108	21	48	1.0
ST+900°F,8hr,AC	190	179	6	35	-
ST+1000°F,8hr,AC	165	154	8	42	-

Table VI. Cold Formability of Beta III and Other Titanium Alloys

Alloy	Heat Treatment	Sheet Thickness, (inch)	Olsen Cup Test		Minimum Bend (R/t)
			Cup Height, (inch)	Load, (lb)	
Beta III (4.5Sn-6Zr-11.5Mo)	1450°F, 5 min, AC	0.065	0.330	12100	1-2
Unalloyed Ti	Mill anneal	0.029	0.290	4600	1-2
Ti-6Al-4V	Mill anneal	0.050	0.118	2600	3-4
Ti-8Al-1Mo-1V	Duplex anneal	0.040	0.148	5500	3-4
Ti-13V-11Cr-3Al	Mill anneal	0.044	0.260	8700	2-3

is solution treated and overaged (for 8 hours), no further aging occurs if the material is not used above the aging or stabilization temperature. It is known that the oxide which is formed on titanium, when exposed to 1100°F-1200°F, is very tenacious and quite resistant to further contaminant penetration (Reference 13).

In the search for efficient load bearing structural members for hypersonic vehicles, the titanium alloys must be given strong consideration as cold-wall structural members. Hence, a large safety margin could be gained.

It has been reported in an Air Force sponsored program (Reference 2) that titanium variable geometry structure is probably the most efficient concept for hypersonic vehicle applications. With a primary titanium load carrying structure, the design and integration of the titanium variable geometry surfaces could be more readily conducted than with a dissimilar metallic load carrying basic structure. Also, titanium could be considered as a candidate for the landing gear structure, thus the integration aspects of that subsystem could be simplified.

The use of beryllium as the prime material of construction in the aft, upper surface area of the vehicle can offer an outstanding overall weight saving. Not only would weight savings be achieved by the substitution of beryllium for the heavier superalloys, steel or titanium alloys which could be used in these areas, but also reduces the necessary forward ballast requirements. Furthermore, the aft, upper section of the vehicle will be designed for bending loads and minimum deflection where beryllium structure finds its most efficient use. Even if the structural design approach with beryllium were to dictate redundancy and increased safety factor, a considerable weight savings could still be realized. Although this report would not advocate any unusual differences in the structural design approach for beryllium as compared with the structural design for ultra high strength steels, it has been observed that the design philosophy in the past for beryllium structure has been characterized by caution. It may be added also, that flight test applications of beryllium generally have been based on cost/formability parameters. Although the development of larger sized beryllium structures present some new areas of investigation, the need for these structures should offer the incentive to move ahead with a larger development effort.

SECTION V

STRUCTURAL MANUFACTURING AND PROCESSES

The costs associated with advanced flight vehicle development and construction is of paramount interest to the Air Force. A pound of payload in orbit is very costly, and each pound of completed structure is expensive as a result of starting material, fabrication, and construction costs.

None of the recommended structural materials or construction methods will require any elaborate tooling or extraordinary procedures to manufacture the details. Some equipment may be unique to the standard fabrication shop, but with modern equipment and qualified personnel no serious problems should occur. Even the newer processes such as electrical discharge machining, chemical milling, Anocut, electrolytic drilling, have become somewhat standard with the major aerospace organizations. These procedures have been used on the refractory metals and titanium with good results.

Niobium and tantalum alloys can be fabricated with very little trouble providing good shop practice is observed and necessary precautions are taken. Molybdenum and tungsten alloy fabrication will be more problematical, but with present-day material quality being greatly improved compared to five years ago, manufacturing difficulty can be minimized. In general, protection against environmental contamination must be carefully controlled in every respect for any of these materials.

Niobium and tantalum alloys are reasonably ductile and in the vacuum-annealed condition may be fabricated at room temperature. Certain fabrication processes for molybdenum (TZM alloy or Mo-.5Ti) may be accomplished at room temperature, while other processes must be performed at some elevated temperature. The fact that present purity of molybdenum has lowered the transition temperature is helpful, however, the narrow efficient utilization range, questionable nature of joining, difference in thermal properties and the overall problems of structural integration make it a dubious selection. Arc cast tungsten can be forged or shear-formed successfully, however, it must be done at a temperature of about 1600°F - 1800°F which is significantly above the ductile-brittle transition temperature of 600-800°F. Also, there is no need for in-process surface protection since the oxide formed is minimal and that which is not mechanically removed by the fabrication process can be easily removed afterward. In the case of the tungsten-thoria frontal section, the fabrication of the tungsten grid and coiled wire network, and the application of the ThO_2 were "hand-operations" with no attempt to mechanize the procedures.

Strong consideration should be given to maximum use of titanium throughout the vehicle substructure which could actually minimize fabrication and manufacturing difficulties. There is no class of structural materials which diffusion bond as readily as the titanium alloys. As a rule, 100% joint efficiency can be realized in titanium diffusion bonds and can be achieved by a number of diffusion bonding methods or procedures. However, care must be taken in using proper processing conditions and protecting titanium from contamination. The roll bonding process offers the potential of providing simple and high integrity tube-wall construction for active cooling substructure. In some respects, there are great differences between titanium and aluminum fabrication, especially joining. The oxide of aluminum is very difficult to control and actually inhibits joining. Aluminum oxide makes resistance welding problematical, almost precludes acceptable gas welding, and currently hinders good diffusion bonding. Titanium oxide, on the other hand, poses no problem since its protective oxide does not restrict joining. Titanium acts as a good "metal solvent" and readily dissolves many metals including itself. The fact that titanium also dissolves its own oxide makes it one of the easiest metals to join.

Since a "shirt-sleeve environment" is being considered for the crew and equipments must be placed in reduced temperature compartments, extensive use of "active regenerative cooling" in addition to insulation, appears to be required.

The double-wall or tube-wall cooling system could be made almost exclusively from titanium, with primary effort on the development of an integral structure-cooling passage system.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The assessment of hypersonic vehicle materials and structures technology, as presented in this report, has attempted to review vehicle design requirements and offer several thermal-structural concept approaches. Certainly, a more comprehensive trade-off analysis is required to enable full justification of the reasoning and conclusions presented in this report. Some of the more significant conclusions and recommendations of this report are summarized in the following paragraphs.

1. In hypersonic vehicle design and trade-off analysis the L/D ratio, volumetric efficiency, center of gravity and structural weight control should be treated as interrelated and inseparable factors.

2. The use of the refractory metal alloys of tantalum, molybdenum, and niobium in heat shield applications could be comparatively evaluated for narrowly defined utilization limits and design efficiencies, in which each could be justified for a certain performance range. However, molybdenum would find a narrow utilization range with the fabrication and structural integration problems essentially rendering its use prohibitive. Tantalum and niobium remain as the more promising candidates for use where the surface temperatures dictate the need for refractory metals.

3. Ballast and other non-payload weight in the stagnation region and forward sections should be converted to more reliable, reusable vehicle structure in order to provide greater flight performance and safety. The stagnation structure could be constructed of the tungsten-thoria composite and other forward stagnation regions could be constructed from either tungsten-thoria, thoria dispersed tungsten or coated tungsten. Immediately adjacent areas would be fabricated from tantalum.

4. Titanium alloys can be efficiently and reliably used as the internal primary load-carrying structural material with a cooled integral structure or tube-wall construction which is fabricated by one or more bonding processes. A wide range of titanium alloys now exist, and an attractive selection is available for use in higher load carrying assemblies at temperatures up to 600°F-800°F and up to 1000°F-1200°F for light or no-load applications. These alloys should be entirely satisfactory for long term usage.

5. In the aft section of the vehicle for the upper body exterior surface, beryllium could be chosen as a major material of construction. Moreover, beryllium can be carefully considered in weight critical regions of the vehicle and where weight control is necessary to permit improved c.g. location.

6. The materials, processes and equipments necessary for the construction of a high L/D hypersonic vehicle are available and the vehicle could be fabricated on the basis of present day technology. There appears to be no unique requirements for specialized tooling or process developments, however certain fabrication procedures must be demonstrated and structural components must be evaluated.

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13. ABSTRACT

An analysis and assessment program was conducted to evaluate the relative merits of candidate radiative thermo-structural configurations for a hypersonic L/D=3 reentry vehicle having a useful payload capacity. The report discusses the effects of vehicle configuration on overall structural design and attempts to assign the refractory metallic alloys to their most efficient range of design utilization expressed in terms of time-temperature-loads environmental inputs. One section of the report is devoted to the conceptual design and integration of variable geometry structure to a high L/D vehicle, with an assessment of the design penalties and problem areas incurred due to the use of variable geometry surfaces.

The report identifies the analysis rationale employed in the derivation of the findings and conclusions offered in this report. The study considered the elements of design efficiency, construction techniques and processes, cost-availability considerations, and reliability in the overall investigation of the several candidate thermostructural systems.

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