Thermostructural Concepts for Hypervelocity Vehicles

Peter K. Shih* and Jack Pruntyt†
General Dynamics Convair Division, San Diego, California 92123
and
Richard N. Mueller‡
Wright Research and Development Center, Wright-Patterson Air Force Base, Ohio 45433

A trade study was performed to obtain a lightweight thermostructural concept for application to a hypersonic vehicle. Aerothermodynamic environments and structural design loads were defined for a selected configuration and given flight trajectory. Thermostructure was sized through the thermal and structural analyses. The trade study included integral vs nonintegral tanks and hot vs thermally protected structures. Material and design options were also explored in this study.

Introduction

IN the design of hypervelocity vehicles (HVV), a key driving parameter is the structural mass fraction of the system. The mass fraction greatly influences the performance and payload capabilities of the vehicle. For example, a reduction of 1 lb of structural weight would effectively translate into an additional pound of payload, or alternatively, approximately 10 fewer pounds of propellant. Through the optimization of thermostructural concepts, a significant increase in overall mission performance can be realized. Such an optimization requires not only good familiarity with the available material options and thermostructural concepts, but also a thorough knowledge of the thermal, inertial, aerodynamic, and control loads on the vehicle as a consequence of hypervelocity flight conditions. This optimization process—the establishment of aeroheating and other critical loads, the consideration of material alternatives, and the formulation of thermostructural concepts—was the primary focus of this study.

Figure 1 shows the HVV configuration selected for this work. This vehicle, derived from the transatmospheric vehicles (TAV) study, was designed for vertical launch using a two-stage expendable booster. This vehicle carries 50,000 lb of internal propellant, which enables the vehicle to perform extensive in-flight maneuvering such as synergetic plane change, which allows the vehicle to execute a change of 45 deg in inclination while conducting a boost-glide mission (see Fig. 2). These selections were followed by a series of inter-related design and analytical tasks, during which a number of thermostructural trade studies were conducted.

The primary results of the study include detailed weight estimates for the candidate thermostructural concepts and the selection of the most promising thermostructural concept for application to future hypervelocity vehicles.

The objective of this study was to obtain the lowest weight thermostructural concept for a selected vehicle and flight environment. A trade study was performed first, which considered only state-of-the-art materials. This was followed with an assessment of advanced materials. The study examined tradeoffs between integral vs nonintegral tanks and hot vs thermally protected structures. Material options were also explored in the trade study, particularly in conjunction with varying structural temperatures in thermally protected areas. Shuttle-type reusable surface insulation (RSI) and other existing systems were excluded by the study ground rules.

Table 1 outlines the technical approach for the trade study. The initial step involved the assembly of an existing data base consisting of a range of overall thermostructural concepts and selection of pertinent detailed thermostructural concepts from industry and government agency sources. The sources used are typified by Refs. 1–4. At the same time, a list of currently available material candidates was also prepared. An initial screening then selected six overall thermostructural concepts for the trade study. A structural arrangement for each of these concepts was prepared to facilitate thermodynamic, loads, stress, and mass properties analyses. In parallel, detail definitions and weight-scaling laws were evolved for the various thermal protection system (TPS) candidates.

Using the detail definitions, thermal models of significant areas of each overall thermostructural arrangement were defined and analyzed to yield structural temperatures and insulation thicknesses. During this phase, structural analyses ranging from the identification of critical external loads to the definition of internal load intensities were also accomplished. Finally, a detailed weights analysis, using the structural analysis and TPS sizing results as input, permitted selection of the minimum weight thermostructural arrangement.

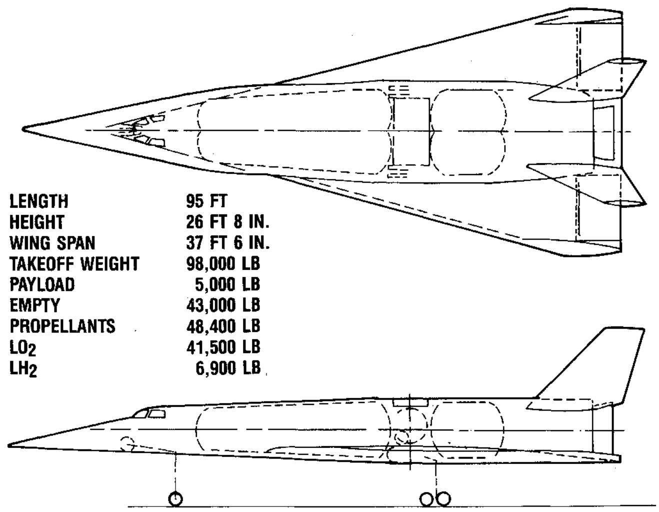


Fig. 1 HVV configuration.

Presented as Paper 88-2295 at the AIAA 29th Structures, Structural Dynamics, and Materials Conference, Williamsburg, VA, April 18–20, 1988; received Feb. 13, 1989; revision received June 7, 1989.

*Senior Engineering Specialist. Member AIAA.

†Consultant.

‡Aerospace Engineer, Flight Dynamics Laboratory.

Table 1 Technical approach

Establish matrix of concepts
Overall thermostructural arrangements
Detail concepts
Initial screening
Specify selected candidate concepts
Overall
Detail
Define thermal models—vary structural temperatures
Select material candidates
Define candidate overall thermostructural arrangements
Define critical load conditions
Compute structural load intensities
Define detail thermostructural concepts
Attachment, stiffening, structural sizing, and weight scaling laws
Compute weights of candidate concepts
Select preferred concept

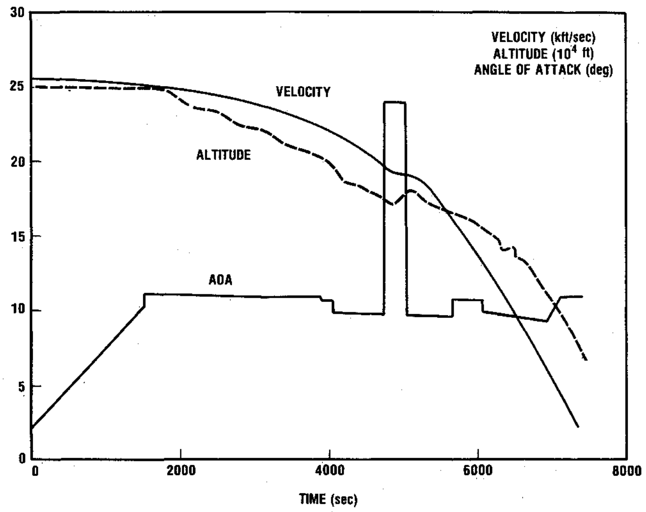


Fig. 2 Synergetic plane change trajectory.

Candidate Thermostructural Concepts

Figures 3 and 4 show the six thermostructural concepts selected for this study. Each of the two primary concepts, nonintegral tanks and integral tanks, was split into three categories. The first of these, a hot structural concept (Fig. 3a), has an arrangement in which the primary load-carrying structure is completely unprotected from the aeroheating. The second, the hybrid concept (Fig. 3b), has protection on only the windward surface. Finally, the TPS concept (Fig. 3c) is an arrangement in which the primary load-carrying structure is completely covered by a TPS.

Within each of the six concepts were five variants involving the use of a variety of structural materials and allowing an investigation of the impact of structural temperature variation.

In all cases, the trade studies were limited to consideration of the body primary structure, the propellant tanks, the wing primary structure, the propellant tank insulation, and where applicable, the TPS. Secondary structural items such as nose caps, leading edges, and control surfaces were not included.

Only state-of-the-art materials were considered in the first part of the study. Advanced materials were addressed later.

Nonintegral Tank Concepts

A baseline structural arrangement for the nonintegral tank concept is shown in Fig. 3. As seen in the figure, the primary structure consists of two major assemblies: 1) body structure; and wing/windward surface assembly (WWSA). The body structure is an open base, arch-shaped structural shell extending from forward of the crew compartment to the extreme aft end of the body. It is a frame-supported, semimonocoque arrangement that is completely exposed to the thermal environment and transmits all of the body primary loads.

The WWSA structure consists of the wing combined with the body's lower surface structure extending forward to the front edge of the body assembly. A significant feature of the WWSA is the continuation of the complete wing structure across the body below the propellant tanks. This arrangement transmits the wing bending moments across the body without the penalties associated with the transition to discrete spars or the transmission of the bending moments around the body structure. With this concept the wing structure also serves as the body's lower surface structure in this area. In view of this situation, the center section structure uses sandwich panel stiffened skins to accommodate the biaxial stresses induced by the wing and body loads.

Table 2 Candidate materials

Materials	Maximum use temperature, °F
Tank	
Al 2219	350
Al-Li	350
301 SS	700
Ti	1,050
718 Ni	1,300
Primary structure	
Al-Li	350
Borsic Al	600
Ti	1,050
718 Ni	1,300
Rene 41	1,600
Cover panel	
HS 188	2,000
CB 752	2,500
C-C	3,000

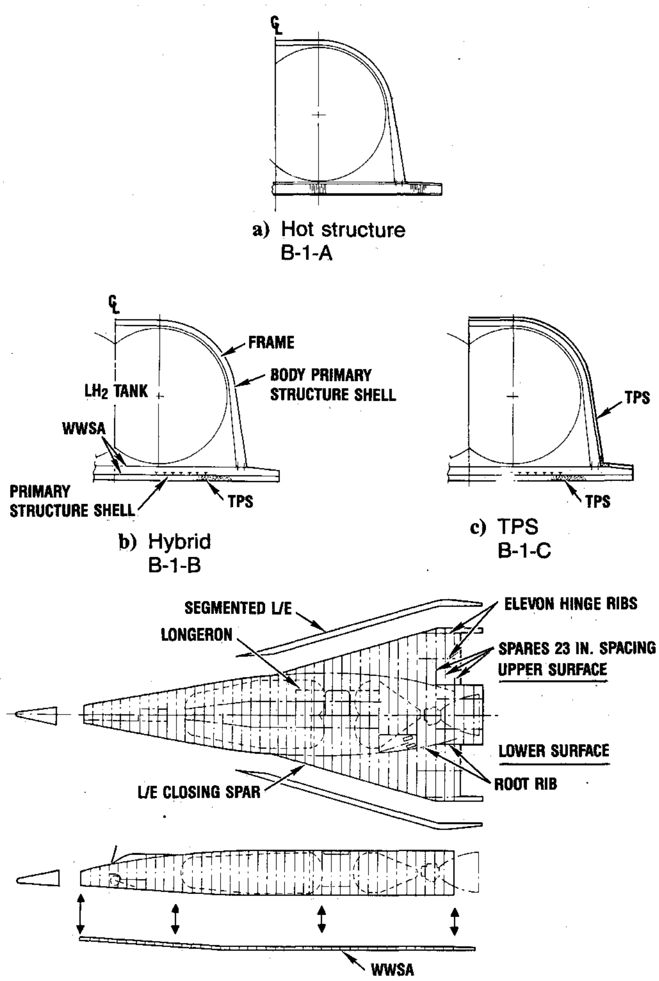


Fig. 3 Nonintegral tank concepts.

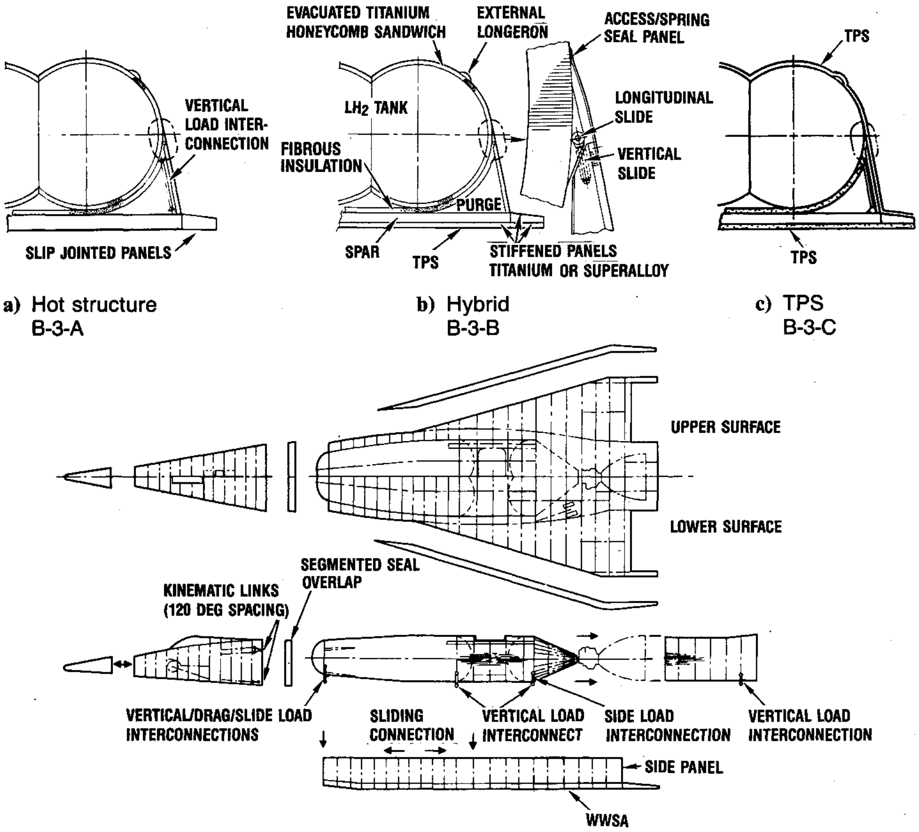


Fig. 4 Integral tank concepts.

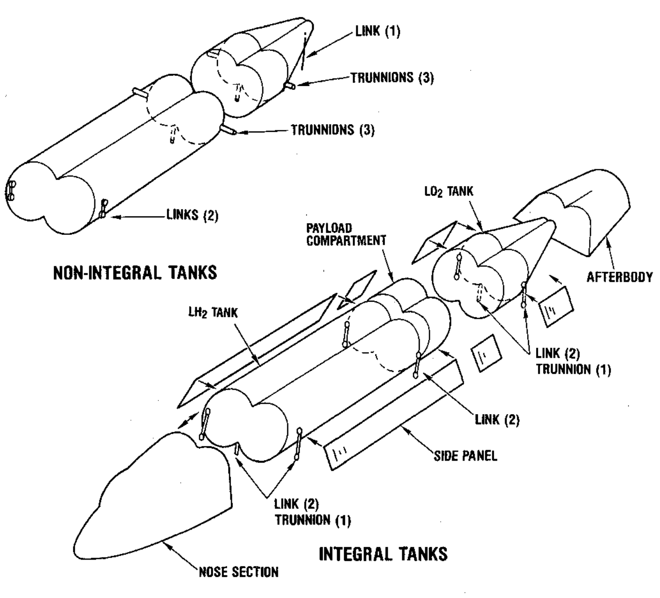


Fig. 5 Propellant tanks.

The propellant tanks that feature the double-lobe cross section (see Fig. 5) are housed within the body's shell structure, with the liquid hydrogen (LH_2) tank forward, the liquid oxygen (LO_2) tank aft, and the payload compartment in between. A unique feature of this arrangement is the introduction of the engine thrust load directly into the LO_2 tank via a thrust cone formed by the aft end of the tank. A contribution to the high structural efficiency is provided by the absorption of 40% of the thrust load by the inertia of the LO_2. The thrust cone concept is an adaptation of the thrust cone arrangement used with success on Atlas boosters.

Each of the tanks is attached to the structure via an essentially kinematic arrangement that permits thermal contraction of the tank and expansion of the structure without inducing strain in either the tank or the body structure.

Integral Tank Concepts

This concept is shown in Fig. 4. The primary load-carrying structure of the body in the tankage area is provided by the tank structure and thereby reflects the double-lobe shape of the tanks in the cross section. Between the LH_2 and LO_2 tanks, continuity is provided by a double-lobe shell structure in the payload area. Immediately aft of the LO_2 tank in the engine compartment area, a shell structure transitions from a double-lobe section at the interface with the tank to a circular section at the extreme aft end. Forward of the LH_2 tank, the structural shell transitions abruptly at the interface with the tank from the tank double-lobe cross section to a closed, arch-shaped structure for the crew/equipment compartment. Low load intensities at the interface station facilitate this transition. Thermal contraction of the tankage relative to adjacent structural shells in the forward area, midsection, and aft end area is accommodated by providing adequate out-of-plane flexibility in the interfacing structural panels. This technique has been well proven in expendable launch vehicle applications.

Basically, the wing structural arrangement is similar to those of a nonintegral tank concept. However, in this case the wing is attached to the body structure by a quasikinematic linkage that permits thermal contraction of the tank relative to the wing without inducing undue strain.

Above the wing, the aerodynamic cross section of the body is completed by an array of side panels extending downward from the tangency on each fuselage lobe to the upper surface of the wing structure. As seen in Fig. 4, the attachment of these side panels to the body's primary structure features vertical and longitudinal sliding arrangement to allow for differential, thermally induced excursions.

Thermal Analysis

The aeroheating analysis was performed using the AEROHEAT[5] code. Figure 6 shows the maximum radiation equilibrium temperatures for the vehicle. Depending on the design, the actual temperatures will be about 10% lower due to heat conduction into the internal components. Carbon-carbon is required for both body windward surface and leading-edge protection.

Figure 7 typifies the thermostructural concepts considered in the trade study analyses. Table 2 lists the state-of-art materials considered in this study. Included in this table is a list of materials and their design temperature limits. Recent developments, such as tailorable advanced blanket insulation (TABI)[6] and multiwall tile,[7] were included in leeward thermal protection analyses. Polyphenylene oxide (PPO) foam, which has shown promise as a cryogenic insulation,[8] was also considered in the analyses.

Aeroheating rates as a function of flight time were imposed on the external surfaces. The transient analysis considers external radiation, heat conduction, internal radiation, and energy absorption by the structure. Temperature-varying thermal properties of the materials were used. A large number of computations were made to cover the permutation of variables (e.g., concepts, locations, materials, insulation types, and thickness, etc.).

Design Loads

A preliminary structural analysis was performed to obtain load intensities in the body shell and wing structure and to facilitate the approximate sizing of structural elements. The external loading conditions considered were ground wind, maximum alpha-q and beta-q, maximum ascent acceleration, hypersonic maneuvers (with both zero and full fuel), gust, and landing load.

The analysis of the external loading conditions identified the design loads listed in Table 3, where the maximum alpha-q and hypersonic maneuver are the prime cases for wing body bending. The maximum ascent acceleration affects the design for pressure in some areas of the tankage, and the landing case

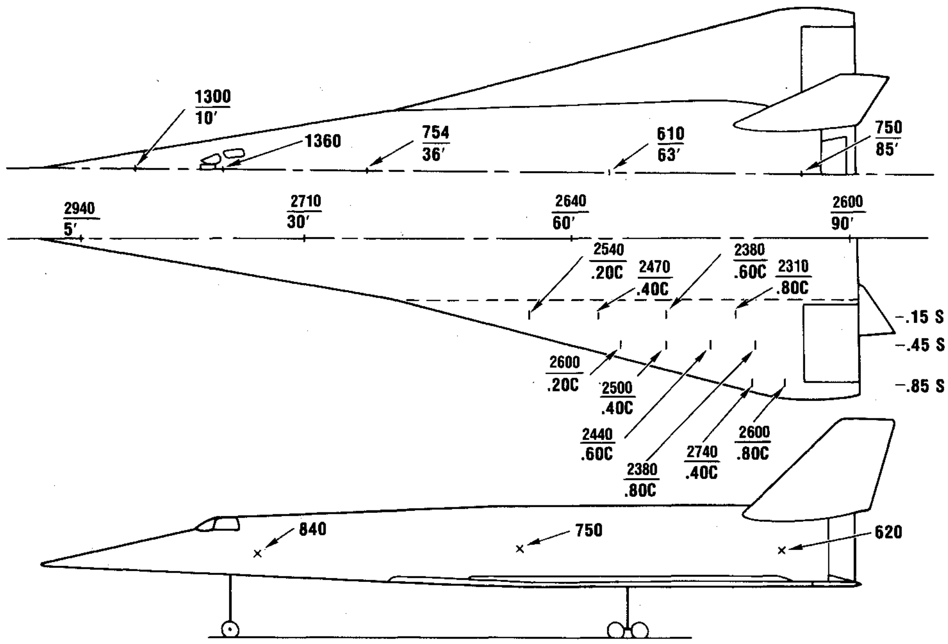


Fig. 6 Maximum radiation equilibrium temperatures.

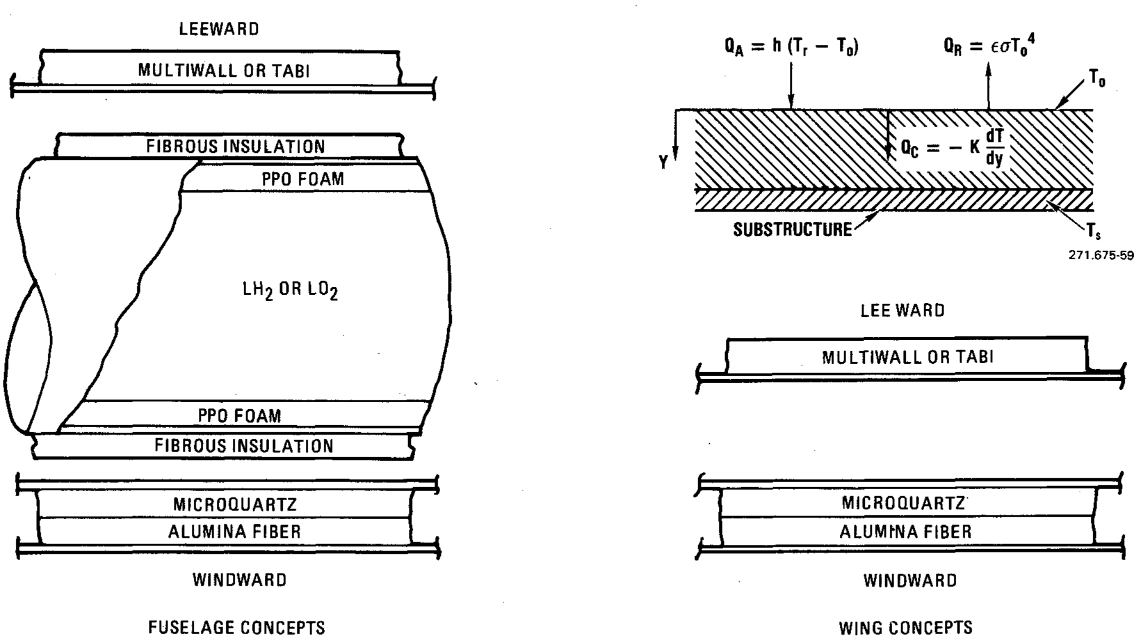


Fig. 7 Thermal model.

Table 3 Design loads

Limit conditions
Maximum αq
0.71 psi air pressure + additive $N_z = 0.5$ g, 1.5 factor on air load on wing for distribution effect
Maximum ascent acceleration
$N_x = 3.0$ g
Hypersonic maneuver, full fuel
$N_z = 2.0$ g condition, maximum thrust (227,000 lb), 0.79 psi airload
Landing
$N_z = 3.0$ g, $\dot{\theta} = \pm 1.6$ radians/s
Factor of safety = 1.40

affects local body panel shear. The design loads were used in the analysis in conjunction with consideration for other phenomena such as resistance to panel flutter, sonic fatigue, and minimum gauge. The choice of skin panel design and the selection of materials were influenced by these considerations.

The design accelerations were used in conjunction with the vehicle mass distribution and air load distribution to determine overall wing and body bending, shear, and axial loads. In conjunction with the section properties, these were used to compute load intensities at a number of stations as typified by the two primary cases shown in Table 4.

Initial Screening

An initial screening eliminated concepts B-1-A (hot structure—nonintegral tanks) and B-3-A (hot structure—integral tanks) on the basis of the lower surface temperature exceeding the 1600°F upper limit for hot metallic structures. Concept B-3-B (hybrid structure—integral tanks) was dropped due to the lack of near-term cryogenic insulation for long heating exposure (large total integrated heat load).

Weight Estimation

Detailed weight estimations based on the load intensities, minimum gauge, and panel flutter consideration were made for the following areas: body shell panels, body lower forward panels, cantilevered wing skin panels, center section skin panels, cantilevered wing spars, and center section wing spars.

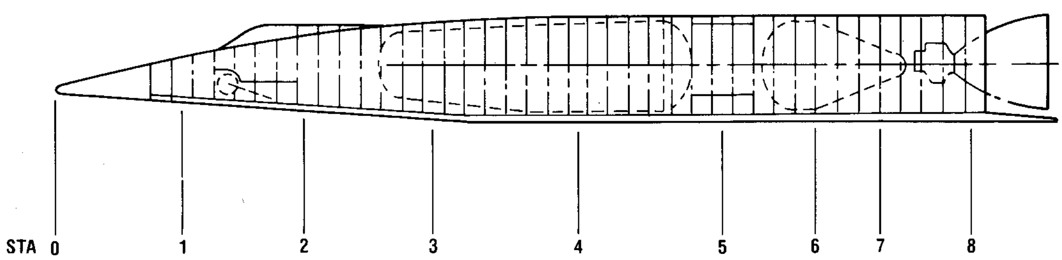
As is usual in the conceptual phase of a program, compatibility with the cost and schedule constraints of the study necessitated several simplifications in this process. It was not possible to evaluate the relative efficiencies of all candidate concepts for stiffening structural skin panels. That would have involved the rigorous analysis of skin-stringer, corrugation, bead stiffened, sandwich, and possibly other concepts for each of the candidate materials. In addition, the task would have been further complicated by the requirement to optimize the detail geometrics for each concept and for each material and by the need to analyze for stability, creep, cyclic fatigue, panel flutter, and sonic fatigue resistance.

For the purpose of this study, the sandwich concept was adopted for all primary structure panels, and the skin-stringer concept was used for the propellant tankage. Sandwich was considered to be a prime candidate in view of the need to provide sonic fatigue and panel flutter resistance in the lightweight panels as indicated by the previously computed load intensities. Skin-stringer construction was used as a basis for propellant tank weights in view of the almost univeral use of this concept for this application. These selections were merely for the purpose of this study and do not imply a recommendation for adoption without further detailed and comprehensive trade studies.

On the basis of these representative structural panel concepts, reasonable values for allowable tension, compression, and creep stresses were adopted for each candidate material at each relevant temperature. These were then applied throughout the structures to the load intensities typified by Table 4 to compute skin gauges and, subsequently, unit weights of the skin panels for the various sections of the structure. In addition, the weights of other structural components, such as wing spars, body frames, and longerons were computed. This was done from the actual loading on spars and longerons and from reasonably sized cross sections in conjunction with the measured periphery in the case of the body frames.

Thermal protection system weights were derived from credible conceptual-type drawings of each TPS concept. Weight

Table 4 Load intensities (limit)



MAXIMUM αq			
	INTENSITY LB/IN		
STATION	SHEAR	AXIAL TOP	AXIAL BOTTOM
1	37	−124	−97
2	119	−112	−102
3	149	−333	−273
4	271	−650	−530
5	434	−1200	−960
6	573	−1869	−1509
7	806	−2641	−2121
8	994	−4511	−3261

HYPERSONIC MANEUVER, FULL FUEL			
	INTENSITY LB/IN		
STATION	SHEAR	AXIAL TOP	AXIAL BOTTOM
1	8	280	−292
2	176	160	−261
3	103	284	−245
4	240	420	−365
5	1006	760	−635
6	1047	263	−110
7	302	−62	96
8	60	−98	92

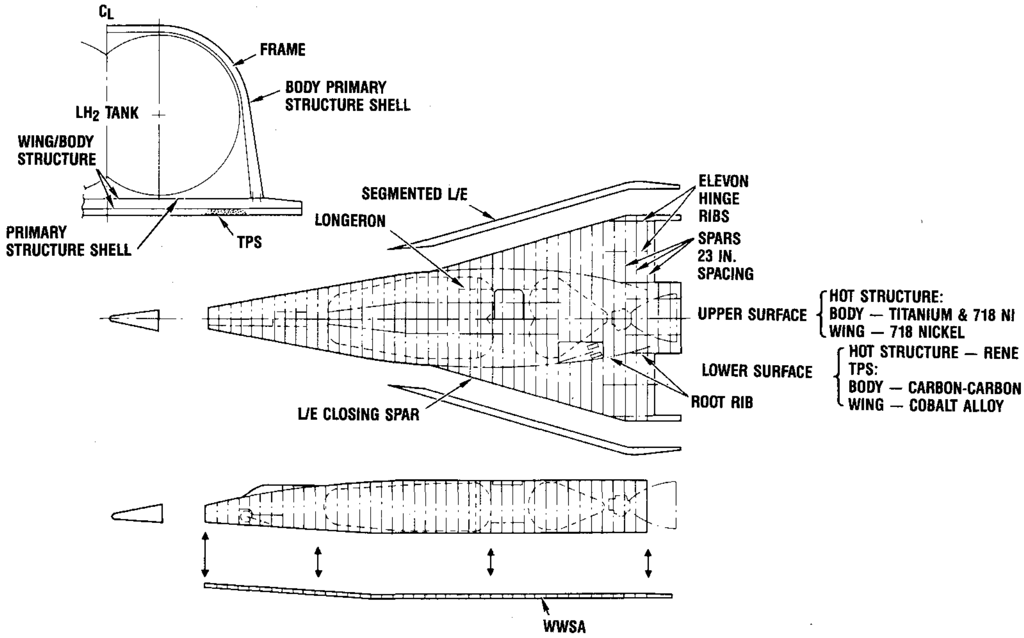


Fig. 8 Recommended thermostructural concepts.

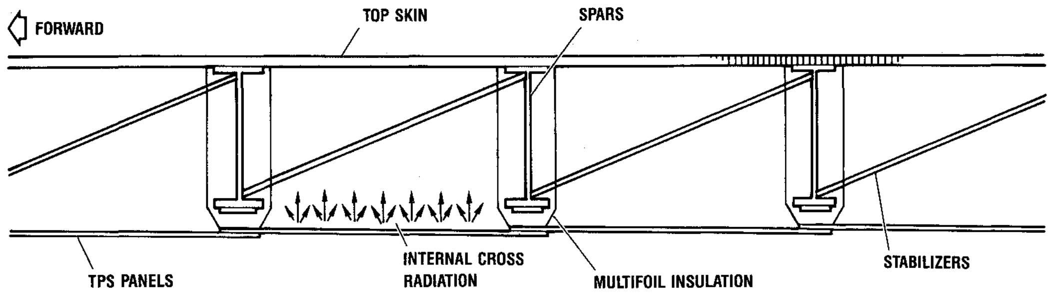


Fig. 9 Wing thermostructural concept.

Table 5 Weight comparison; summary of study (lbs)

CONCEPT		B-1-B NON-INTEGRAL-HYBRID					B-1-C NON-INTEGRAL, TPS					B-3-C INTEGRAL, TPS				
VARIANT NO.		1A	1B	1C	1D	1E	1A	2A	3A	3B	3C	1A	2A	3A	4A	5A
STRUCTURE	WINDWARD	RENE	↔	↔	↔	RENE	ALUM	Al-Li	Ti	↔	Ti	Al-Li	BORSIC-Al	Ti	718	RENE
	BODY LEEWARD	Ti	↔	↔	↔	Ti	↕	↕	Al-Li	↔	Al-Li	↕	Al-Li	Al-Li	Al-Li	Al-Li
	WING LEEWARD	718	↔	↔	↔	718	↕	↕	Ti	↔	Ti	↕	BORSIC-Al	Ti	718	Ti
TANKAGE	LH_2	ALUM	Al-Li	301SS	Ti	718	↕	↕	Al-Li	301SS	Ti	↕	Al-Li	Al-Li	Al-Li	Al-Li
	LO_2	ALUM	Al-Li	301SS	Al-Li	718	ALUM	Al-Li	Al-Li	301SS	Al-Li	Al-Li	Al-Li	Al-Li	Al-Li	Al-Li
1	TANKAGE:												ELIMINATED AT THIS STAGE — NO CREEP DATA		ELIMINATED — NOT 100% TPS	ELIMINATED — LEEWARD TITANIUM TEMPERATURES NOT FEASIBLE
2	LH_2 STRUCTURE	1096	978	1360	937	1397	1096	978	978	1360	937	2203		2203		
3	LO_2 STRUCTURE	952	843	1291	843	1347	952	843	843	1291	1347	1270		1270		
4	LH_2 PPO	—	—	—	—	—	—	—	—	—	—	354		354		
5	LH_2 INSULATION	1082	1082	726	547	285	0	0	720	494	0	0		720		
6	LO_2 INSULATION	567	567	333	567	147	0	0	308	178	308	0		308		
7	SUPPORT STRUCTURES	216	216	216	216	216	216	216	216	216	216	184		184		
8	PRIMARY STRUCTURE:															
9	BODY	6317	6317	6317	6317	6317	5147	4529	4529	4529	4529	4802		4802		
10	WING	3648	3648	3648	3648	3648	3275	2882	3695	3695	3695	2658		3520		
11	SIDE PANELS	—	—	—	—	—	—	—	—	—	—	512		512		
12	OTHER	7539	7539	7539	7539	7539	6379	5741	6549	6549	6549	6379		6439		
13	TPS WINDWARD															
14	BODY	2527	2527	2527	2527	2527	5117	5117	2903	2903	2903	5116		3098		
15	WING	1102	1102	1102	1102	1102	1678	1678	1275	1275	1275	1678		1275		
16	TPS LEEWARD															
17	BODY	—	—	—	—	—	3772	3772	3772	3772	3772	3772		3772		
18	WING	—	—	—	—	—	1071	1071	326	326	326	1071		326		
19																
20	HELIUM SYSTEM	474	474	474	474	474	474	474	474	474	474	—		—		
21	BOIL-OFF	700	700	992	1060	1865	299	299	376	517	662	305		377		
22																
23	TOTAL	26220	25993	26525	25777	26864	29476	27600	26964	27579	26993	30304		29160		

scaling laws were derived to allow for the effect of variation in insulation thickness. Using the results of the thermal analysis as applied to the relevant vehicle areas, TPS weights were determined as shown in Table 5.

Estimates were made in areas listed above for each of the remaining thermostructural concepts—B-1-B (hybrid structure—nonintegral tanks), B-1-C (TPS structure—nonintegral tanks), B-3-C (TPS structure—integral tanks)—and for each of the structural materials variants applicable to each concept.

Using this methodology, the weight tabulation presented in Table 5 was derived. In addition to the tankage, primary structure, and TPS weights, propellant boiloff and helium purge system weight were also included as weight penalties.

Selected Concept

Based on the results shown in Table 5, the B-1-B hybrid concept with the aluminum-lithium tankage (variant 1B) was selected as the recommended thermostructural concept. However, the lower-weight B-1-B concept (variant 1D) is retained as an alternative in case current doubts as to the compatibility of titanium with hydrogen propellant can be dispelled.

The B-1-B hybrid thermostructural arrangement is essentially a hot, primary load-carrying structure isolated from the aerothermal environment on the windward surface only. As seen in the cross section in Fig. 8, the body's primary structure is an arch-shaped shell arrangement that is fastened to the wing assembly at each foot of each frame and longitudinally along each lower edge. Essentially, it is a frame-supported monocoque structure. The base of the body structure is provided by an assembly of the center section of the wing and a forward lower panel.

Inconel type 718 nickel alloy is used for the basic shell in the forward crew/equipment compartment area. For the bottom panel in this area, however, Rene 41 is used to allow a peak structural temperature of 1600°F. Aft of the crew/equipment area, the major portion of the shell is Titanium 6A 1-2Sn-4Zr-2Mo, a high strength-to-weight ratio material with a peak temperature capability of 1050°F. The exception to this in the aft area is a strip of type 718 nickel alloy along each side in the area of wing/body junction. This material has a capability for a peak temperature of 1300°F.

Figure 8 shows that the wing is a multispar arrangement with the major load-carrying components located at a 23 in. spacing. The wing structure is unusual in that whereas bending-induced loads are transmitted in the upper surface by a skin panel, in contrast, at the lower surface, these loads are carried by discrete caps on the multiple spars. In this concept, air loads on the lower surface are transmitted to the spars by the TPS cover panels. Drag loads are carried entirely by the upper skin panel, and torsional effects are resisted by differential bending of the spars. As seen in Fig. 9, this design allows internal cross radiation from the lower TPS panels to reduce the temperature of these panels and to alleviate internal thermal gradients and the consequential thermal stresses.

The spars in the baseline design feature sinusoidal corrugated webs—an efficient stiffening concept for minimum gauge panels such as these. Diagonal stabilizing braces between spars (see Fig. 9) are provided at suitably spaced intervals to ensure lateral stability of the lower caps in a negative bending condition. The material for the spars is Rene 41 nickel alloy, which allows a peak structural temperature of 1600°F. The material for the sandwich upper skin of the exposed wing is type 718 nickel alloy, which is compatible with the peak temperature prediction near 1250°F. In the case of the center section, however, Rene 41 nickel alloy with a higher temperature capability is used.

The B-1-B thermostructural concept includes a TPS on the windward surface only. This is a radiative-type system consisting of in the body area, slip-jointed, carbon-carbon cover panels over a blanket of encapsulated fibrous insulation, and in the wing area, slip-jointed superalloy cover panels with minimal insulation around each individual spar. In this arrangement, the hot load-carrying structure forms the outer surface of the vehicle, except for the windward surface. Consequently, over most of the surface area, the vehicle features a rugged, airplane-like metallic skin. Furthermore, on the remaining area—the windward surface—the proposed radiative TPS is also relatively durable and easy to maintain.

The propellant tankage is of the nonintegral type designed for propellant containment only. It consists of separate tanks for the LH_2 and LO_2 propellants. Each tank is suspended

Table 6 Unit weight comparisons (PSF)

	BODY (1)(3) PSF	WING (2)(3) PSF
CONCEPT B-1-B (5)	4.85	6.88
CONCEPT B-1-B + TANKS (4)	6.10	6.88
STS ORBITER (6)	7.7	9.7
FSTS STUDY (7) (6) (INSULATED ALUMINUM)	4.40	5.05

(1) ON WETTED AREA INCLUDING WING CARRY-THRU, AND BODY "TRAILING EDGE" NOT INCLUDING BASE
(2) ON PLANFORM AREA OF CANTILEVERED WINGS INCLUDING L/E AND ELEVONS
(3) TOTALS, STRUCTURE + TPS
(4) INCLUDING INSULATION AND SUPPORTS
(5) SPC TRAJECTORY
(6) BENIGN TRAJECTORY
(7) REFERENCE 3

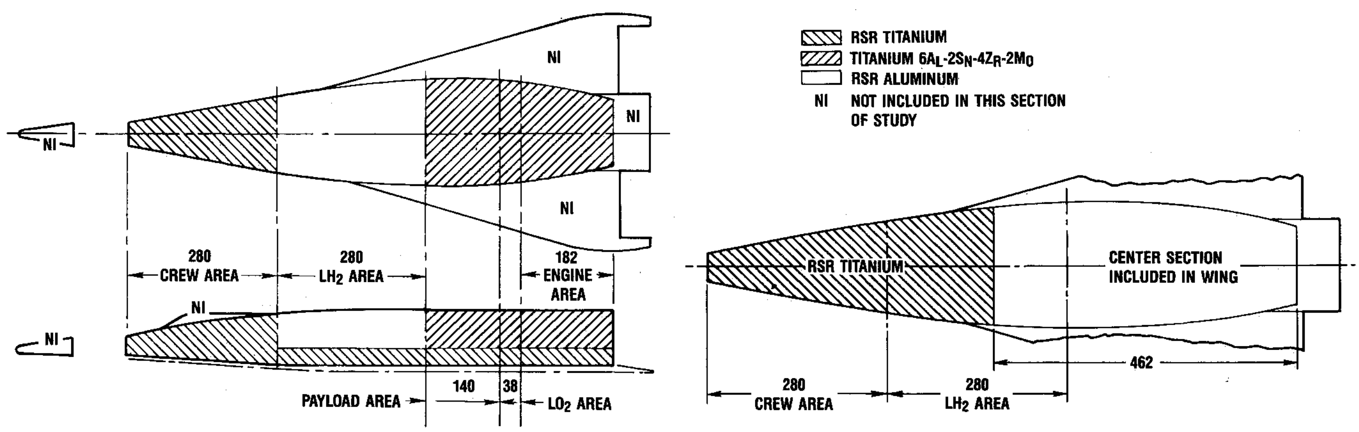


Fig. 10 Study selections—advanced materials.

Table 7 Advanced materials for HVV

Material System	Maximum use temperature, °F
Metal matrix composites	
SiC/Al	800
B-SiC/Al	800
SiC/Ti (uncoated)	1,000
SiC/superalloy	2,000
RSR[a] materials	
RSR Al	900
RSR Ti	1,800
Ceramics	
Coated carbon-carbon	3,100
Organiz matrix composites	
Graphite polymide	500

[a]Rapid solidification rate (RSR)

within the body's hot structural shell by a kinematic linkage that prevents transmission of thermally and mechanically induced strains between the primary structure and the tank. In the case of the LH_2 tank, a cryogenic insulation system is provided in conjunction with a helium atmosphere between the tank and the primary structure. This performs multiple functions to inhibit propellant boiloff, to prevent air liquefaction, to control the tank structural temperature, and to prevent the accumulation of ice on the outer surface of the vehicle.

This concept is designed for a severe 7400-s, synergetic plane change trajectory with a peak temperature of 2550°F on the windward centerline. This condition necessitates the provision of carbon-carbon TPS cover panels on the body and superalloy panels on the wing. With minimal change to the structure, an orbital or boost/glide vehicle dedicated to the less severe nominal glide return trajectory can use superalloy panels in lieu of carbon-carbon body panels and can employ a simple hot structure for the wing. This feature may be advantageous from the operational standpoint.

With further analyses, this concept becomes more and more appealing. The continuous wing structure fully integrated with the body structure is certainly a more efficient structural arrangement than the alternative of transmitting all wing bending moment around the fuselage frames. The structural design and analysis functions should participate fully in the configuration evolution of any future hypervelocity vehicle and, in participating, should strongly promote this approach.

Also, as shown in our trade study analysis, integration of the wing center section with the body's lower structure is a prime factor in causing the nonintegral propellant tank concept to be the lightest. With the increasing emphasis on safety, this is fortuitous. The reliability potential of the simple nonintegral tank structure should be substantially greater than for the alternative integral arrangement for several reasons. Fracture mechanics considerations are greatly aided by the simplicity of the tank structure and the relatively simple and well defined stress distributions. The number of failure modes and potential points of failure are significantly less than in the case of an integral tank. Furthermore, the simple kinematic tank attachment arrangement is far less trouble-prone than the several high thermal stress-inducing interfaces that exist between integral cryogenic tanks and the immediately adjacent hot structural components. Special features of the concept include:

1) dispensing with the acreage of weight-costly, minimum-gauge wing lower skin in favor of discrete spar caps of high-bending efficiency and low thermal-stress potential;

2) use of internal cross radiation in conjunction with the structural arrangement described above to reduce lower surface temperatures and to minimize thermal stress in the wings and center section by reducing thermal gradients; use of this technique should be considered for all thermostructural arrangements that employ TPS only on the windward surface; severe transient temperature gradients can be induced by the immediate thermal response of the upper hot structure in contrast to the delayed response of the thermally protected lower structure;

3) a unique TPS cover panel design that is structurally efficient, provides fail-safe attachments, and is easily removable for in-the-field inspection or repair; and

4) an adaptation of the proven Atlas thrust cone to evolve a highly efficient thrust structure in which 43% of the thrust load is reacted directly by the inertia of the LO_2.

Overall, the concept is well suited to military operations in view of the following features:

1) provision of a rugged metallic airplane-like outer shell over most of the surface area of the vehicle;

2) use of a simple, damage-tolerant TPS on the windward surface; the proposed cover panels are easily removable for inspection and repair or for access to internal components, yet feature fail-safe attachments;

3) a complete tankage and propulsion system can be installed on the wing platform and checked out prior to envelopment by the fuselage shell;

4) the preceding feature also facilitates field maintenance and repair by providing reasonable access for all operations up to and including propellant tank replacement; and

5) cryogenic insulation system positively prevents atmospheric cryopumping and permits all-weather operation by

Table 8 Overall weight summary

	Current materials study		Advanced materials study	
	Material	W, lbs	Material	W, lbs
Tankage:				
LH_2 structure	Aluminum lithium	978	Aluminum lithium	978
LO_2 structure	Aluminum lithium	843	Aluminum lithium	843
LH_2 insulation	—	1,082	—	1,082
LO_2 insulation	—	567	—	567
Supports	—	216	—	170
Primary structure:				
Body	Ti, 718, Rene	6,317	Ti, RSR Al, RSR Ti	5,054
Wing	718, Rene	3,648	RSR Ti, Rene, Si-C superalloy	2,804
Other	—	7,539	—	6,258
TPS windward:				
Body	Carbon-carbon	2,886	Carbon-carbon	2,527
Wing	HS 188	1,102	Si-C superalloy	989
TPS leeward:				
Body	—	—	—	—
Wing	—	—	—	—
Helium system	—	474	—	474
Boil-off	—	700	—	700
Totals		26,352		22,446

inhibiting the accumulation of frost and ice on the outer surface of the vehicle.

Unit Weight Comparison

Although the primary objective of the trade study was to obtain reasonably good weight differentials between the competing candidates as opposed to the derivation of well-honed absolute weights a comparison of unit weights with those for the Shuttle Transportation System (STS) orbiter and projected values for other advanced vehicles is of interest. Table 6 presents such a comparison. The unit weights in psf are based on the definition given by notes 1–4 on the table. The weights for the selected concept B-1-B are given with and without propellant tanks for comparison with the existing STS orbiter, which contains no tankage and with a prediction for a future space transportation system (FSTS) vehicle, which does have tankage.

A crucial consideration in evaluating this comparative data arises from the differences in trajectories applicable to these vehicles. As indicated in the table, the B-1-B concept is sized for the severe 7400-s synergetic plane change trajectory. In contrast, both versions of the STS vehicle are sized for a relatively benign return from orbit trajectory. This difference significantly affects the weight of the thermostructural system.

Advanced Materials

The objective of this part of the study was to provide an estimate of the weight reduction that may be attainable for a specific hypervelocity vehicle by the application of advanced materials to the thermostructural system. For this investigation, it was assumed that advanced material developments[9–11] were applicable. Table 7 presents eight advanced materials that were considered in this study. Figure 10 illustrates the selection of representative advanced materials adopted in the areas for the purpose of this study. The overall weight summary for the advanced materials applications is compared to the results of the current materials study in Table 8.

The end result of this advanced materials study shows that for items directly affected by the material change, the weight saving is about 18%. In view of this, the percentage saving should be higher if advanced materials are applied in other areas, such as propellant tanks and cryogenic and high-temperature insulation systems. Furthermore, the saving indicated here may be restricted by the limited scope of this study. In a more rigorous study, development of detailed structural concepts better suited to the characteristics of the advanced materials would improve the percentage benefit. In addition, the application to vehicles having different overall and/or local geometries, and/or subject to different loading conditions, may not be as affected by minimum gauge constraints. This circumstance would probably yield greater percentage weight differentials.

Conclusions

On the basis of the results of this study, several conclusions were drawn:

1) The study has defined a lightweight, durable, thermostructural concept suited to high lift/drag vehicles for the most demanding military missions.

2) A promising concept exists for TPS cover panels that are lightweight, fail-safe, rugged, and easily installed and removed.

3) An estimation of the weight savings accruing from the use of advanced materials has been provided, and an appreciation of the application and development requirements in this field has been gained.

4) Uncertainties remain with respect to the compatibility of titanium as a LH_2 tank material in the applicable environment.

5) The study has identified a potential problem area that affects several thermostructural concepts under consideration in the aerospace industry. This concerns the thermal gradient induced by a transition from an insulated to an unprotected primary structure.

Acknowledgment

This research was sponsored under U. S. Air Force Contract F33615-85-C-3022.

References

[1]Scipio, L. A., "Structural Design Concepts," NASA SP-5039, 1967.

[2]Hepler, A. K., and Swegle, A. R., "Hot Structure Development Advanced Space Transportation System Application," AIAA Paper 79-0876, May 1979.

[3]Taylor, A. H., MacConochie, J. O., Jackson, L. R., and Martin, J. A., "The FSTS Study—Structures and Subsystems," *Astronautics and Aeronautics,* Vol. 21, June 1983, pp. 55,56,62.

[4]Taylor, A. H., Jackson, L. R., Davis, R. C., Cerro, J. A., and Scotti, S. J., "Structural Concepts for Future Space Transportation System Orbiters," *Journal of Spacecraft and Rockets,* Vol. 22, May–June 1985, pp. 333–339.

[5]Fivel, H. J., "Numerical Flow Field Program for Aeroheating Analysis," Vol. I and II, Air Force Flight Dynamics Lab., TR-79-3128, Sept. 1979.

[6]Sawko, P. M., and Tran, H. K., "Strength and Flexibility Properties of Advanced Ceramic Fabrics," *SAMPE Quarterly,* Vol. 17, Oct. 1985, pp. 7–13.

[7]Shideler, J. L., Kelly, H. N., Avery, D. E., Blosser, M. L., and Adelman, H. M., "Multiwall TPS—An Emerging Concept," *Journal of Spacecraft and Rockets,* Vol. 19, July 1982, pp. 358–365.

[8]Yates, G. B., "Reusable Cryogenic Insulation," General Dynamics Convair Div., San Diego, CA, GDC-ERR-1421, Dec. 1969.

[9]DeMario, W. F., "New Word for Aerospace Composites," *Aerospace America,* Oct. 1985, pp. 36–42.

[10]Jackson, L. R., Dixon, S. C., Tenney, D. R., Carter, A. L., and Stephens, J. R., "Hypersonic Structures and Materials: a Progress Report," *Aerospace America,* Oct. 1987, pp. 25–30.

[11]Ronald, T. M. F., "Advanced Materials to Fly High in NASP," *Advanced Materials and Processes,* Vol. 135, May 1989, pp. 29–37.