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Structural Concepts for a Mach 5 Cruise Airplane LH_2 Fuselage Tank

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A matrix of structural concepts suitable for Mach 5 hydrogen-fueled hypersonic vehicles are defined and a thermostructural analysis is presented. The thermal environment encountered in this flight regime mandates hot structures of superalloy materials or insulated structures using more conventional materials such as titanium, aluminum, and composites. This paper compares the thermostructural performance of several concepts. The various structures are initially sized to carry a 2.5 *g* subsonic maneuver load. The structural weights are determined, and these components are then evaluated in a transient heating program along with various thermal protection systems to determine the minimum weight combination. The temperature profiles generated for these minimum-weight solutions are used as input to a structural analysis along with a model of the appropriate structural concept to calculate thermal stresses. Generally, hot-structure concepts have higher thermal stresses. In most cases, the thermal stresses are below the yield strength of the material. It is shown that integral tanks have weights similar to nonintegral tank concepts for the same level of technology. Moreover, an insulated tubular aluminum-composite structure with nonintegral tanks appears attractive for near-term vehicles.

Introduction

INNOVATIVE structural concepts will be required to provide an optimum Mach 5 cruise airplane. The structure selected will be required to endure thermal cycling generated by aerodynamic heating and contact with the cryogenic fuel. These thermal loads must be resisted for many cycles with little or no maintenance. Additionally, the structure must be durable, easily fabricated, and inexpensive for these type of vehicles to be viable.

Several conceptual designs for a Mach 5 cruise aircraft have been proposed.[1] The present paper describes the results of the analyses of a matrix of structural concepts suitable for the fuselage of such an aircraft. The structural concepts may be divided into two basic groupings—those with integral and those with nonintegral tanks. Four integral tank concepts were evaluated. Three were integrally Z-stiffened aluminum structures, with the first two employing an external multiwall[2] thermal protection system (TPS) with external and internal foam insulation,[3] respectively, on the tank structure. The third concept uses a titanium standoff heat-shield TPS, with fibrous insulation between the structure and the heat shield and internal closed-cell foam on the tank structure. The fourth integral tank concept incorporates multiwall TPS shielding on evacuated aluminum honeycomb structure with titanium core.

Three nonintegral tank structures were also evaluated. All three had an aluminum tank with internal foam and external fibrous insulation. The first structure was a hot honeycomb concept of Inconel on the lower surface and titanium on the upper portions. The second concept used the same materials with beaded structural panels. The final nonintegral concept was an insulated tubular aluminum structure where the aluminum structure was protected by a multiwall TPS.

These structures were all sized for a 2.5 *g* subsonic air load which established the initial component sizes. The amount of TPS required for each structure was then optimized along with fuel boiloff establishing a minimum weight combination of structure and TPS. The thermal profiles through each concept were then used as input to calculate the maximum thermal stresses, which occur later in the flight than the 2.5 *g* subsonic load, thus the maximum air and thermal load-induced stresses are not additive. The best candidates for this application are the minimum weight concepts which have acceptable thermal stress levels.

Aircraft Configuration

The Mach 5 cruise aircraft configuration depicted in Fig. 1 is typical of the concepts currently proposed[1] and was selected for this analysis. The aircraft is in the 200,000 lb weight class with a 5000 n.mi. range carrying a 4500 lb payload. This aircraft utilizes a dual mode propulsion system consisting of a hydrocarbon-fueled turbojet for takeoff, acceleration, and landing. A liquid hydrogen-fueled ramjet is used for the cruise portion of flight. The low density of the liquid hydrogen mandates that the majority of the fuselage volume be used for cryogenic tankage.

The forward LH_2 tank in Fig. 1 is a multilobe nonintegral tank approximately 90 ft long, 15 ft deep, and 30 ft wide. For this study, a fuselage section 20 ft in diameter and 90 ft long was used to simplify the analysis.

The relatively small wing area of this configuration produces high bending loads in the fuselage structure during subsonic flight. In supersonic and hypersonic flight, the lift is more uniformly distributed over the planform, and the weight is lower due to fuel depletion and the limit maneuver load is reduced to 2 *g*'s, these factors significantly reduce the fuselage bending loads. For these reasons the 2.5-*g* subsonic maneuver condition sizes the fuselage structure.

Trajectory

A typical flight envelope for a Mach 5 cruise airplane is shown in Figs. 2 and 3. The flight Mach number is plotted against altitude in Fig. 2. The cruise altitude is shown to be 100,000 ft, and for reference, a constant dynamic pressure

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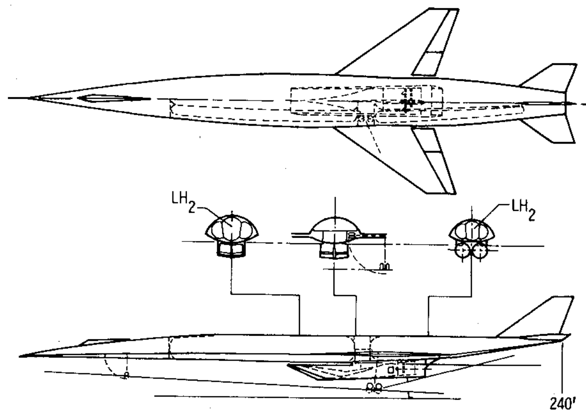

Fig. 1 General arrangement—hypersonic cruise airplane.

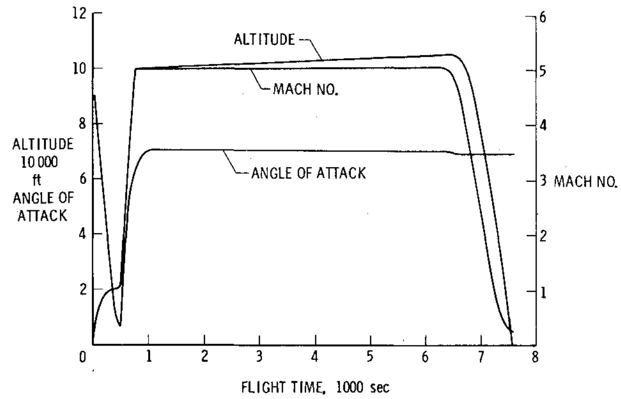

Fig. 3 Hypersonic airplane trajectory.

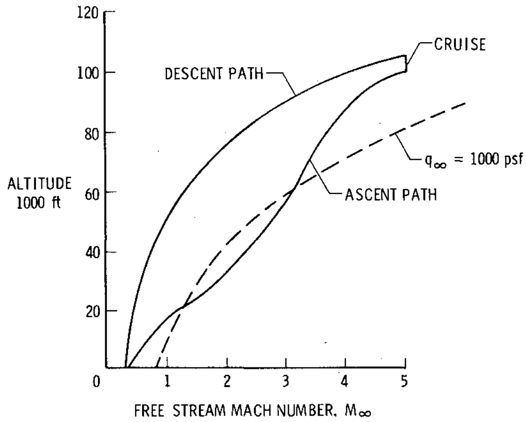

Fig. 2 Hypersonic airplane flight envelope.

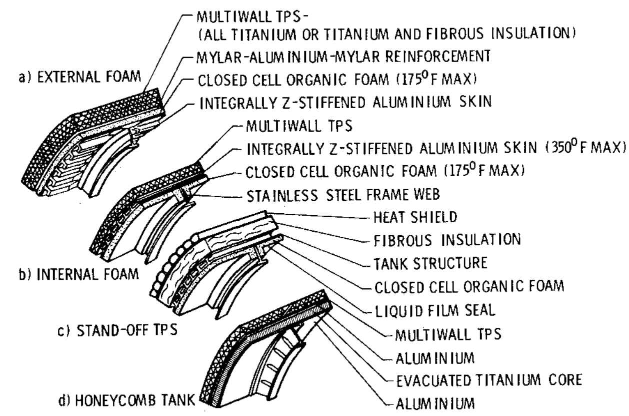

Fig. 4 Integral tank structural concepts.

curve at 1000 psf is also shown. Figure 3 plots Mach number, altitude, and angle of attack against flight time. The Mach 5 cruise portion of the flight is about 1.5 h and angle of attack is held constant during this period at 7 deg.

These parameters are used as input to the thermal analysis to calculate local heating rates.

Structural Concepts

A large number of structural concepts were investigated. Most of these were derivatives of the seven concepts selected for this analysis and can be divided into two broad categories: those with integral and those with nonintegral tank arrangement, both hot and insulated structures are considered.

Integral Tank Structures

The four integral tank structural concepts selected are shown in Fig. 4. All the concepts have a thermal protection system (TPS) insulating the primary structure from aerodynamic heating. The TPS is thicker on the more highly heated bottom surface and thinner at the top surface. The inner surface of all the structures is initially exposed to the cryogenic liquid hydrogen fuel. As fuel is depleted, the inner surfaces near the top of the fuselage are exposed to hydrogen gas. Additionally, all the integral tank structures have ring frames on 20-in. stations stabilizing the tank structure.

The first concept, Fig. 4a, is an integrally stiffened skin stinger concept using 2219 aluminum alloy. A typical joint is shown in the ring frame where a locally thicker skin is provided in order to butt weld the skin panels. This is done to maintain leak-free construction and adequate margins in the structure where the material allowables are degraded in the weld zone. An integral tab is provided on the skin to mechanically attach the aluminum ring frame web and inner cap. The exterior surface is also insulated with a closed-cell polyurethane foam to further insulate the cryogenic tank and prevent air condensation in the outer surface. Additionally, a vapor barrier is bonded to the foam primarily to reinforce the foam and to seal any gaps in the foam. The TPS is shown as titanium multiwall tiles.

Two versions of multiwall tiles are studied. The first is an all-metal multiwall consisting of layers of dimpled and plain foils diffusion bonded together and sealed along scarfed edges with beaded foil closures. The tiles are watertight; however, a vent hole is provided in the hidden face to equalize pressures. Between the tiles and the foam are strips of silicone foam to prevent lateral airflow under the tiles. This multiwall TPS is shown in structural concepts 4a, b, and d. The second version of multiwall tiles is externally identical to the first version except some of the center layers are replaced by a fibrous insulation, TG15000. Two titanium or superalloy dimpled layers with plain foil layers form a structural panel for the outer surface of the tile. This panel is connected along its periphery to a single dimpled sheet sandwich that forms the inner surface of the tile. This multiwall TPS is depicted on structural concept 5c. The tiles are prefabricated and mechanically attached, thus simplifying installation on the airplane.

In this first structural concept, Fig. 4a, the high conductivity of the aluminum structure combined with the external insulation maintains the entire structure at nearly constant temperature, thus minimizing thermal loads. However, the foam is limited to a 175°F maximum reuse temperature and has little mass and extremely low conductivity. Additionally, a limit of −280°F on the foam hot face must be maintained during ground hold to prevent nitrogen or air liquifaction. Therefore, more TPS than the optimum for fuel boiloff is required to satisfy these temperature constraints.

The second concept, shown in Fig. 4b, is similar to the first concept. In this concept, the closed-cell foam is installed on the inner surface of the tank allowing the use of external stringers. As before, a multiwall TPS is employed. However, it is thinner than that required for concept 4a, as the aluminum structure has a reuse temperature limit of 350°F; however, the foam contacting the aluminum limits the structure to a maximum temperature of 175°F. This higher structural temperature than concept 4a results in a higher temperature difference between the inner frame cap and outer skin producing higher thermal stresses. To minimize fuel boiloff, a low conductivity stainless steel or Inconel frame web is used.

The standoff TPS in concept 4c uses the same structure as concept 4b, but the multiwall TPS is replaced by a corrugated titanium erosion shield and fibrous insulation. The erosion shields are slip-jointed every 20 in. and attached to flexible standoff supports. The shields protect the fibrous insulation (TG15000) from wind shear; however, means to avoid water retention in the fibrous insulation require more study. As before, the 175°F temperature of the structural skin and the cold inner frame caps will be the source of thermal stresses in the tank structure.

The last integral tank concept uses a near-art evacuated honeycomb tank structure protected by multiwall TPS as shown in Fig. 4d. The honeycomb has aluminum face sheets, frame caps and webs, but the core material is titanium to reduce conduction between the honeycomb faces, thus serving the function of the foam in the previous concepts. The aluminum faces are compatible with the fuel and the honeycomb structure is more efficient than the Z-stiffened skin structures. The outer face sheet, which may be heated to an allowable peak temperature of 350 deg, induces thermal stresses when its expansion is resisted by the cold inner face sheet and ring frame.

Nonintegral Tank Structures

The three nonintegral tank concepts evaluated are shown in Fig. 5. All three use a common nonintegral welded aluminum tank with internal closed-cell foam and external fibrous insulation (TG15000). Variations of these were also examined, such as a combination of the concept shown in Fig. 5c used for the lower surface with concept 5b used for the upper surface.

The hot honeycomb structure, in Fig. 5a, uses evacuated honeycomb, similar to the integral concept in Fig. 4d. However, the higher temperatures encountered during exposure to the aerodynamic heating preclude the use of aluminum. In fact, the low mass of the outer face sheet and low conductivity of the evacuated core result in an outer skin temperature above 800°F, which necessitates the use of nickel alloys to ensure a reasonable service life. Inconel 718 was selected for this case. However, the upper-surface areas not subjected to temperature over 600°F could use titanium honeycomb to save weight.

The second nonintegral tank structure, Fig. 5b, is a beaded hot structure. The concept shown is a heavier but simpler

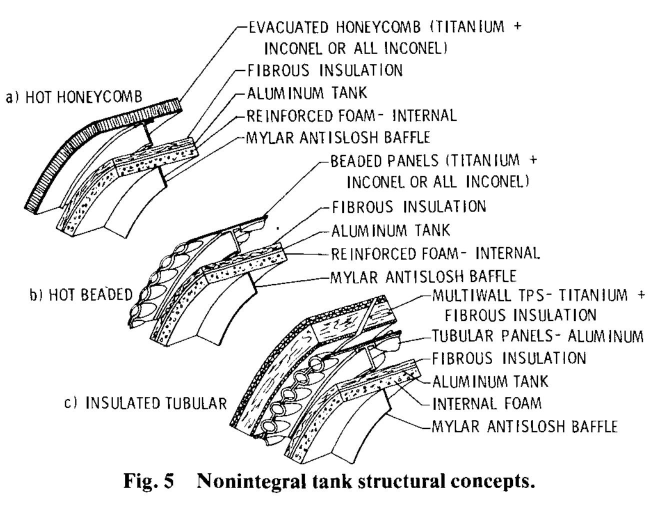

Fig. 5 Nonintegral tank structural concepts.

alternative to the honeycomb structure. The lightly beaded outer skin is stiffened by a deeply beaded inner skin. As before, the lower surfaces require Inconel 718 and the upper surfaces have the option of titanium.

A further possibility is to use this concept, Fig. 5b, for upper fuselage surfaces and a variation of the insulated structure, Fig. 5c, for lower surfaces. This concept, however, uses a titanium structure throughout. The use of Ti 6Al-4V alloy requires a greater percentage of insulated surface than the Ti 6-2-4-2 alloy, which is limited to 800°F in this study instead of the 600°F limit for the first material. However, the tubular panels used for insulated structure are more efficient than beaded panels used for hot structure, so a weight comparison was made and reported later.

The final nonintegral tank structure, shown in Fig. 5c, is an insulated tubular aluminum concept. The all-aluminum tubular structure is protected by a multiwall sandwich TPS which uses fibrous insulation between the multiwall faces. It also has two variations, an all-aluminum structure and a selectively reinforced aluminum-composite structure. In this concept, most of the fibrous insulation covers the structure with a relatively thin layer of fibrous insulation on the tank, whereas in the other concepts, the fibrous insulation is only on the tank.

Structural Sizing

The various structural concepts were sized for the same bending moment of 170×10^6 in.-lb and same diameter of 20 ft. The bending moment was calculated from the load and shear diagrams. A limit load factor of 2.5 was used with a safety factor of 1.5. This resulted in an ultimate load intensity of 8900 lb/in., which is used for stress calculations; however, an additional load factor of 2.25 was used to obtain weights. This factor yields weights about 50% greater than those indicated for the ultimate load intensity and provides better correlation between weights of actual structures and those obtained by the optimization analyses used in this study.

Figure 6 shows the weight of the several types of structure studied as a function of buckling load[4,5] at room temperature. As indicated, a cylinder of tubular panels results in the least weight for a given load. Moreover, aluminum is lighter than the titanium or nickel alloy, provided the stresses are below the yield strength of aluminum. At higher loads, titanium is the lightest of the materials shown since its yield strength is considerably greater than aluminum. However, at all loads shown, composite materials would yield least weight.

Results of the structural sizing were applied to finite-element models for thermal and structural analyses of the concepts. The unit-area weights of the structures are listed in Tables 1 and 2. These weights are discussed after the thermal analyses, which provide weights of the various thermal protection systems. This allows comparison of the total unit weights including boiloff of liquid hydrogen. The discussion of comparative weights is followed by results of thermal stress analyses of the concepts, since the weights are determined by subsonic loads and thermal stresses do not influence the weights.

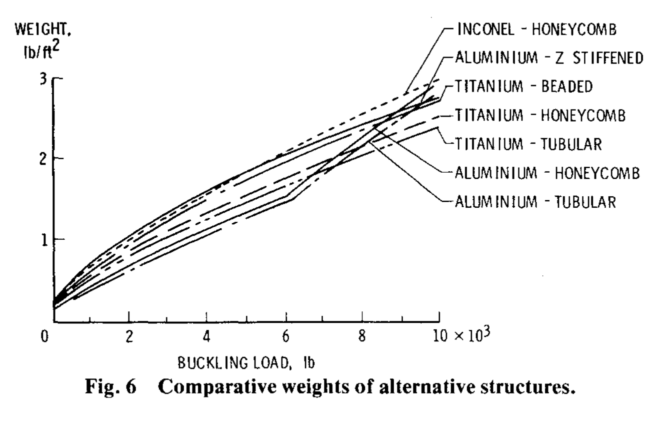

Fig. 6 Comparative weights of alternative structures.

Table 1 Average weights of integral tank structural concepts

	Structural concept				
	Figure 4a	Figure 4a	Figure 4b	Figure 4c	Figure 4d
Component	All-metal multiwall external foam internal Z's	TG15000 multiwall external foam internal Z's	TG15000 multiwall internal foam external Z's	Stand/off TPS internal foam external Z's	TG1500 multiwall honeycomb aluminum skins, Ti. core
Skins + rings	2.76	2.76	2.88	2.88	1.53
Core + braze	---	---	---	---	0.82
Internal structure	1.24	1.24	1.25	1.25	1.10
Nonoptimum	0.40	0.40	0.42	0.42	0.40
Total structure	4.40	4.40	4.55	4.55	3.85
External TPS	1.45	0.98	0.75	1.22	0.89
Foam	0.13	0.16	0.67	0.68	–
Boiloff	1.00	0.38	0.47	0.41	0.80
Total TPS	2.58	1.52	1.89	2.31	1.69
Total weight	6.98	5.92	6.44	6.86	5.54

Table 2 Average weights of nonintegral tank structural concepts

	Structural concept							
	Figure 5a		Figure 5b		Figures 5b and 5c		Figure 5c	
	Hot honeycomb		Hot beaded		Hot beaded + insulated tubular all titanium		Insulated tubular	
	All	Inconel + titanium	All	Inconel + titanium	Percent insulated		All	Aluminum +
Component	Inconel	half each	Inconel	half each	30[b]	70[c]	aluminum	composites
Skins + rings	2.14	1.68[a]	3.55	3.04[a]	3.04[d]	2.21[e]	2.00	1.52
Core + braze	1.01	0.72[a]	----	----	----	----	----	----
Internal structure	1.20	0.92[a]	1.40	0.95[a]	0.95[d]	0.95[e]	0.90	0.68
Nonoptimum	0.55	0.40[a]	0.71	0.67[a]	0.67[d]	0.49[e]	0.40	0.30
Total structure	4.90	4.31	5.66	5.16	4.36	3.95	3.30	2.50
Tank	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Tank/external TPS	0.23	0.23	0.23	0.23	0.44	0.55	1.00	1.00
Foam	0.41	0.41	0.49	0.49	0.46	0.43	0.31	0.31
Boiloff	0.46	0.46	0.46	0.46	0.43	0.45	0.31	0.31
Total TPS	1.10	1.10	1.18	1.18	1.33	1.43	1.62	1.62
Total weight	7.25	6.66	8.09	7.59	6.94	6.63	6.17	5.37

[a]Titanium structure. [b]Ti-6-2-4-2 structure. [c]Ti-6Al-4V structure. [d]Beaded panels. [e]Tubular panels.

Thermal Analyses

Thermal analyses were performed for each structural concept and variations thereof. These analyses determine the minimum weights of the thermal protection systems and temperature distributions through the walls. Both lower- and upper-surface locations were analyzed. Before presenting results of the thermal analyses, a review of the thermal conductivity of the various insulations selected for this study is given with the aid of Fig. 7.

As indicated, polyurethane foam has the lowest conductivity, which is much lower external to the tank than internal where hydrogen permeates the foam. The foam is limited to 175°F reuse temperature, thus for higher temperatures a fibrous insulation, TG15000, was selected for study. This insulation has a very low density, which makes it more efficient for cruise airplane applications than the other insulations shown. This is because the thermal efficiency for this quasi-steady-state cruise condition is proportional to the square root of the density-conductivity product of the insulation. The space shuttle reusable surface insulation (LI-900) is shown for reference. Placing the TG15000 inside a titanium multiwall package causes an increase in apparent conductivity and density due to the metal edge closures of the tiles. An all-metal titanium multiwall tile has a conductivity of about 30% greater than TG15000 and a much higher density. Moreover, the TG15000 insulation is more efficient than the shuttle material; however, TG15000 is limited to a reuse temperature of about 750°F, which is of little use for the shuttle which has a higher operating temperature, but well-suited to a Mach 5 airplane application.

Each of the structural concepts was modeled for a transient heating analysis.[6] This analysis couples aerodynamic heating with the radiation from the aerodynamic surface and with heat conduction into or out of the wall. An aerodynamic surface emittance of 0.8 was assumed for all analyses. The convective heat-transfer coefficient was calculated based on the surface temperature required to satisfy the heat balance at the surface at a given time. Surface isotherms vary by about 100°F over the length of the tank along the lower centerline at Mach 5. All elements of the wall including ring frames are modeled. Hydrogen boiloff was determined from the heat absorbed by the heat sink, which had properties selected to represent the essentially constant temperature fuel. Apparent thermal conductivities were calculated for air gaps as well as for the metal layers of multiwall TPS or erosion shields.

Results of Thermal Analyses

Minimum weight was determined for the thermal protection system based on least sum of boiloff and TPS. Temperature distributions are given at this minimum weight.

Figure 8 shows a typical plot of TPS weight as a function of multiwall TPS thickness. As indicated, the thicker the TPS, the lower the boiloff and the heavier the TPS. A minimum sum for this concept, Fig. 4b, exists at a multiwall TPS thickness of about 3.0 in., where the boiloff is about 0.6 lb/ft^2. This boiloff is equivalent to about 2 in. of additional wall thickness. Additionally, this structural concept requires a 3.5-in. thickness of internal foam; thus, a total thickness of 6.5 in. is utilized for the TPS function. The weight of the various structural and thermal protection system components are listed in Tables 1 and 2.

Temperature extremes and maximum temperature differences are given in Table 3 for selected structural concepts. The temperatures at the aerodynamic surface or hot face of the multiwall for the external foam integral tank concept, Fig. 4a, vary from 50°F to 838°F. The lower surface data are shown and since liquid hydrogen is present throughout the flight, the tank structure remains cold. The external foam exceeds the 175°F reuse limit temperature, and prior to flight, the hot face of the foam is so cold that nitrogen purge gas would condense. This may be avoided by increasing the ratio of foam thickness to multiwall thickness; however, the maximum temperature of the foam would then increase during flight. Therefore, it is also necessary to increase the thickness of the multiwall TPS. Thus the weight would be increased above the minimum weight value given in Table 1, based on boiloff alone.

Placing the foam inside the tank, Fig. 4b, results in foam temperatures that satisfy both lower and upper limits of minimum weight based on boiloff. The internal foam concept optimized on boiloff is heavier than the external foam system and about equal wall thickness. However, the weight of the external foam system will increase, as discussed, when foam temperature limits are maintained. Thus, internal foam and external foam offer about equal weight.

Temperature extremes for various locations within the wall of the insulated honeycomb integral tank concept, Fig. 4d, are also shown in Table 3. Both upper- and lower-surface temperatures are given. As seen, the honeycomb hot face is above

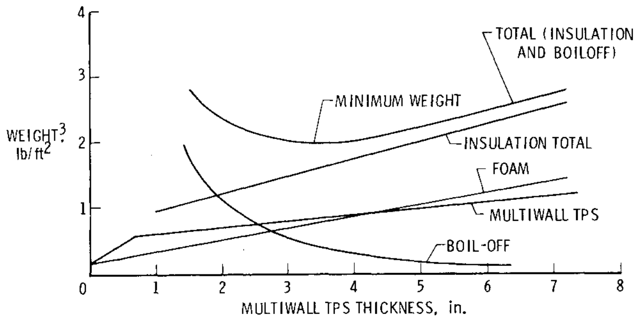

Fig. 8 Typical minimum weight analysis shown for structural concept shown in Fig. 4b.

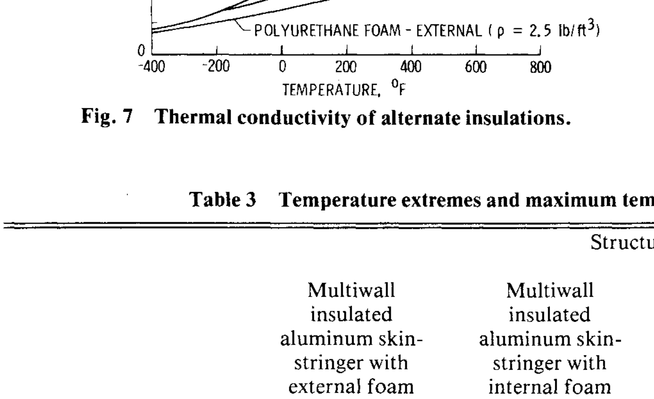

Fig. 7 Thermal conductivity of alternate insulations.

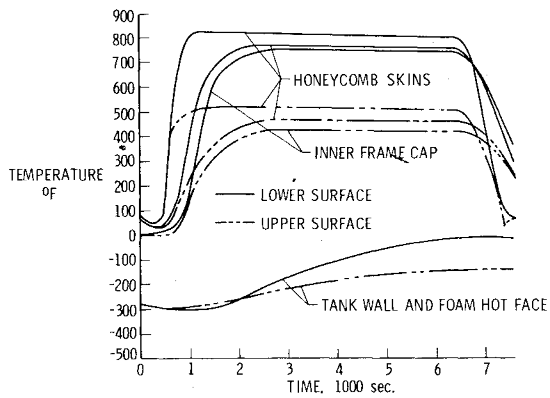

Fig. 9 Temperature histories of lower and upper surfaces of hot honeycomb concept.

Table 3 Temperature extremes and maximum temperature differences for selected structural concepts, °F

	Structural concept											
	Multiwall insulated aluminum skin-stringer with external foam		Multiwall insulated aluminum skin-stringer with internal foam		Multiwall insulated aluminum honeycomb				Hot Inconel honeycomb			
	Figure 4a		Figure 4b		Figure 4d				Figure 5a			
	Lower		Lower		Lower		Upper		Lower		Upper	
Structural element	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Multiwall hot face	838	50	838	50	838	50	550	50	–	–	–	–
Honeycomb outer skin					–110	–320	–120	–250	838	50	550	50
Foam hot face	190	–350	135	–250	–	–	–	–	–	–	–	–
Tank wall	–420	–420	135	–250	–420	–420	–320	–420	0	–300	–150	–300
Honeycomb inner skin	–	–	–	–	–420	–420	–320	–420	760	50	450	20
Inner frame cap	–420	–420	–420	–420	–420	–420	–320	–420	750	0	420	0
Maximum structural temperature difference	0		550		300		200		590		490	

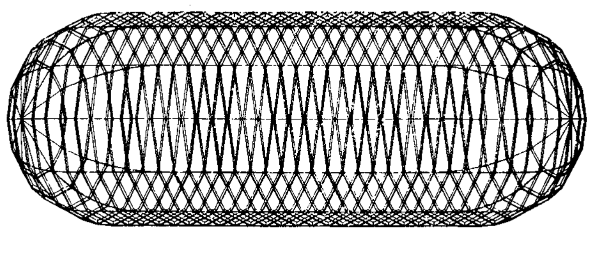

Fig. 10 Finite element structural model.

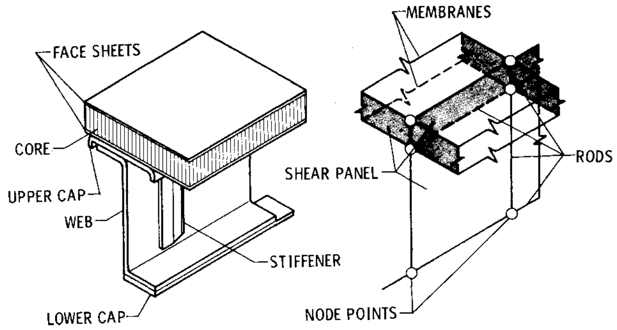

Fig. 11 Finite element simulation of structure.

the nitrogen condensation temperature of $-280°F$ and the aluminum hot face is not heated to the upper limit of 350°F for a system sized for minimum weight based on boiloff. The insulating value of the titanium core performs the function of foam quite well; however, the honeycomb must be vacuum leak-free.

Figure 9 shows temperature histories of lower and upper surfaces of the hot honeycomb structure with a nonintegral tank, Fig. 5a. This temperature history is typical for the previously described temperature extremes and temperature differences in concepts which are presented in Table 3. The internal foam remains within its temperature limits. However, a potential problem is indicated by the large temperature difference between the honeycomb faces occurring during ascent. Thermal stress is evaluated in a subsequent section.

Comparison of Structural Concepts

Referring to Table 1, it is seen that the all-metal multiwall TPS (Fig. 4a) is heavier by about 1 lb/ft^2 than the TG15000-filled multiwall tiles. The all-metal version of multiwall is suited to areas of low heat load where the tile thickness is less than 0.75 in. At this thickness, three dimpled layers fill the tile, which is the greatest number required for stiffness and strength.

Table 1 indicates that internal foam (Fig. 4b) is about 0.5 lb/ft^2 heavier than external foam (Fig. 4a). Part of the weight increase is caused by the use of the external Z stiffeners on the integral tank. External Z stiffeners are theoretically less efficient than internal Z's, each with internal ring frames. However, as discussed earlier, the external foam at minimum TPS weight based on boiloff does not satisfy temperature limits. Additional multiwall and foam would be required to satisfy temperature limits. Thus, the external foam concept will weigh about the same as the internal foam concept.

Standoff TPS, shown in Fig. 4c, is seen in Table 1 to be heavier than the TG15000-filled multiwall concept with the same tank structure, Fig. 4b. The erosion shield is titanium of equal stiffness to an identical superalloy shield. However, the optimization of the geometry for titanium would lower the weight of the standoff concept to about equal the multiwall concept. Consequently, the structural concepts shown in Figs. 4a-c are about equal weight of about 6.5 lb/ft^2.

The advanced integral-tank concept using multiwall TPS on evacuated aluminum-faced honeycomb with titanium core has potential of saving 1.0 lb/ft^2 or would weigh about 5.5 lb/ft^2.

Table 2 lists weights of nonintegral tank concepts. The use of honeycomb hot structure is seen to be lighter than the beaded panel structure, which is a simpler construction. The use of a mixture of materials, Inconel for the hotter half of the fuselage and titanium for the cooler upper half, is lighter for both honeycomb and beaded hot structures that are made of all Inconel.

The use of a partially insulated structure of titanium is as light as the best hot structure studied. The TPS weight for partial insulating is offset by the use of efficient tubular panels where TPS is used. The greater the percentage (70 vs 30) of shielded area, the lower the total weight. The tubular panels plus the multiwall TPS combined weight is less than the noninsulated hot beaded structure that was replaced.

This trend continues as 100% of the structure is insulated when tubular panels and lower density materials are used. The results indicate that an insulated aluminum structure is lighter than the partially insulated or hot structures each with nonintegral hydrogen tanks. This result would not be true for loads causing the structure to be based on the yield strength limit rather than elastic buckling. However, composites have high yield strengths, thus a structure employing composite materials is potentially the least-weight structural concept.

Comparing data in Tables 1 and 2 indicate that for a given level of technology, nonintegral tank concepts are about equal in weight to integral tank concepts. Moreover, several near-art concepts, both integral and nonintegral, weigh about 6.5 lb/ft^2, whereas, the advanced concepts weigh about 5.5 lb/ft^2.

Structural Analyses

The temperature profiles yield maximum temperature differences which are now used as input for a thermal stress analyses along with a finite-element model of each structure. The SPAR system of computer programs was selected for the structural analysis.[7]

Structural Model

A graphic representation of the finite-element model created for the integral tank structures is shown in Fig. 10. It has 720 nodal locations and over 1800 degrees of freedom. The node points are connected by 916 rods and 1035 quadrilateral elements representing the structure. The nonintegral tank structure representation is similar, except end domes are not used.

Figure 11 shows the simulation used to model the honeycomb concept. The face sheets are modeled with quadrilateral membrane elements which are separated by the core thickness and interconnected with peripheral shear webs representing the shear resistance of the core. Rods are then used in each corner to represent the tension-compression capacity of the core which has a density of 1.6% of the parent material.

The tubular and beaded panels are simulated by thin quadrilateral membranes representing 5% of the average skin gage to account for the lower extensional stiffness of the skin in the hoop direction; the remainder of the skin is modeled as rods and shear panels like the honeycomb. The hoop-direction elements have approximately 10% of the average skin gage effective while 100% of the skin is effective in the axial direction.

The integrally Z-stiffened aluminum concepts are considerably less complex, only two nodes are used to represent the frame depth. The outer nodes are connected with membranes for the skin and with rods for the stiffeners and outer frame caps. The inner nodes are connected by rods in the

Table 4 Summary of thermal stresses in structural concepts, psi

	Structural concept					
	Multiwall insulated aluminum skin-stringer with internal foam	Heat shield insulated aluminum skin-stringer with internal foam	Multiwall insulated aluminum honeycomb	Hot Inconel honeycomb	Hot Inconel beaded	Hot Inconel beaded upper insulated titanium tubular bottom
Structural element	Figure 4b	Figure 4c	Figure 4d	Figure 5a	Figure 5b	Figures 5b and 5c
		Upper surface on center line				
Skin, axial	−1,700	−500	−12,300[a] 13,700[b]	−11,100[a] 12,900[b]	−15,700	−20,900
Skin, hoop	−7,500	−6,500	−17,800[a] 7,900[b]	− 300[a] 4,500[b]	−16,100	−27,500
Frame cap, outer	−6,400	−6,400	34,500	−8,800	7,400	6,200
Frame cap, inner	45,700	40,200	35,100	34,300	3,800	
		Lower surface on center line				
Skin, axial	−2,200	−700	−17,100[a] −18,800[b]	−57,200[a] −63,500[b]	−27,900	−6,600
Skin, hoop	−10,300	−8,600	−23,700[a] 11,800[b]	−44,300[a] 46,800[b]	−47,700	−10,300
Frame cap, outer	−9,600	−8,300	42,800	−29,800	−8,700	900
Frame cap, inner	63,800	53,600	42,600	−36,800	30,900	7,100

[a] Outer face sheet. [b] Inner face sheet.

hoop direction for the inner frame cap simulation. The frame cap nodes are then interconnected with shear panels representing the frame webs.

It is imperative that the correct material properties be input to the finite-element model, especially when such large thermal excursions are encountered. For this model the material properties at the appropriate temperature were input for each element group. The properties of Ref. 8 are used for most of the input except where Mil-HDBK-5A (Ref. 9) properties are available.

Thermal Stresses

As previously noted, the structure is sized to carry a subsonic maneuver load. These structures are now evaluated for maximum thermal stress levels which occur later in the flight. The results of the SPAR analyses show the baseline insulated aluminum tank concept, Fig. 4a, and the insulated aluminum tubular nonintegral tank concept, Fig. 5c, have negligible thermal stresses in the primary structure. This was anticipated due to the lack of any appreciable temperature differences through the structure. The stresses in the remaining concepts will be discussed in the order presented in Figs. 4 and 5. The skin stresses in both the axial and hoop directions and in both the inner and outer frame cap for selected concepts are presented in Table 4.

Integral Tank Concepts

The structural concept in Fig. 4a employs external closed-cell foam which maintains the entire structure at a uniformly low temperature. In the concepts shown in Figs. 4b and 4c, the closed-cell foam is moved to the inner surface of the integral tank structure. This reduces the external TPS requirements as the tank skin absorbs more of the heat than the external foam and, since the skin has a large mass compared to the foam, it forms an effective heat sink. This results in a higher tank wall temperature. As shown in Table 3, a temperature difference of 585°F exists between the inner frame cap and the skin of the tank. The skin (tank wall) is attempting to expand while the inner frame cap remains at cryogenic temperature and resists the growth of the skin. As shown for the concept in Fig. 4b, the inner caps, sized to carry the fuselage bending loads, are stressed by the thermal loads well above the yield strength of aluminum, while the skin and outer caps remain at very low stress levels.

These thermal stresses, while significant, are not considered unmanageable. First, for a very small weight penalty, the entire frame could be insulated with the closed-cell foam reducing the temperature differences between the inner and outer caps. Alternately, or in combination with the added insulation, the inner frame caps would be increased in size and the Inconel frame web could be replaced with an aluminum web.

Normally, an increase in frame cap in area will not reduce thermal stress levels. In this instance, however, the centroid of the frame is very near the outer surface. An increase in inner frame cap size will move the centroid nearer to the inner cap, which will increase the outer skin and cap stress while reducing the inner cap stress levels. It should be noted that the reduction in temperature differences through the frame will reduce the stress levels throughout the structure.

Table 4 also depicts the stresses in the structural concept of Fig. 4c. The heat shield in this concept is heavier than the multiwall/fibrous insulation sandwich and provides somewhat better insulation properties, which reduces the temperature difference through the frame. As before, in Fig. 4b, the inner cap stresses are still unacceptable, but may be reduced without a significant weight penalty by providing internal insulation for the entire frame and/or more inner cap area with a change in frame web material from Inconel to aluminum.

The last integral tank concept, the insulated honeycomb concept of Fig. 4d, was the lightest integral tank concept studied. The evacuated honeycomb is an excellent insulator and requires less TPS than the other integral structures and the temperature gradient through the frame-honeycomb thickness is less severe than in either of the internal foam baseline cases. The thermal stress levels indicate that all components of the structure have adequate margins over the material yield strength. It should be noted that this structural concept, while most promising, is not yet considered state-of-the-art. The sealing integrity of an evacuated honeycomb core has yet to be demonstrated.

Nonintegral Tank Concepts

The hot honeycomb structure and the hot beaded structure shown in Figs. 5a and 5b experience the highest external structure temperatures of all concepts investigated. The maximum temperature is 838°F, as shown in Fig. 9. The inner face sheet of the honeycomb does not attain the same temperature as the outer sheet. Figure 9 shows this difference to be 75°F for the upper surface and 45°F for the lower surface during the cruise portion of the flight. There is also a 300°F temperature difference between the top and bottom surfaces of the structure. The thermal stresses for this condition were found to be relatively small.

During the ascent portion of the trajectory, at approximately 750 s in Fig. 9, the differences in honeycomb face sheet temperatures are maximized at about 590°F for the lower surface and 490°F for the upper surfaces. The stresses generated by this temperature difference are shown in Table 4. The stresses are quite high relative to the insulated structures, but since Inconel 718 is used on the bottom panels and titanium is used on the top and sides, the stresses are well within the material allowables at the temperatures encountered.

The beaded hot structure concept experiences a similar thermal environment. However, the beaded panels are not evacuated since their relatively thick skins are less subject to oxidation than the core of honeycomb; therefore, the inner surface is more rapidly heated and the temperature differences between the face sheets is significantly smaller than in the hot honeycomb concept, a maximum of 60°F. Also, the beaded inner panel offers less resistance to growth in the hoop direction as it has much less extensional stiffness in this direction. Consequently, the stress levels are lower.

As previously mentioned, the lower surfaces of these concepts could be insulated with a sufficient amount of TPS to allow the use of all titanium structures. The stresses shown are representative of these concepts. The magnitude of the stresses in these hot structures can be reduced twofold by employing this concept.

Concluding Remarks

Thermostructural analyses of a fuselage section of a Mach 5 airplane were made for both integral and nonintegral hydrogen tank structural concepts.

Results show that at a given level of technology, integral and nonintegral tank concepts have about equal weight. The near-art approaches weigh about 6.5 lb/ft^2, and the more advanced concepts weigh about 5.5 lb/ft^2.

Cryogenic foam may be installed either internal or external to the tank wall at about equal weight and wall thickness. The use of internal foam with integral tanks requires the ring frames to be fully covered with foam to avoid excessive thermal stress. Multiwall tiles filled with a fibrous insulation are lighter than all-metal multiwall tiles; however, all-metal multiwall is useful for low heat load applications. Standoff TPS weighs about the same as multiwall TPS, but multiwall TPS is more resistant to water entrainment and is easier to install on the airplane.

Of the integral tank concepts studied, a multiwall TPS on an aluminum-faced honeycomb tank with titanium core offers least weight. Of the nonintegral tank concepts studied, a fully insulated aluminum structure of tubular panels is lighter than either partially insulated or hot structure. An aluminum structure with composites, as applicable, offers potentially the least-weight structural concept for nonintegral tanks; however, use of an aluminum matrix composite for the honeycomb faces for the integral tank concept could result in less or equal weight.

The results indicate that fiber-filled multiwall titanium tiles, and beaded and tubular panels warrant serious study for high-speed airplanes. Other technologies warranting further study are aluminum-faced, titanium core honeycomb integral tanks and composite structures of tubular panels for nonintegral tank structures.

Thermal stresses did not seriously effect the concepts for this Mach 5 application, since in all concepts, except as mentioned above, the thermal stresses were less than the yield strength of the materials.

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