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ABSTRACT

Thermal protection systems for large reentry vehicles, such as a Space Shuttle booster or orbiter, comprise a significant percentage of the total weight of the vehicle and the total cost of the program. Therefore, to achieve a Shuttle system that is cost- and weight-effective, it is imperative to select an optimized thermal protection system.

One type of thermal protection system considered for the Space Shuttle consists of radiative heat shield panels, or "shingles," supported from the primary structure. This paper summarizes the results of a design and analytical study of five such titanium-superalloy thermal protection systems for the Space Shuttle booster.

INTRODUCTION

The Space Shuttle mission imposes severe and complex load and thermal environments on both the orbiter and booster vehicles. The reentry thermal environment is of particular concern because it necessitates the use of a thermal protection system over large areas of both vehicles. Because of the large surface areas requiring thermal protection, a small difference in unit weight can have a significant influence on potential payload weight. And because of the large areas, small differences in unit costs result in tremendous differences in total program cost. Therefore, the selected thermal protection system must be optimized for both weight and cost.

One basic type of thermal protection system considered for Shuttle application is the radiative metallic panel. This paper presents the results of a study of five titanium-superalloy metallic panel configurations.

The five candidate configurations, shown schematically in Figure 1, were analyzed and designed for the load and thermal environment of a representative Shuttle booster configuration, Figure 2. Unit costs were determined for each candidate configuration based on a "bottoms up" analysis. The total program cost, based on estimated cost of the hardware plus a delta weight value, was used as the basis for selection.

DESIGN CRITERIA

The following design criteria were used for the Booster Metallic Heat Shield Trade Study. These criteria are considered representative of design conditions that would include most of the vehicle surface to be shielded. Extreme design conditions applying to local portions of the surface were not considered pertinent to this trade study.

Discrete Loading Conditions

Static strengths were determined using ultimate ($1.4 \times$ limit) externally applied pressures normal to the surface, superimposed on coexisting limit-induced temperatures throughout the panel. The design temperature for each material was considered the limit temperature for panels of that material. Thermal stresses induced at the limit temperature by the most severe gradient conditions were added to stresses induced by ultimate pressures.

Limit static pressures are listed in Figure 3 for selected locations on the surface of the vehicle. These pressures were applied at the maximum temperature. The limit pressure (1.84 psi) was applied to windward surfaces (assumed temperatures above 1350°F for material selection) because it covered the range of pressures over most of these surfaces. This pressure was based on maintaining a (constant lift) normal load factor of 3.0 during entry. A limit pressure of 1.0 psi was applied to leeward surfaces (assumed temperatures below 1350°F for material selection). This pressure was arbitrarily established as a practical minimum for design although the actual pressures over most of the leeward surfaces are lower. Likewise, a negative (internal cavity) pressure (0.5 psi) was applied to each heat shield panel (windward and leeward) at the design temperature of the panel. A preliminary study of anticipated venting characteristics indicated that this cavity pressure was a conservative maximum.

No overpressures or other hazards resulting from abort conditions were applied to the panels.

Deflection

The permissible maximum deflection of a panel normal to the air flow was limited to the following:

$$H = 0.0125L \text{ for } X \leq 10 \text{ ft}$$

$$H = 0.0250L \text{ for } X > 10 \text{ ft}$$

where

H = Wave height (in.)

L = Wavelength (in.)

X = Distance aft of a forward leading edge, such as the nose of the vehicle.

Panel Flutter

Dynamic flutter requirements for simply supported panels during ascent were in accordance with Reference 1, as shown in Figure 4 for the critical Mach number. A factor of 3.5 was applied to the ordinate of Figure 4 to account for the adverse effect of unidirectional stiffness, contrasted with isotropic stiffness. The local dynamic pressure (q_{max}) was 588 psf.

Acoustics

A peak octave band sound pressure level of 162 db was selected for panel design. Based on a preliminary estimate of booster external acoustics, this value exists approximately 25 ft from the engine nozzle. Since the severity of exposure varies considerably over the vehicle, this value will be conservative for some areas and unconservative for others.

MATERIALS

The titanium and superalloy materials selected for this study were:

Material	Design Temperature
Ti-6Aℓ-4V STA	850°F
Inconel 718	1350°F
René 41	1600°F
L-605	1800°F

The selection of materials and their maximum design temperatures was based on the results of a materials study presented in Reference 2.

The strength properties used to size the heat shield panels and support structure, shown in Table 1, are minimum values for each alloy and were obtained from the references cited in Figure 5.

The oxidation characteristics of the alloys, shown in Figure 5, represent a compilation of data from References 3 and 4. The values presented are the maximum values from these references and are for oxidation in still air during a single continuous exposure. The dashed portion of the L-605 curve represents an extrapolation beyond the range of available data.

DESIGN AND ANALYSIS

The five candidate configurations shown in Figure 1 were evaluated for this study. The skin-corrugation, skin-stringer, and honeycomb configurations were designed with edge supports; the honeycomb and isogrid configurations, with a five-point support system. All configurations and supporting structure were designed to meet the strength and stiffness requirements defined previously.

Edge-Supported Configurations

An evaluation of panel lengths showed that a 20-in. length produced the lightest unit weight for the edge-supported configurations. A panel width of 17 in. was established to coincide with the length of the support rail, to minimize the design problems associated with expansion joints at the panel edges, and to coincide with hard points on the booster body structure. Simple supports were chosen for the panels and support rails to minimize thermal stresses induced by edge restraints and redundant supports.

The support rails are oriented circumferentially on the booster body (Figure 6). The inner rail is permanently attached to the booster hard points by standoff fittings that fix the inner rail at one end and permit thermal expansion at the other. Pinning the inner rail to the standoffs also provides for rotation due to differential expansion. The panel is fixed on pins at one end to the lateral flanges of the inner rail. With both the inner rail and the panel fixed at the same end, parallel circumferential thermal expansion can occur between these members. A slot on one side of the panel provides for fore and aft expansion of the panel. The outer rail attaches to the inner rail at three places and can be removed to inspect or replace a panel.

The skin-stringer and skin-corrugation panels were considered simple beams in order to calculate bending moments and deflections from pressure loads and thermal gradients. The edge-supported honeycomb panel was analyzed as a wide beam. For each material at its design temperature, dimensions were varied to obtain a minimum weight configuration that would meet the strength and stiffness requirements.

The bending strengths of the skin-corrugation panels were governed by the allowable crippling of the section in compression. The bending moment allowed for the skin-stringer panels was based on skin buckling or T-section crippling, whichever was critical. Crippling allowables were calculated in accordance with Reference 8. Minimum gages for the skin-corrugation panel were established at 0.010 in. for the skin and 0.005 in. for the corrugation. For the skin-stringer configuration a minimum gage of 0.015 in. was set by machining limitations.

The bending strength of the edge-supported honeycomb panels was, in general, limited by skin wrinkling strength. The core configuration was dictated by shear requirements and by the need to resist wrinkling and dimpling of the facing skins. Minimum gage of the honeycomb face sheets was set at 0.008 in.

Post-Supported Configurations

The size of the post-supported panels was selected as 20x34 in. after evaluating several sizes that could be symmetrically supported at five places from the booster hard points. The panels are fixed at the center post and allowed to slide at the corner posts to permit in-plane thermal expansion or contraction (Figure 7). Panel removal is accomplished by taking out the screws and the holddown fittings at the five posts. This exposes the sealing strips, which are removed by pulling them from the grooves in the panel edges.

A finite-element digital computer program was used to analyze the post-supported rectangular panels for both pressure loads and thermal gradients. Because the bending moment over the central support cannot be reliably calculated using a single node point between elements, it was analyzed using Equation 96 of Reference 9.

Because of the concentration of shear and moment loads at the central support that results from both pressure loads and thermal gradients, local reinforcement was required in each post-supported panel. However, from the standpoint of weight, local reinforcement is feasible since the most highly stressed region represents a relatively small percentage of the total area of the panel. This local reinforcement method was used in analyzing panel weights for the four different materials. For the honeycomb panels, this reinforcement consisted of densifying the core and adding circular doublers around the center post. The isogrid panel was reinforced near the center post by increasing the thickness of both the stiffeners and the skin.

RESULTS

The results of the study are presented in Figures 8 thru 12 and Tables 2 thru 4. Figures 8 thru 12 give a detailed description of each configuration, showing dimensions, unit weights, and critical design conditions. The sizing of all configurations for all materials was established after evaluating all design conditions -- namely, pressure loads plus thermal stresses, deflection, panel flutter, and acoustics. Also, an oxidation loss for René 41 and L-605 was included by adding additional material, based on the oxidation behavior curves of Figure 5. The oxidation loss was based on keeping the panels at design temperature for 10 hr. Table 2 summarizes the unit weight of panels and supporting structure for each configuration.

The unit cost for each configuration, Table 3, was based on a detailed analysis discussed in Reference 10.

Unit weights and unit costs from Tables 2 and 3 were used to calculate the program costs shown in Table 4. The total weight (W) of each material is based on the unit weight of each panel and its supporting structure times the surface area per booster for that material. The program cost (C) is equal to the unit cost times the surface area per booster times the number of booster heat shields for the total program plus or minus the performance influence. For the particular booster used for this study, the effect of delta weight on performance was valued at $6226 per pound. The skin-corrugation configuration was assumed to be the baseline. Program costs for other configurations were calculated relative to this baseline.

CONCLUSIONS

Based on the program costs shown in Table 4, the most effective configuration for all materials except titanium is the post-supported honeycomb configuration. For titanium, the isogrid configuration is more effective. However, because the difference is small, and because it is desirable to eliminate the complexities of mixing configurations, the post-supported honeycomb configuration is recommended for all the materials evaluated in the study. Not only does it give the most cost-effective Shuttle thermal protection system, but also the lightest -- approximately 2000 lb lighter than the other systems that were evaluated.

It should be recognized that where the weight and cost differences are small, the conclusions could be different if the environment were changed.

Additional effort, both analytical and testing, is required to fully assess the effects of the cyclic load and thermal environment on the heat shield design for all of the materials evaluated in this study before the structural integrity of the metallic heat shield panels can be assured. Specific determinations should be made of the following cyclic effects: allowable creep; residual strength; lifecycle fatigue; acoustic strength and fatigue; and oxidation behavior.

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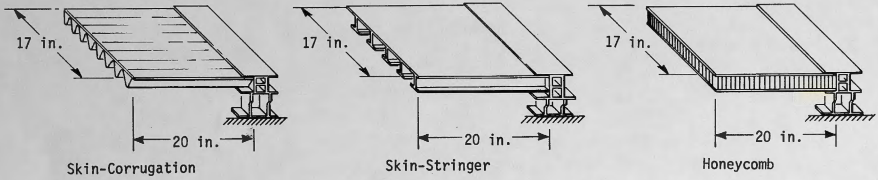
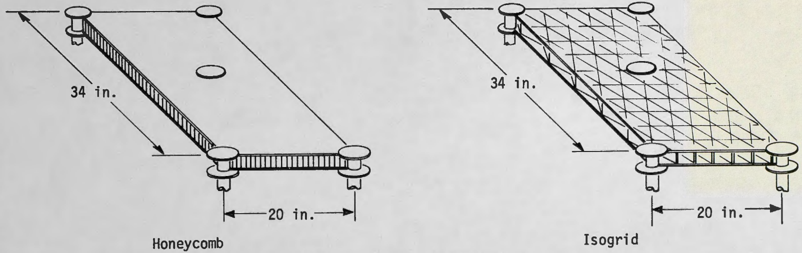


(a) Edge-Supported Configurations



(b) Post-Supported Configurations

Figure 1 Candidate Configurations

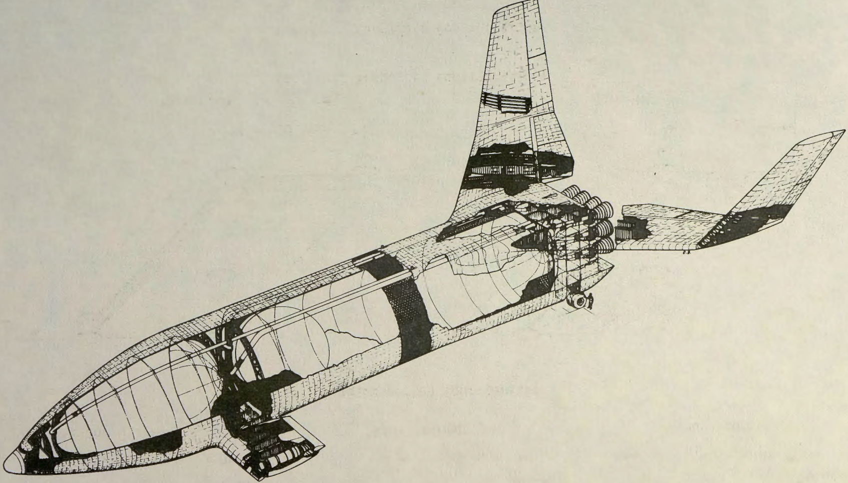


Figure 2 Single-Body Canard Booster

Location	α (deg)	Pressure Coefficient, C_{p_o}	Dynamic Pressure, q_s (psf)	p (psi)*
1	23.5	0.46	325	1.56
2	23.5	0.19	325	0.65
3	Arbitrary Maximum			1.00
4	43.0	1.24	160	2.06
5	43.0	1.10	160	1.84

*$p = C_{p_o} \; q_s \times \text{Dispersion Factor}/144$

(Dispersion Factor = 1.5).

For the trade studies, 1.84 psi was applied to windward surfaces, and 1.00 psi was applied to leeward surfaces (the canard, location 4, accounts for a very small percentage of the total surface area).

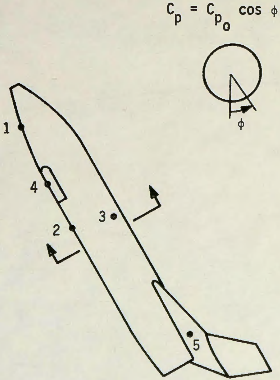


Figure 3 Limit Static Pressures (p) on Heat Shielding during Booster Entry (Applied at Maximum Temperature)

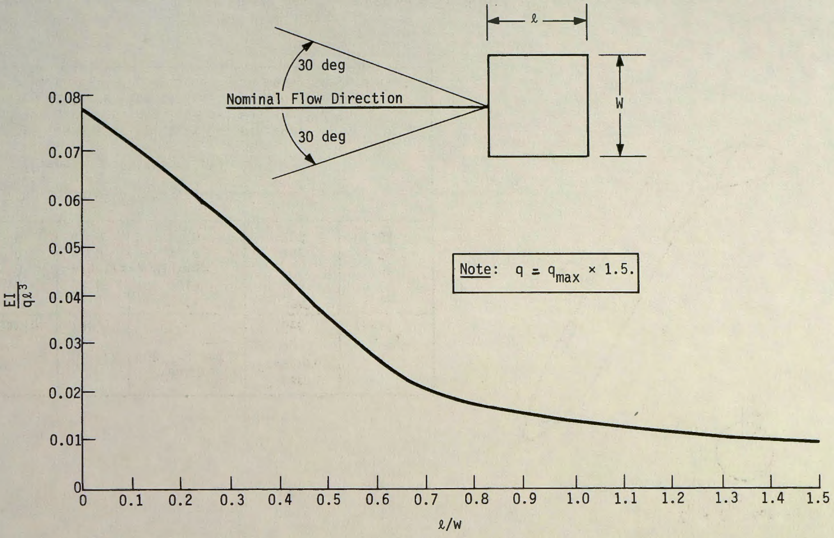


Figure 4 Panel Flutter Stiffness Requirements for Isotropic, Simply Supported Panels

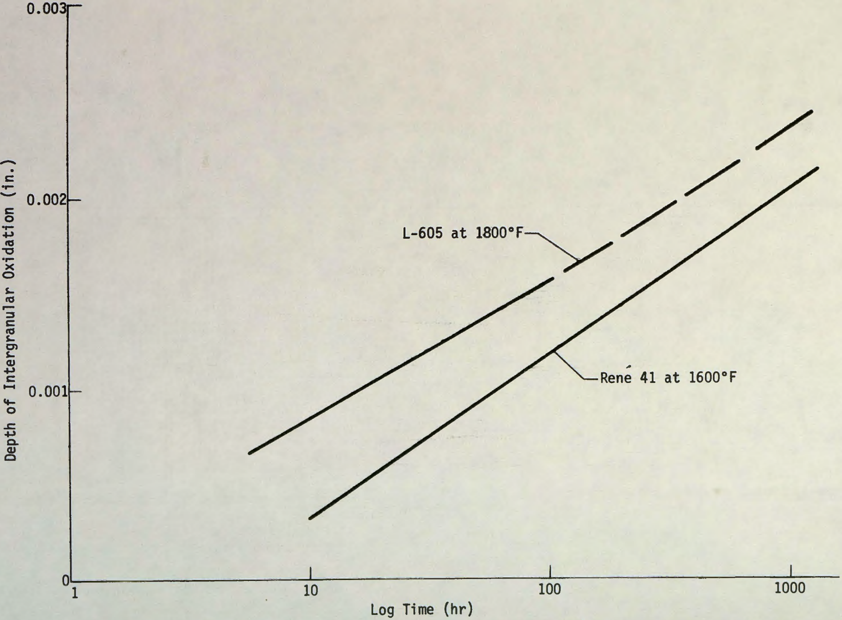


Figure 5 Oxidation Behavior of L-605 and René 41

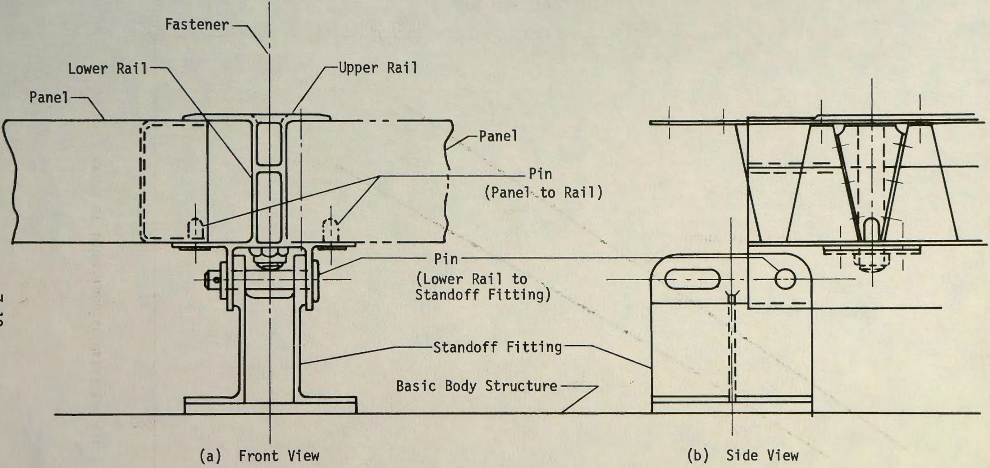
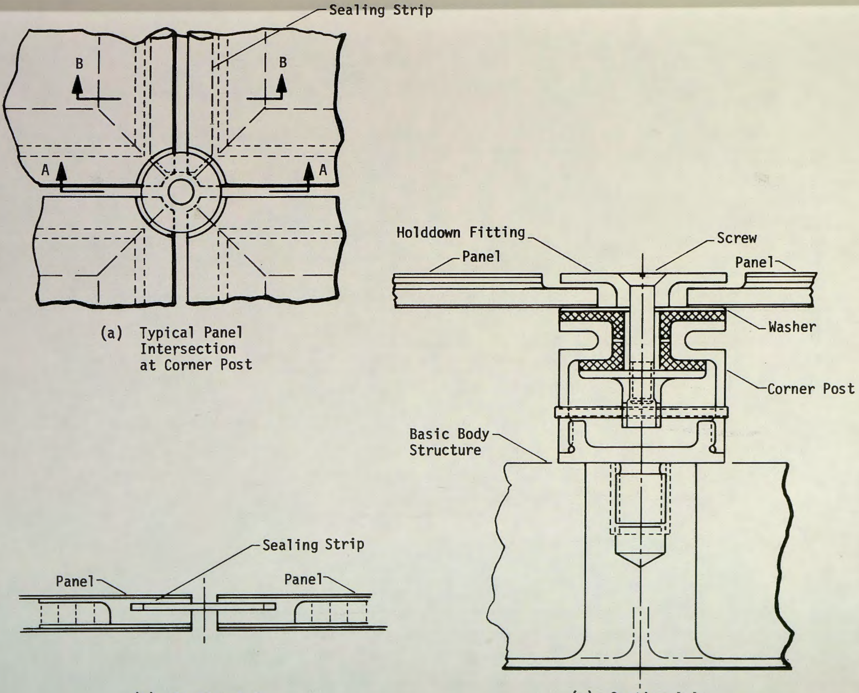


Figure 6 Edge-Supported Panel Rails

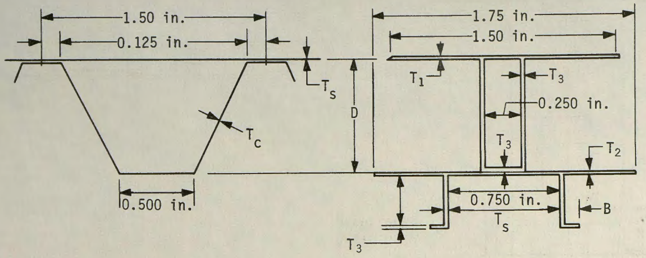


(a) Typical Panel Intersection at Corner Post

(b) Section B-B

(c) Section A-A

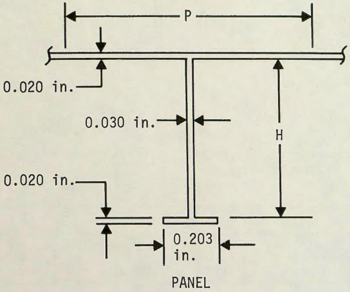
Figure 7 Typical Corner Post for Post-Supported Panel



PANEL SUPPORT

Material	Panel Configuration			Support Configuration					Unit Weight			Design Condition
	H (in.)	T_c (in.)	T_s (in.)	B (in.)	D (in.)	T_1 (in.)	T_2 (in.)	T_3 (in.)	Panel (psf)	Support (psf)	Total (psf)	
Ti-6Aℓ-4V STA at 850°F	0.500	0.008	0.010	--	0.563	0.030	0.030	0.030	0.472	0.296	0.768	Acoustics
Inconel 718 at 1350°F	0.625	0.008	0.010	--	0.125	0.030	0.030	0.030	0.926	0.530	1.156	Acoustics
René 41 at 1600°F	0.500	0.011	0.011	--	0.500	0.050	0.040	0.040	1.090	0.710	1.868	Acoustics
L-605 at 1800°F	0.750	0.014	0.012	0.125	0.625	0.060	0.060	0.050	1.627	1.009	2.636	Strength

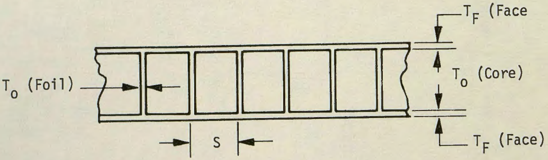
Figure 8 Summary of Skin-Corrugation Heat Shield Design Configurations



Support Configuration Similar to That for the Skin-Corrugation Heat Shield Panels

Material	Panel Configuration		Unit Weight			Design Condition
	H (in.)	P (in.)	Panel (psf)	Support (psf)	Total (psf)	
Ti-6Aℓ-4V STA at 850°F	0.410	1.000	0.810	0.296	1.106	Flutter Stiffness
Inconel 718 at 1350°F	0.340	1.120	1.265	0.530	1.795	Flutter Stiffness
René 41 at 1600°F	0.340	1.000	1.420	0.710	2.130	Acoustics
L-605 at 1800°F	1.040	1.500	2.030	1.009	3.039	Strength

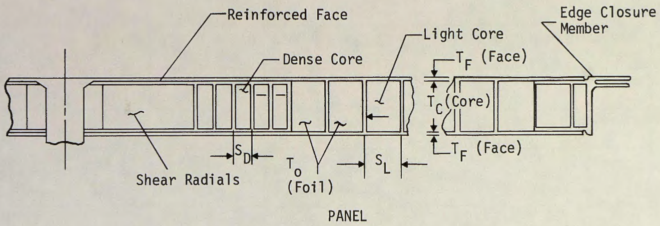
Figure 9 Summary of Skin-Stringer Heat Shield Design Configurations



Support Configuration is Similar to That for Skin-Corrugation Heat Shield Panels

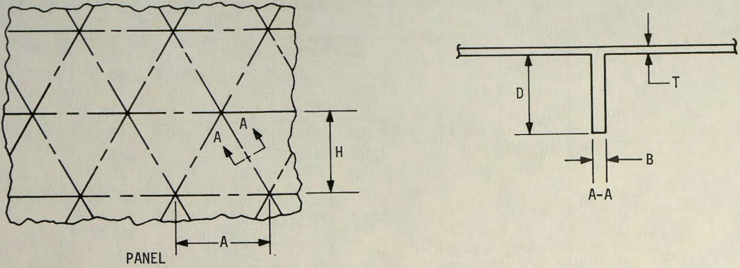
	Panel Configuration				Unit Weight			
Material	T_c (in.)	T_F (in.)	T_o (in.)	S (in.)	Panel (psf)	Support (psf)	Total (psf)	Design Condition
Ti-6Aℓ-4V Annealed at 850°F	3/8	0.008	0.002	7/32	0.569	0.284	0.853	Strength
Inconel 718 at 1350°F	5/16	0.008	0.002	9/32	0.991	0.499	1.490	Strength
Rene 41 at 1600°F	13/32	0.008	0.002	1/4	1.209	0.681	1.890	Strength
L-605 at 1800°F	13/16	0.009	0.002	5/16	1.590	0.968	2.558	Strength

Figure 10 Summary of Edge-Supported Honeycomb Sandwich Heat Shield Design Configuration



Material	Panel Configuration					Unit Weight			Design Condition
	T_C (in.)	T_F (in.)	T_0 (in.)	S_D (in.)	S_L (in.)	Panel (psf)	Support (psf)	Total (psf)	
Ti-6Aℓ-4V Annealed at 850°F	5/16	0.008	0.002	1/8	7/32	0.814	0.062	0.876	Strength
Inconel 718 at 1350°F	1/4	0.008	0.002	1/8	9/32	1.447	0.116	1.563	Strength
René 41 at 1600°F	5/16	0.008	0.002	1/8	9/32	1.515	0.133	1.648	Strength
L-605 at 1800°F	1/2	0.009	0.002	5/32	9/32	2.160	0.188	2.348	Strength

Figure 11 Summary of Post-Supported Honeycomb Sandwich Heat Shield Design Configurations



Material	Panel Configuration					Unit Weight			Design Condition
	A (in.)	B (in.)	D (in.)	H (in.)	T (in.)	Panel (psf)	Support (psf)	Total (psf)	
Ti-6Aℓ-4V STA at 850°F	2.89	0.030	0.435	2.50	0.021	0.890	0.062	0.952	Strength
Inconel 718 at 1350°F	2.89	0.022	0.414	2.50	0.020	1.540	0.116	1.656	Strength
René 41 at 1600°F	2.89	0.026	0.546	2.50	0.020	1.690	0.133	1.832	Strength
L-605 at 1800°F	2.89	0.030	0.990	2.50	0.020	2.370	0.188	2.558	Strength

Figure 12 Summary of Post-Supported Isogrid Heat Shield Design Configurations

Table 1 Properties of Selected Thermal Protection System Materials*

Alloy	Temperature (°F)	Density (lb/in.^{3})	F_{c_y} (ksi)	F_{t_u} (ksi)	E (ksi × 10^3)	Reference
Ti-6Aℓ-4V STA	RT	0.16	152	157	16.4	5
	500		105	126	14.4	5
	850		86.5	105	12.6	5
Ti-6Aℓ-4V Annealed	RT		132	134	16.4	
	500		95	109	13.9	
	850		80.5	88	11.3	
Inconel 718 1750°F Solution Treated & Duplex Aged	RT	0.297	150	180	29	6
	850		139	162	25.5	6
	1350		93	105	23	6
René 41 2150°F Solution Treated & 1650°F Aged	RT	0.298	90	130	31.6	5
	1350		82	108	23.1	5
	1600		64	80	21.2	5
						5, 7
L-605	RT	0.330	55	130	34.2	5
	1600		23.6	31	19.2	5
	1800		17.6	20.8	14.0	5
	2000		10.5	13	7.9	5

Table 2 Booster Metallic Heat Shield Unit Weights

Material		Unit Weights (psf)				
		Edge-Supported Configurations			Post-Supported Configurations	
		Skin-Corrugation	Skin-Stringer	Honeycomb	Honeycomb	Isogrid
Ti-6Aℓ-4V at 850°F	Panel	0.472	0.810	0.569	0.814	0.890
	Support	0.296	0.296	0.284	0.062	0.062
	Total	0.768	1.106	0.853	0.876	0.952
Inconel 718 1350°F	Panel	0.926	1.265	0.991	1.447	1.540
	Support	0.530	0.530	0.499	0.116	0.116
	Total	1.456	1.795	1.490	1.563	1.656
René 41 at 1600°F	Panel	1.090	1.420	1.209	1.515	1.690
	Support	0.710	0.710	0.681	0.133	0.133
	Total	1.800	2.130	1.890	1.648	1.823
L-605 at 1800°F	Panel	1.627	2.030	1.590	2.160	2.370
	Support	1.009	1.009	0.968	0.188	0.188
	Total	2.636	3.039	2.558	2.348	2.558

Table 3 Booster Metallic Heat Shield Unit Costs

Material	Unit Cost ($/ft²)				
	Edge-Supported (20x17-in.) Configuration			Post-Supported (20x34-in.) Configuration	
	Skin-Corrugation	Skin-Stringer	Honeycomb	Honeycomb	Isogrid
Ti-6Aℓ-4V	1016	1238	1205	824	738
Inconel 718	1208	1256	1280	848	813
René 41	1270	1385	1282	845	885
L-605	1052	1870	1217	816	1011

Table 4 Booster Metallic Heat Shield Program Cost

Material [Area (ft^2)]	*	Edge-Supported Configurations			Post-Supported Configurations	
		Skin-Corrugation	Skin-Stringer	Honeycomb	Honeycomb	Isogrid
Ti-6Aℓ-4V	W	8,950	12,850	9,930	10,200	11,100
[11,650]	C	95	139	118	85	82
Inconel 718	W	9,180	11,300	9,400	9,850	10,400
[6300]	C	61	76	65	47	49
René 41	W	11,150	13,200	11,700	10,200	11,300
[6190]	C	63	82	67	36	45
L-605	W	27,000	31,100	26,200	24,100	26,200
[10,250]	C	86	178	95	49	78

*W = Total Weight = Weight of Panel + Support per Booster (lb)
C = (Unit Cost x Area per Booster x Number of Sets) ± Delta Weight Value (Millions of Dollars)