N71-17770

NASA CR-111814

LOW COST ABLATIVE HEAT SHIELDS FOR SPACE SHUTTLES

By R. E. Dulak and A. M. Cecka

Prepared under Contract No. NAS 1-9947 by
FANSTEEL INC.-REFLECTIVE LAMINATES DIVISION
Newbury Park, California

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Fansteel Inc.-Reflective Laminates Division

SUMMARY

Ablative heat shields provide reliable and efficient thermal protection for entry vehicles. However, the present high cost and single-mission life of the heat shields impose a constraint on their application to reuseable logistic vehicles. Therefore, low cost ablative systems must be developed to make them feasible for the Space Shuttle.

Cost reductions can be achieved through the use of materials, tooling and methods that provide for ease of fabrication and require fewer man-hours of labor. Actual fabrication of full-size panels provides a basis for realistic cost estimates of heat shield production.

This approach was investigated in a study of two ablation material systems and a honeycomb panel configuration designated by the National Aeronautics and Space Administration. One material was a phenolic/nylon/Microballoon powder system. The other was a silicone elastomer/Microballoon mixture. Each material was prepared to produce nominal panel densities of 15 and 27½ lb/ft^3. The ablation materials were applied to 1/4 and 3/8 inch cell size fiberglass reinforced phenolic honeycomb cores bonded to fiberglass/epoxy resin face sheets. One flat and one curved panel was fabricated from each material combination for a total of eight panels. Production cost estimates were prepared from the cost data and suppliers material prices.

Fabrication of the honeycomb panels by the one-step cure and primary bond method was successful. The ablation materials were mixed and sifted with conventional equipment. The ¼ inch core was successfully filled with the phenolic/nylon powder system. However, a minimum of 3/8 inch cell size was required for application of the elastomeric material.

INTRODUCTION

Ablative heat shields have provided thermal protection for reentry of ballistic missiles and spacecraft from the inception of space flight to the present. The high degree of reliability of ablative systems was successfully demonstrated in the Gemini and Apollo programs. Ablative materials are a promising approach for Space Shuttles and the National Aeronautics and Space Administration is conducting studies on several candidate materials.

Because of the sacrificial function of ablative heat shields their usefulness is expended in a single mission. Due to limited production and the specialized nature of the application, their costs are high. Application on reusable logistic vehicles would require replacement of the heat shield after each flight. Therefore, to be economically feasible, the present high cost of heat shields must be greatly reduced.

Research on low-cost ablative heat shields involves the following steps:

A. Selection of materials for ease of fabrication while meeting all reliability and performance requirements.

B. Optimization of fabrication methods and processes for the least number of operations and the lowest manpower expenditure.

C. Design of tooling to simplify the fabrication process.

D. Fabrication of full-size heat shield panels simulating large quantity production to arrive at realistic cost estimates.

The work reported here was undertaken to determine the cost of fabricating replaceable ablative heat shield panels and to prepare production cost estimates based on actual experience. To meet the objective of this effort, experimental subscale-size panels were fabricated during the analytical phase of the program for evaluation of the handling characteristics of the ablation materials. Then, eight panels were fabricated in support of the manufacturing cost study. Two ablation material compositions, each in two densities, were used to fill the cells of prefabricated honeycomb panels. These panels were delivered to the National Aeronautics and Space Administration, Langley Research Center.

All panels met the density specifications. However, difficulties in varying degrees were encountered with the selected hand-filling methods. Additional work is recommended to solve the problems or to demonstrate required manufacturing process modifications.

I. TOOLING

The tooling used in the manufacture of the ablative heat shield panels consisted of one flat and one curved mold each with a detachable frame cavity and pressure plate (see Figures 1 and 2).

The mold base was fabricated from ½ inch thick plate. The removable frame comprised 2½ inch high by 1½ inch wide rails bolted and doweled to the base plate to form a 24 inch by 48 inch cavity for producing panels to the final dimensions without trimming. The pressure plate was made from .09 inch thick sheet with sufficient clearance to fit freely in the mold cavity. All of the mold materials were 6061-T6 aluminum.

Each mold was supported on a mild steel stand. A geared mechanism incorporated in the stand provided for rotation of the curved mold.

Drill bushings were located in the mold base plate for drilling the attachment hole patterns in the heat shield panels.

II. HEAT SHIELD FABRICATION

A. Configurations and Materials

Two ablative materials systems were used to fabricate the heat shield panels. One system was a powder composed of phenolic, nylon and Microballoons (very small hollow phenolic spheres). The other system was an elastomeric composition of liquid silicone resin and Microballoons.

Each system was fabricated in two densities. Two panels, one flat and one curved, were made of each material in each density. Each panel was approximately two (2) by four (4) feet by two (2) inches thick. The radius of curvature for the curved panels was 24 inches.

The configurations consisted of a full depth non-metallic honeycomb, bonded to a non-metallic face sheet and filled with ablative material. The honeycomb was bonded to the face sheet before the ablative material was applied to allow visual inspection of the bondline. The bond between the honeycomb and face sheet provided sufficient strength to support a one (1) psi tensile load normal to the bondline at 300°F.

Provision was made for six (6) panel attachment points using a stud-nut fastener. Holes were drilled in the face sheet to accept a ¼ inch stud. The ablative material was cored out to a diameter of 3/4 inch to accomodate the nut attachment. Plugs of ablation material were supplied to fill the 3/4 inch holes.

The ablative materials, the constituent proportions for each system, and the allowable overall densities for each composition are listed in Table 1.

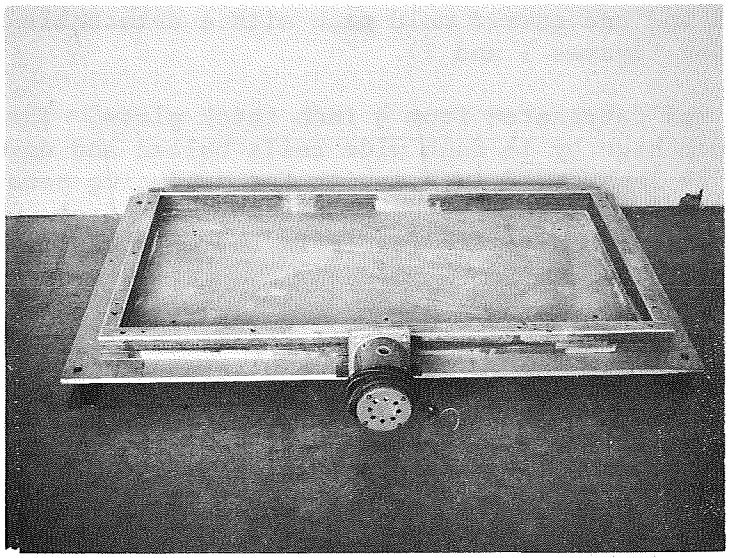


Figure 1. Mold for Flat Panels-Vibrator Attached

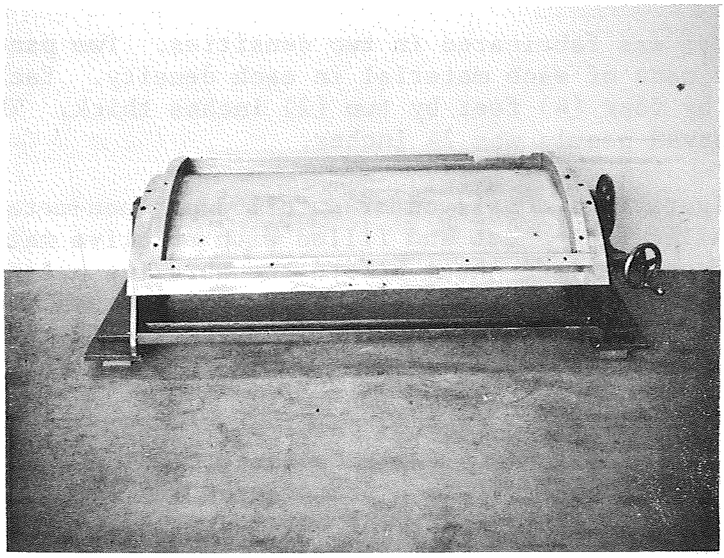


Figure 2. Mold for Curved Panels

TABLE 1.

ABLATIVE MATERIAL COMPOSITIONS

Material System	Composition	Percent by Weight
13-17 lb/ft^3 Phenolic/nylon	BRP-5549 B-stage Phenolic (a)	15
	Polypenco 66-D Nylon (b)	15
	BJO-0930 Microballoons (a)	70
25-30 lb/ft^3 Phenolic/nylon	BRP-5549 B-stage Phenolic	50
	Polypenco 66-D Nylon	50
13-17 lb/ft^3 Elastomeric	Sylgard 182 Silicone resin plus hardener (c)	20
	BJO-0930 Microballoons	80
25-30 lb/ft^3 Elastomeric	Sylgard 182 Silicone resin plus hardener	67
	BJO-0930 Microballoons	33

(a) Product of Union Carbide

(b) Product of Polymer Corporation

(c) Product of Dow Corning, mix ratio of resin to hardener is 10:1

The material used for the face sheet was an epoxy impregnated 120 style fiberglass. The material designation was Narmco 500/120 produced by Whittaker Corporation. The face sheet was a 3-ply isotropic layup. The warp direction of the plies was positioned -60°, 0°, and +60° to the longitudinal axis of the heat shield.

Two basic types of honeycomb were used in the heat shields - a ¼ inch cell nylon/phenolic (NP) impregnated fiberglass material and a 3/8 inch cell heat resistant phenolic (HRP) impregnated fiberglass material. Both materials are products of Hexcel Corporation designated as NP-¼-4.0 for the ¼ inch cell material and HRP 3/8-3.2 or HRP-OX3/8-2.7 for the 3/8 inch cell material. The OX signifies an "over-expanded" condition while in all cases, the number following the fraction signifies the core density in pounds per cubic foot. The honeycomb materials selection (e.g. nylon/phenolic vs heat resistant phenolic) was made primarily on the basis of material availability at the time of performance of work under this contract and did not have any bearing on the fabrication process unless otherwise discussed in the report.

B. Face Sheet to Honeycomb Bonding

The face sheet and honeycomb core panels for the ablative heat shields were assembled by a one-step primary bond and cure process. Excellent core to sheet adhesion was obtained and the face sheet quality was good for all panels.

The surfaces of the mold base plate and the disassembled rails were cleaned with MEK and coated with RAM 225 release agent. The drill bushing holes were filled with plaster and sealed from the bottom side of the plate. The epoxy/glass cloth pre-preg was layed up on the plate into an isotropic laminate and all air and wrinkles were rubbed out (see Figure 3).

The lay-up for the first three panels was trimmed to net size by positioning the rails and trimming the lay-up to the rail edge. This was intended to eliminate any final trimming of the face sheet after cure. The resulting lay-up tended to blister or curl up at the edges because of the lack of pressure in the open cell areas. Also inaccuracy of the trimming produced uneven facing edges. Consequently it was necessary to dress the face sheet edges after cure. The net trim of the face sheet lay-up was discontinued and the remaining panels were produced with oversize face sheets requiring final trim after honeycomb bonding.

In all cases, the honeycomb core used to produce the heat shield panel was trimmed to net size (see Figure 4). The core was positioned onto the face sheet lay-up after mounting of the rails on the base place, as shown in Figures 5 and 6. A ply of bleeder fabric was layed over the core and the assembly was bagged with nylon film sealed to the mold with zinc chromate putty. A vacuum pressure of 25 inches Hg was applied and the assembly checked for leaks.

All panels were cured for 30 minutes at 200°F and 60 minutes at 250-260°F.

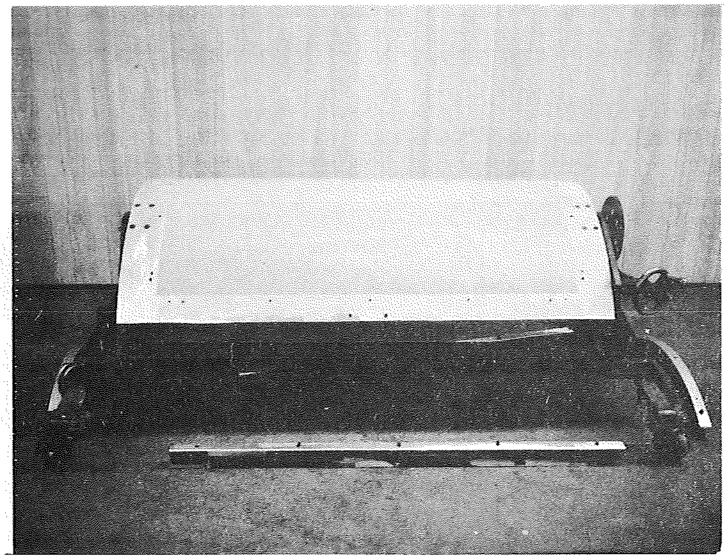


Figure 3. Face Sheet Lay-up Prior to Mounting of Rails

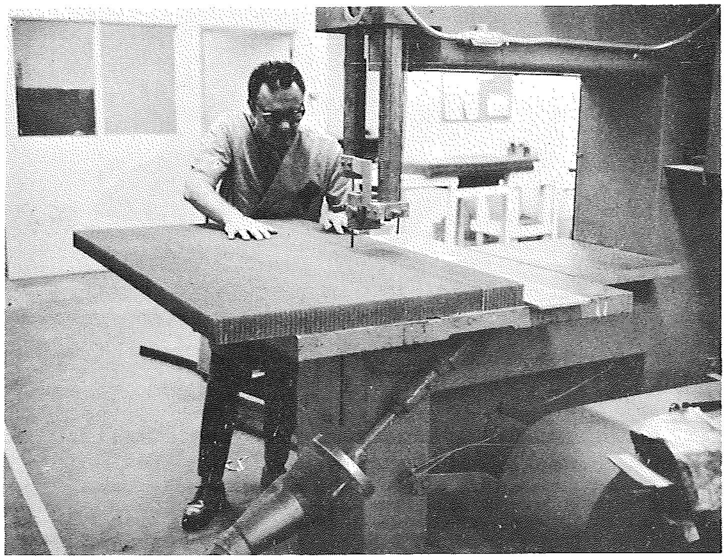


Figure 4. Bandsawing of ¼ inch Cell Honeycomb

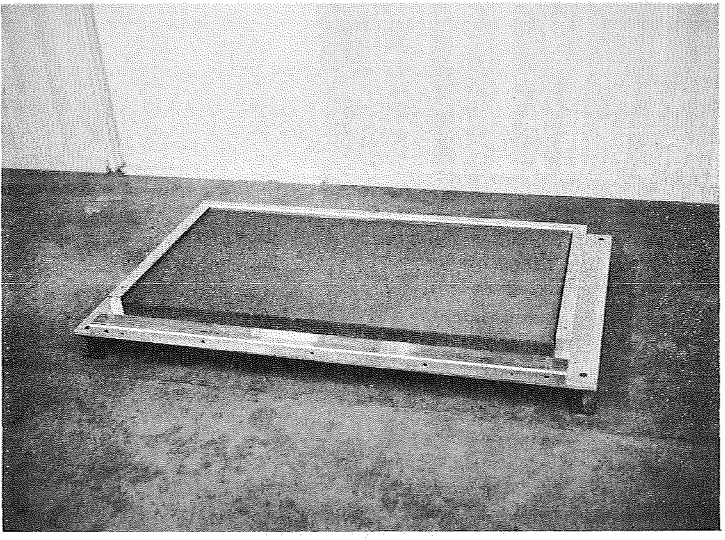


Figure 5. Honeycomb Positioned onto Face Sheet Lay-up

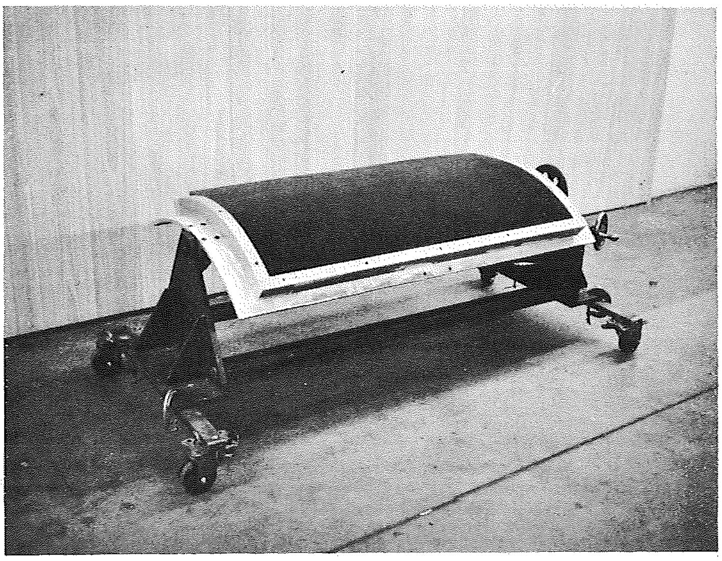
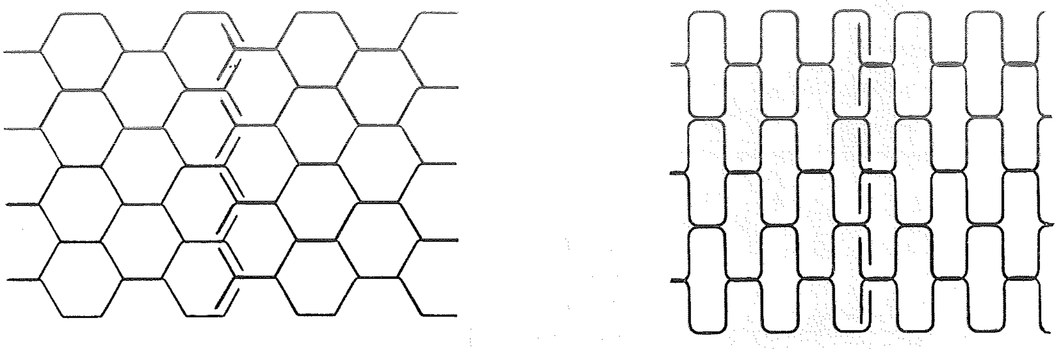


Figure 6. Curved Panel Honeycomb and Face Sheet Ready for Bonding



STANDARD
CELL DESIGN

OVER-EXPANDED
CELL DESIGN

Figure 7. Interlock Nesting of Honeycomb Cells Splice Technique

The flat panels were cured in an air circulating oven using only vacuum pressure. It was necessary to cure the curved panels in an autoclave at 80 psi to insure a uniform bond of core to face sheet. First attempts in curing of curved panels using only vacuum pressure resulted in unbonded areas. This was attributed to the vacuum pressure being insufficient to remove any nonconforming areas of the core curvature relative to the mold surface curvature.

The ¼ inch cell core used for the curved panels was obtained from the supplier heat formed into the curved condition. The 3/8 inch cell core for curved panel application was the OX type which conformed to the curved surface of the panel lay-up.

All ¼ inch cell panels were of one piece core construction. The flat 3/8 inch cell panels had a core splice running over the full width of the panel approximately eleven (11) inches from one end. The curved 3/8 inch cell panels had two core splices running over the length of the panel. One splice was located approximately three (3) inches from one side and the other splice ten (10) inches from the first.

The splice technique used was an interlock nesting of the cell walls which were bonded with 3M1357 contact adhesive prior to bonding of the core to face skin (see Figure 7). This method of splicing was selected because it made possible a core splice that did not significantly reduce the original cell size nor result in a splice seam of a material that was not of the ablative composition. Reduction of cell size would have been detrimental to the material filling process while a conventional core splicing adhesive would introduce a foreign material into the heat shield.

The cells of all the bonded honeycomb panels were primed with SC1008 phenolic resin, a product of Monsanto. The resin was diluted to a solid concentration of 35 to 45 percent with isoprophyl alcohol. The cells were coated by pouring the resin solution into the cells, then inverting the panel and allowing the excess resin to drain.

The panel was then placed into an air circulating oven and the resin coating dried at 170°F for 60-90 minutes. This process staged the coating by removing all volatiles and leaving a "tack-free" uncured resinous surface.

Resin pick-up was nominally 500 gms for the ¼ inch cell panels and 300 gms for the 3/8 inch cell panels.

C. Mixing Ablative Materials

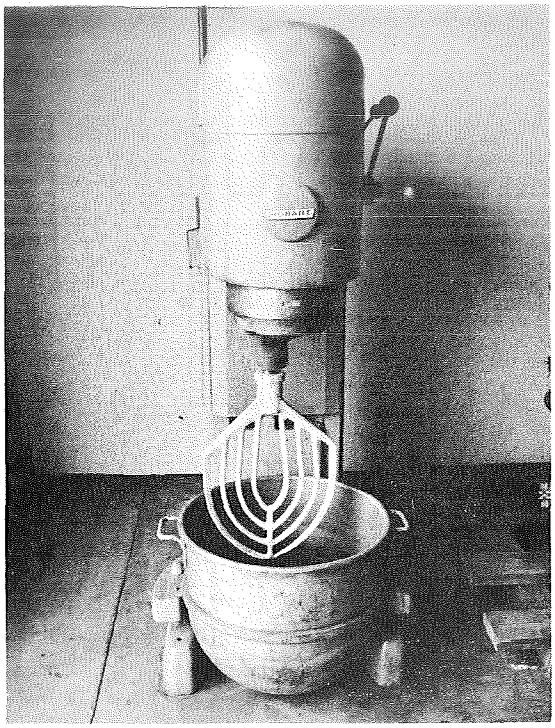


Figure 8. Hobart Planetary Mixer

All four ablative material systems were mixed in a Hobart Model No. M-802 mixer using a multi-fluted mixer blade (see Figure 8). This is a planetary type of mixing machine and operates with a ratio of 2¼ revolutions of the mixing blade to one revolution of the planetary spindle. All compounds were mixed at a rate of 25 revolutions per minute of the planetary spindle.

Mixing the phenolic/nylon powder systems was accomplished by adding the required proportions of the constituent materials into the Hobart mixer and mixing for 20 minutes (see Figure 9). The ablative compound after being thoroughly blended, was then sifted through a 40 mesh screen in a Sweco Vibro Energy Separator, Model No. LS24S44, operating at a speed of 1200 revolutions per minute (see Figure 10). The particles of phenolic which had not been dispersed during the mixing operation were broken up at this time. At the end of the sifting operation some particles of nylon would not pass through the 40 mesh screen. The sifted mixture plus the remaining nylon particles were then returned to the Hobart mixer for a final blending of approximately 15 minutes.

Mixing the liquid silicone resin and Microballoon systems was accomplished by placing the premixed resin and hardener into the Hobart mixing container and then gradually adding the sifted Microballoons while continuously blending the mixture. After the Microballoons were added, thorough blending of the materials was performed by mixing for 20 minutes.

The Microballoons required for the various ablative compositions were dried in an air circulating oven at 210°F for two (2) hours. This step was

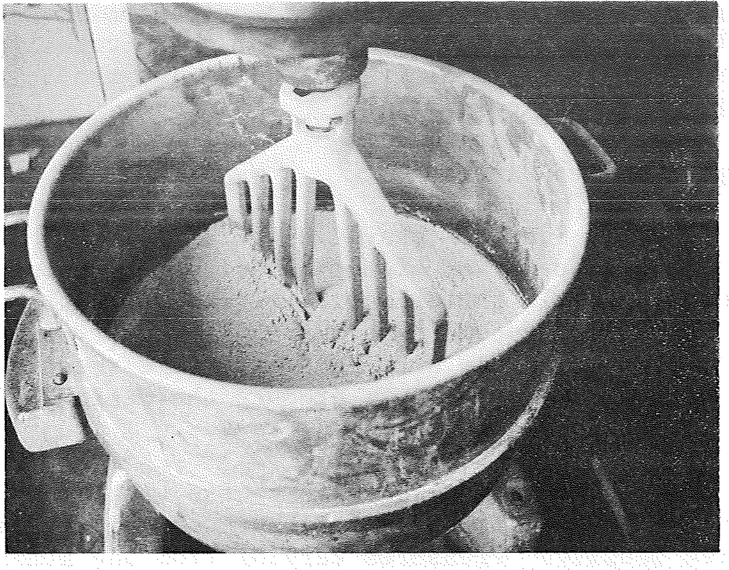


Figure 9. Mixing of High-Density Phenolic/Nylon Material

Figure 10. Sweco Separator

incorporated into the process as a result of tests which indicated a moisture content as high as 5% in the Microballoons when received from the supplier. The presence of moisture gave the Microballoons a tendency to pack into clumps. When dried and sifted through the 40 mesh screen, the Microballoons had a loose and fluid characteristic which was desirable for mixing the ablative compositions and for filling the honeycomb cells.

D. Filling Honeycomb Panels

Twenty-six (26) subscale panels were fabricated to evaluate the handling and filling characteristics of the ablation materials. Properties of interest were the material bulk factor, cure shrinkage, density uniformity, fill rate and compaction. Honeycomb panels of ¼ inch cell size, ranging in size from 6 x 6 inches to 12 x 12 inches were bonded to face sheets. A pre-weighed charge of ablation material calculated to produce the desired finished panel density was loaded into the panel.

The phenolic/nylon powder specimens were vibrated to induce settling of the material into the honeycomb cells. Subsequent compaction under pressure produced the required density. Pressures varying from one atmosphere to 100 psi were investigated and 100 psi was selected for the full scale panel fabrication. Panels filled without vibration or those compacted at lower pressures had a high incidence of voids and, in some cases, had low density. Satisfactory cure was obtained under one atmosphere of pressure after completion of the compaction cycle. Shrinkage of the phenolic resin did not result in separation if the honeycomb cells were first coated with resin. The bulk factor was manageable and reproducible. Therefore the material overfill that can be compacted into the cells can be readily determined and uniform density panels, requiring a minimum amount of final surface dressing, can be produced.

The elastomeric specimens fabricated from ¼ inch cell size honeycomb could not be filled without voids. Several techniques were tried including hand troweling followed by compaction under pressure up to 200 psi and evacuating the air from the cells prior to filling under pressure. It was concluded the frictional resistance of the compacted material "plug" was excessive for the 2 inch cell depth. Therefore the honeycomb cell size was changed to 3/8 inch which was filled satisfactorily. The fill method selected for the full size panels consisted of hand troweling and applying a compaction pressure of 100 psi during the first four hours of the cure cycle. The cure was completed under one atmosphere of pressure. The desired density values and uniformity were achieved. The bulk factor was manageable and reproducible facilitating density control and eliminating major panel surface dressing.

1. Low-density phenolic/nylon system

The ¼ inch cell honeycomb was used to fabricate the low-density phenolic/nylon panels. The filling procedure for both panels was the same except for the axial rotation of the curved panel into a vertical cell position.

The resin coated panel was placed on the mold base plate and the rails were mounted to form the cavity. The panel was held in contact with the base plate by using double-sided adhesive tape around the panel periphery.

The pre-mixed and pre-weighed powder material was then poured directly into the cells until the total panel area was covered. One-half of the arc area of the curved panel was filled first while the honeycomb cell columns were positioned in a nominally vertical plane. The panel was then rotated to position the cell columns of the second half of the area into a nominally vertical plane before filling. The weight of the charge was based on a final panel density of 15 lb./ft^3 for both panels.

Due to the bulk factor and the electrostatic adherence of the material to the cell walls, it was necessary to vibrate the mold assembly to induce settling of the compound. This was done initially on the flat panel using a portable pneumatic vibrator which operated at a frequency of 4000 vibrations per minute with a low (approximately .010 inch) amplitude. This vibration technique worked to a degree, but was not sufficient to completely settle the compound into the cells. Furthermore, the procedure was very slow and, after the settling ability was expended, separation of the phenolic and nylon particles from the Microballoons was initiated.

When it became evident that particle separation was beginning to occur, this method of vibration was discontinued. The material was then further settled by a high amplitude vibration or shock technique, accomplished by jarring the mold in a vertical plane. The ablation material which had essentially reached a stagnation point of entry under low amplitude vibration readily settled deeper into the cells with no visual evidence of particle separation.

Filling the curved panel was done by using only the shocking technique for settling the material. In this case, it was necessary to cover the first one-half segment filled with a heavy fabric blanket to prevent unsettling of material while filling the second half.

After filling the cells of each panel using vibration, some material remained above the cells due to the residual bulk factor. This material was spread evenly across the cell surface to a depth of approximately 3/16 inch. Two plies of bleeder cloth were layed over the surface of the material and the pressure plate was positioned. The assembly was sealed in a vacuum bag. A vacuum of 25 inches Hg was applied and the panel was placed into the autoclave.

The final step in the filling procedure was to pressurize the bagged assembly in the autoclave at 100 psi to compact the material into the cells. The pressure cycle consisted of a 5-7 psi per minute pressure rise with a final dwell at 100 psi for 10 minutes. The pressure was released and the assembly removed from the autoclave. It was then placed into an air circulating oven while remaining under vacuum and the cure cycle was started.

2. High-density phenolic/nylon system

The high-density phenolic/nylon heat shields were also made with ¼ inch cell honeycomb.

The filling procedure was basically the same as that described in the preceding section. This ablative composition, also a powder system, differed in handling characteristics from the low-density phenolic/nylon material. While the low-density phenolic/nylon system was loose and fluid, the higher density system had a self-adherent, free-standing nature.

When poured on the honeycomb panel the material had a tendency to support itself in mounds above the cells (see Figure 11). The material was troweled across the cell surface to break up the mounds. The resistance of the mixture to settling into the cells was greater than for the lower density composition apparently due to the higher bulk factor and electrostatic adherence to the honeycomb cells (see Figure 12). This material characteristic combined with the greater friction of the inclined cells in the curved panel is believed to have contributed to the difference in the densities of the flat and curved panels. The curved panel density is approximately 6% less than that of the flat panel, whereas the densities of the curved and flat panels of the low-density composition are virtually the same. An increase in density could probably have been achieved by filling a smaller section of the arc (1/4 or 1/3 of the arc length) at one time instead of one-half section of the panel.

The material which did not enter the cells of the flat panel was spread evenly across the surface. Two plies of bleeder cloth and the pressure plate were applied over the compound and hand pressure was applied to the plate. The bleeder and plate were removed for examination of the fill. The material above the honeycomb had compacted to a depth of .30 inch above the cells (see Figure 13). The bleeder cloth and pressure plate were re-applied and the assembly was bagged and vacuum drawn. The flat panel assembly was then subjected to the 100 psi autoclave pressurization cycle as described in the preceding section, after which it was placed into the oven for cure.

The overfill material on the curved panel was spread across the cells (Figure 14) and the assembly bagged and pressurized in the autoclave in the same manner as the flat panel. Before proceeding to cure, the assembly was removed from the vacuum bag and the results of pressurization were observed (see Figure 15).

The material remaining above the cells was in a compacted state with a depth of approximately .10 inches. This material was removed and weighed to determine if the material in the cells was sufficient to produce the required density. Calculations indicated that the density would be approximately 25.6 lb/ft^3. Part of the material which had been removed was replaced and spread evenly across the surface of the panel. This was done so that sufficient material would be available to completely fill the honeycomb cells when the panel was again compacted during the final vacuum bag cure. Removal of some of the material (see note - Table 2) remaining above the cells after initial compaction eliminated the need for the major surface dressing of the curved panel which was

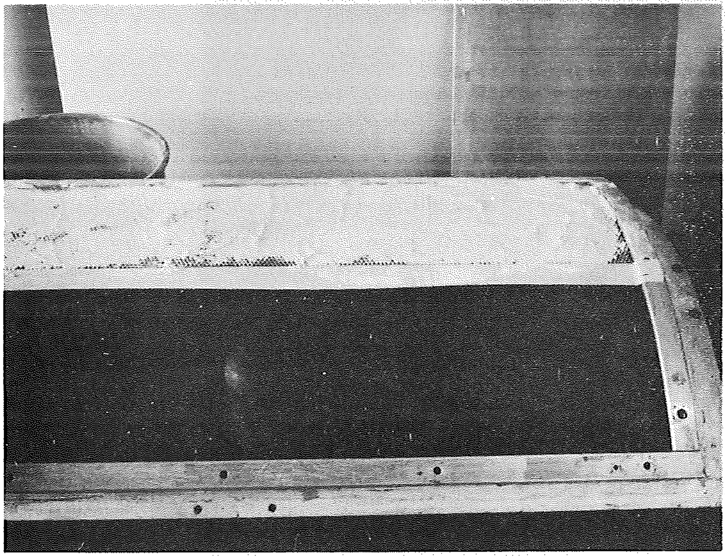


Figure 11. Filling of High-Density Phenolic/Nylon Curved Panel

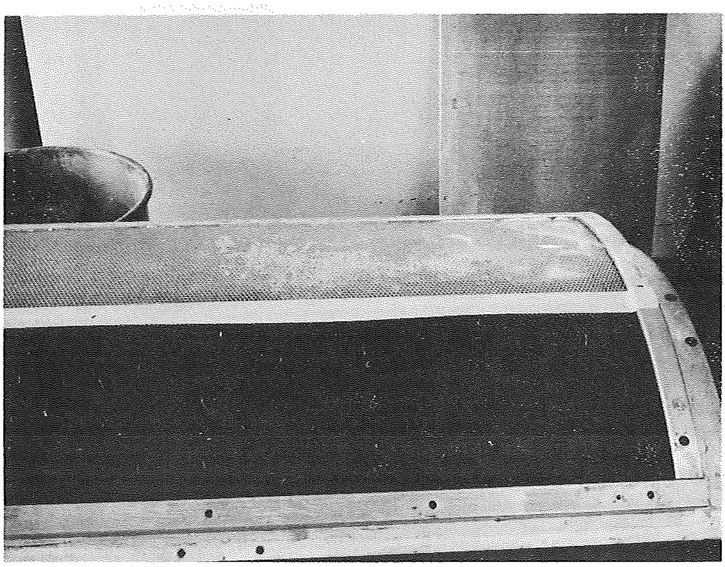


Figure 12. Same View as Figure 11-After Material Settled by Vibration

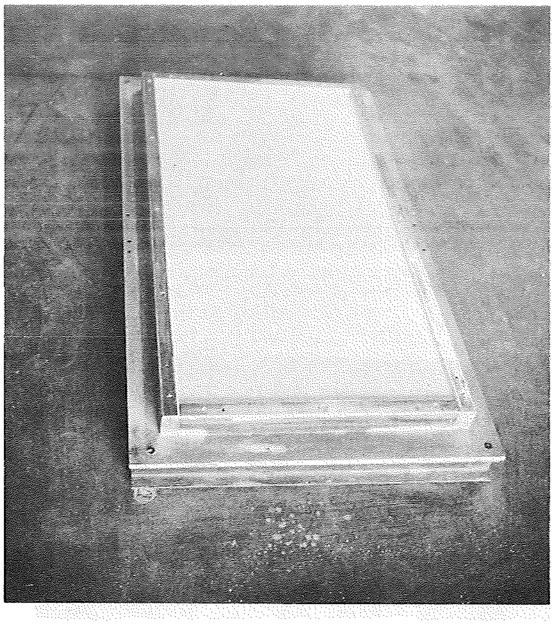


Figure 13. High-Density Phenolic/ Nylon Flat Panel After Filling

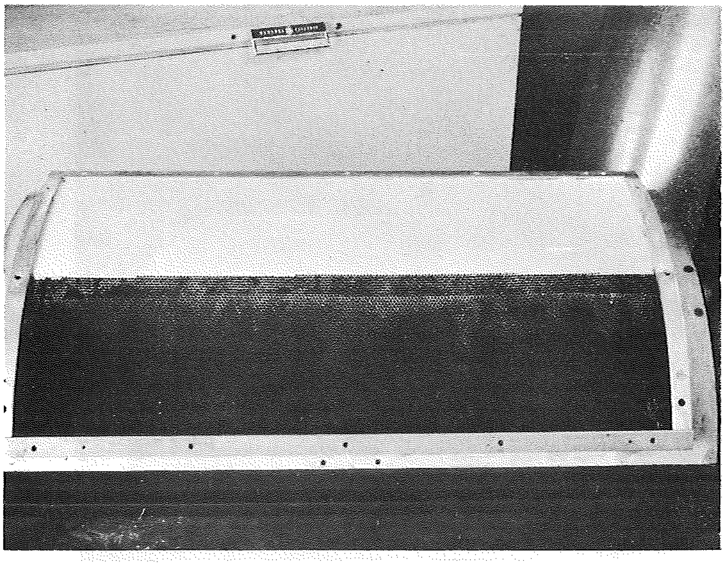


Figure 14. High-Density Phenolic/ Nylon Panel-One-half Section Filled

required on the flat panel as discussed in Section II F.

3. Low-density elastomeric system

The low-density elastomeric panels were made with 3/8 inch cell honeycomb. The standard cell type was used for the flat panel and the over-expanded (OX) type for the curved panel. The panel was placed on the mold base plate and the rails were mounted to form the cavity. Unlike the phenolic/nylon panels, it was not necessary to adhere the panel to the base plate because vibration was not required to fill the cells.

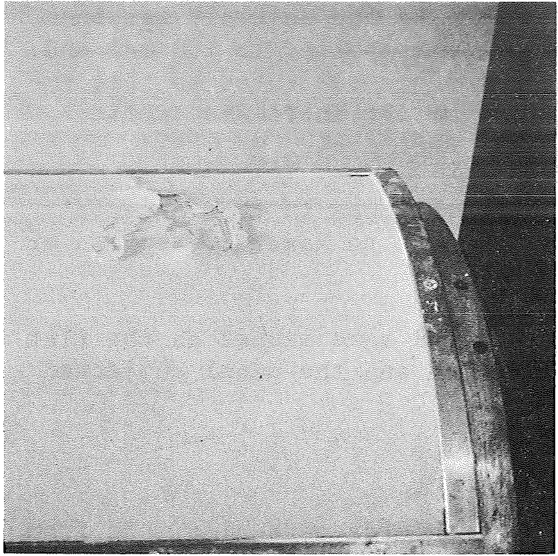


Figure 15. High-Density Phenolic/ Nylon Panel After 100 psi Cycle

The pre-mixed ablative compound was hand troweled and pressed into the honeycomb cells. The total area of the panel was worked uniformly to assure an even fill. The remaining mixture was rolled evenly across the top of the cells with a 3 inch diameter roller. Original attempts to spread the material using a template were unsuccessful due to the self-adherent nature of the material.

The depth of the material overfill on the flat panel prior to the pressurization cycle was approximately ¼ inch. For the curved panel, the overfill was approximately 5/8 inch deep. The main reason for this difference is that the flat panel material charge was calculated on a basis of 15 lb/ft^3 nominal density whereas the curved panel was calculated for the 17 lb/ft^3 maximum density. This increase was a precautionary measure to preclude the possibility of incompletely filled cells because of non-uniform honeycomb expansion. The cell shape of the OX core used for the curved panel tended to be closed or "necked-down" when compared with the standard hexagon type cell. In some sections the cells were overexpanded to such a degree that the open area was approximately one-half the width of the uniform cells. These conditions resulted in greater resistance to entry of the material when compared to the standard 3/8 inch cell core.

When fabricating the flat panel, the overfill material was rolled evenly over the surface, two plies of bleeder fabric were applied, the assembly bagged with nylon film and vacuum drawn. Then the assembly was placed into the autoclave and subjected to a 10 minute dwell at 100 psi after a pressurization rate of 5-7 psi per minute. After completing the pressure cycle, the assembly was removed from the autoclave and the bag and bleeder removed. The ablation material above the cells was observed to have partially entered the cells but in an uneven pattern. This variation of compaction is attributed to the non-uniformity of filling by hand troweling. The excess material originally ¼ inch deep, was re-rolled evenly to a depth of approximately 1/8 inch. The bleeder fabric and the pressure plate were reapplied and the assembly was then bagged and again placed in the autoclave. Pressure was applied to 100 psi and the autoclave temperature raised to 200°F. The panel was subjected to this cycle for four (4) hours after which it was removed from the autoclave, while under vacuum, and placed in an oven to complete the cure cycle.

Due to the resilience of the Microballoons in this material system, it was necessary to initiate cure under pressure to assure retention of maximum compaction in the honeycomb cells.

The curved panel was processed in the same manner as the flat panel except the initial pressure cycle was eliminated and the panel subjected directly to the pressure and 200°F cure cycle.

4. High-density elastomeric system

The high-density elastomeric heat shields were also made from 3/8 inch cell honeycomb panels. The standard cell type was used for the flat panels and the overexpanded (OX) type for the curved panels. The filling procedure used for both the flat and curved panels was the same as that described for the low-density elastomeric panels.

The first panel produced was the flat configuration. The material charge was based on a nominal density of 27½ lb/ft^3. The amount of overfill was approximately 1/8 inch deep. Observing the flat panel after the cure cycle, it was noted that the nominal material charge was totally accepted by the cells except for a small area around the panel periphery.

Based on the same reasoning as was stated for the low-density panels, the material charge for the curved panel was increased to the maximum 30 lb/ft^3 density. Despite this increase in material charge weight and the condition of the over-expanded cells, all except approximately 1/8 inch of material entered the cells by the hand troweling process (see Figures 16 and 17).

Both panels were processed after filling using the same procedure described for the low-density curved panel, that is, subjected directly to the pressure/200°F cure cycle.

E. Curing

The phenolic/nylon panels were cured in an air circulating oven under a vacuum pressure of 25 inches Hg for 16 hours at 300°F. The initial part of the temperature cycle was a stepwise increase and with dwell times as follows:

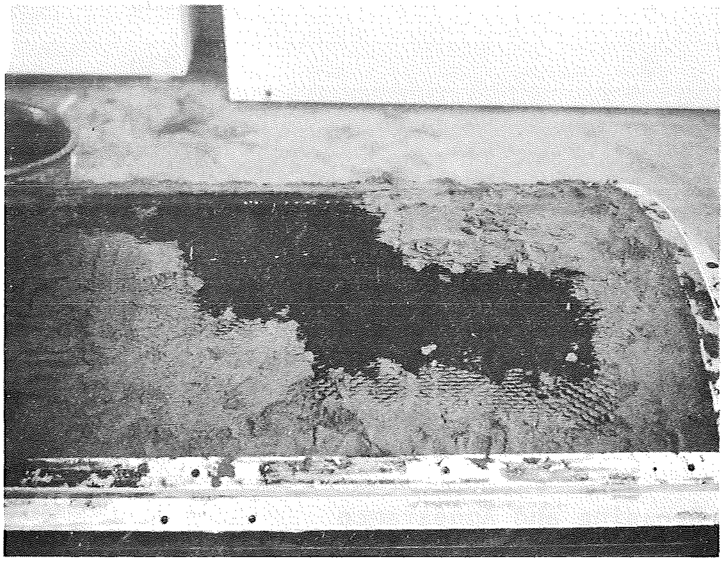


Figure 16. Partially Filled High-Density Elastomer Panel

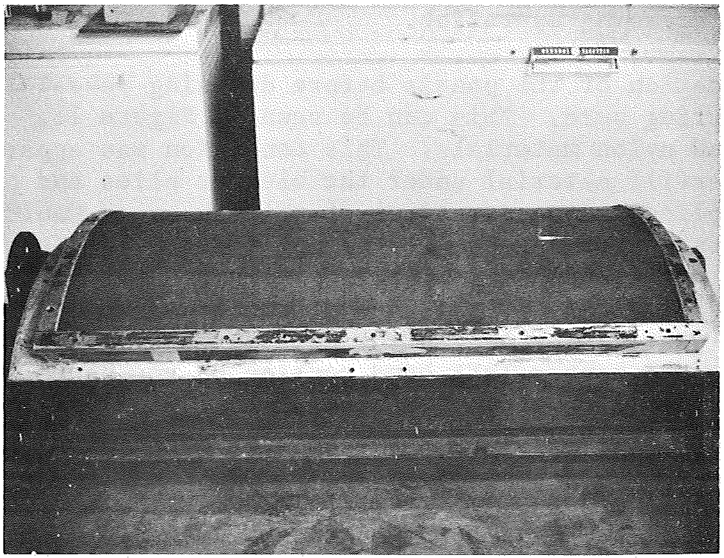


Figure 17. High-Density Elastomer Panel After Filling

Time, Hours	Temperature, °F
2	180
3	230
3	280

The temperature was then increased to 300°F at ½°F per minute. The panels were cooled to 120°F maximum prior to releasing the vacuum pressure.

The first four (4) hours of the cure cycle for the elastomeric panels took place in an autoclave at 100 psi and 190-210°F while a vacuum pressure of 25 inch Hg was maintained on the panels. After this step, the panels were removed from the autoclave under vacuum and transferred to an oven. The balance of the cure was continued for 20 hours at 180°F. After completion of cure, the panels were colled to 120°F under vacuum.

F. Final Dressing and Appearance

All heat shields required surface dressing to some degree. The methods of dressing were varied. The amounts of excess material which were removed by dressing are listed in Tables 2 and 3.

The obvious characteristic of the low-density phenolic/nylon heat shields was the extreme fragility of the cured ablation material. This created a problem from both the surface dressing and handling standpoints. The slightest contact of the panel against hard objects tended to break or crush the material. Even though caution was excercised, the top edges of the panel tended to chip during the dressing operation.

Examination of the panels before dressing revealed evidence of material migration during cure. This can be seen in Figure 18. The light areas are the phenolic and nylon materials. This condition was apparently caused by movement of the overfill material under the bleeder plies and pressure plate when vacuum was applied. Concentrations of whitish areas would appear to be the result of the separation of the heavier phenolic and nylon material from the Microballoons while the material was migrating. There were several areas on both the flat and curved panels where the vacuum induced migration resulted in voided cells along the panel edges and on the cell surfaces. The rivulet appearance of the dark area in the center left hand section of the panel shown in Figure 18 was caused by severe erosion of the material during migration, or by massive air flow such as could be present with a leaking vacuum seal (see Figure 19 for close-up). The maximum depth of the voids was approximately 1/16 inch.

Surface dressing of the low-density phenolic/nylon panels was accomplished by shaving off the excess material using a sharp bevel edged putty knife. The tool was held at a low angle with the bevel edge away from the surface and moved slowly while riding on top of the cell surface. As was stated earlier, it was difficult to prevent chipping the panel edges when dressing the

TABLE 2.

PHENOLIC/NYLON HEAT SHIELD DATA
TWO (2) x FOUR (4) FOOT PANELS

				Wt. (gms) of		Wt. Loss (gms) by	
Density/Type	Final Density (lb/ft^3)	Net Vol.(ft^3)	Final Wt. (gms)	Coated Panel	Material Charge	Dressing	Mixing/ Filling/Curing
Low Flat	13.92	1.333	8,425	3230	5,790	148	447
Low Curved	14.15	1.282	8,235	3291	5,790	176	669
High Flat	27.32	1.333	16,533	3398	13,640	350	155
High Curved	25.16	1.282	14,642	3315	12,700	100	1273*

*Of this amount, 550 gms of mixture was discarded prior to cure because of overfill.

TABLE 3.

ELASTOMERIC HEAT SHIELD DATA
TWO (2) x FOUR (4) FOOT PANELS

				Wt. (gms) of		Wt. Loss (gms) by	
Density/Type	Final Density (lb/ft^3)	Net Vol.(ft^3)	Final Wt.(gms)	Coated Panel	Material Charge	Dressing	Mixing/ Filling/Curing
Low Flat	15.01	1.333	9,084	2627	6,560	62	41
Low Curved	14.21	1.282	8,275	2370	7,520	1195	305
High Flat	26.60	1.333	16,100	2530	14,110	40	300
High Curved	29.35	1.282	17,085	2350	15,100	15	350

ablative surface.

Figure 18. Phenolic/Nylon Migraion, Low-Density Panel

In order to protect the fragile surfaces of the low-density phenolic/nylon panels, an application of a dilute solution of Monsanto SC1008 phenolic resin and isoprophyl alcohol was made by spraying. The panels were then heated in an oven at 180°F for 90 minutes to stage the resin. This coating served as a surface material binder to a depth of approximately 1/32 inch and helped to protect the material during handling.

The high-density phenolic/nylon heat shields appeared to have uniform surface texture upon examination prior to dressing. There was no evidence of material migration except for one corner of the curved panel (see Figure 20). This condition occurred only in the excess surface material and did not result in voided cells. However, another corner of the curved panel had major voiding of the cell edges. This was attributed to location of the vacuum outlet in this area which subjected the material to the maximum influence of the vacuum induced gas flow.

Areas of poor edge fill and chipping were observed on the curved phenolic/nylon panels. The poor edge fill is attributed to the pressure loss in the peripheral area caused by bridging of the bleeder fabric and vacuum bag combined with poor initial fill resulting from the inclined cell condition. The edge chipping resulted from the slightly undersize core at some points which produced unsupported ablation materials. The chipping occurred during removal of the panel from the mold and the dressing operation.

The amount of overfill material dressed from the flat panel was .08 - .10 inch thick. The dressing was accomplished by routing the overfill to slightly above the cell surface and then finishing by hand sanding with 120-C grit paper. The curved panel was dressed only by hand sanding due to the light overfill of material.

Discoloration of the panels near the edges was observed for all the phenolic/nylon heat shields (see Figures 20, 21 and 22). Areas of brown stains on the higher density panel were only surface conditions and were removed by dressing. The lower density panel discoloration was sub-surface and remained after dressing. The exact reason for the discoloration of the panels is not clear. The appearance would seem to indicate a localized over-heating or an

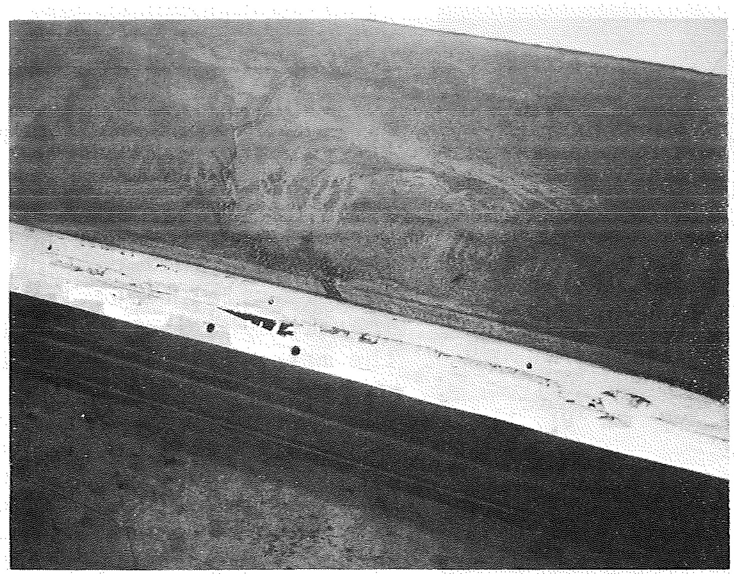


Figure 19. Eroded Cell Surface of Low-Density Phenolic/Nylon Curved Panel

oxidation condition. However, because of the uniform heating environment of the circulating air ovens the former is the least probable reason. On the other hand bleed-out of air into the flow passages around the periphery or vacuum seal leakage could have provided the supply of oxygen for oxidizing the ablation materials if either of these continued at elevated temperatures.

Both the flat and curved high-density and flat low-density elastomeric panels accepted nearly all of the overfill material which remained above the cells prior to cure. The only surface dressing required was in a small area ½ to 2 inches wide at the periphery of the panels.

As mentioned earlier in Section II. D. 3, the low-density elastomeric curved panel was overcharged with a material quantity which was based on the maximum allowable density. Of the 5/8 inch material overfill prior to cure, approximately ¼ inch remained above the cells after the cure cycle. The reduction of the overfill is attributed to further entry and compaction into the honeycomb cells during the pressurization process.

Dressing of the elastomeric panels was done by first shaving off the majority of the excess material using a sharp edged tool and then finishing to the cell surface by sanding with 120-C grit paper.

Before dressing of the low density curved elastomeric panel, it was noted that there were several areas on the surface and along the panel edges that appeared to be uncured. The material in these areas was soft and could be displaced with minimal pressure. The soft areas were approximately ¼ inch deep on the surface and one cell deep on the edges. The surface areas of soft mater-

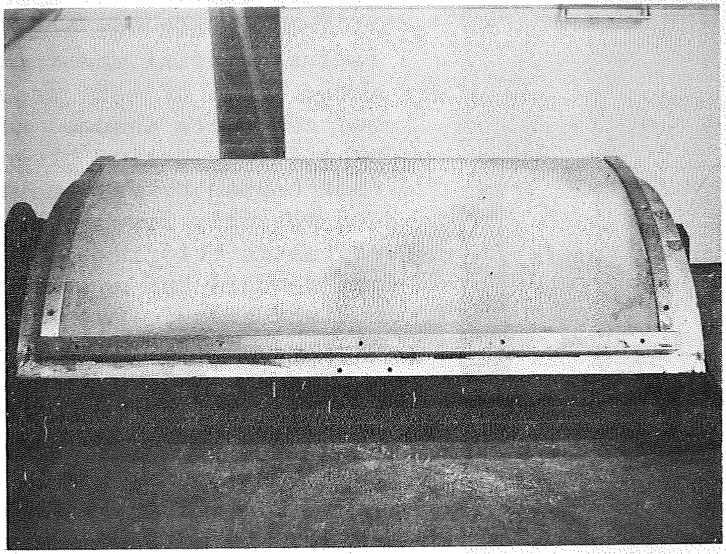


Figure 20. Eroded Corner (lower right) and Discoloration of High-Density Phenolic/Nylon Panel After Cure

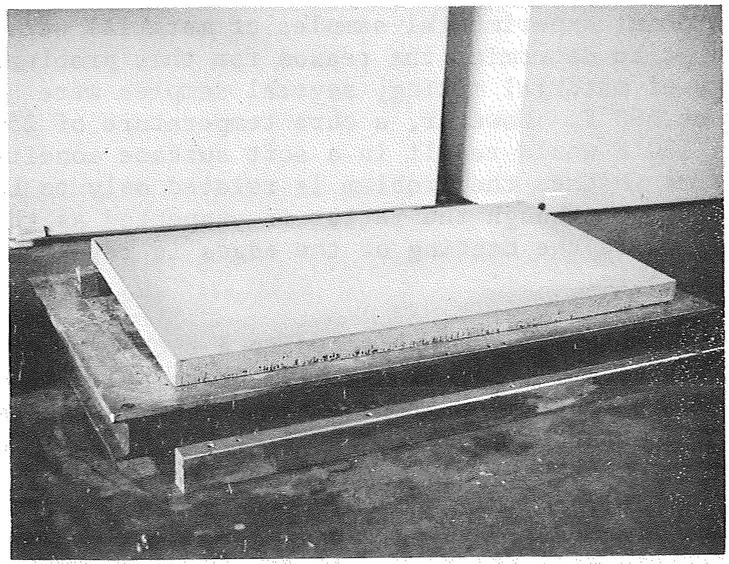


Figure 21. Discoloration (upper left) of High-Density Phenolic/Nylon Panel After Cure

ial were coincident with the areas where masking tape was used to position the bleeder fabric. It appeared that the silicone resin was bled out from the ablative material under the masking tape. Those areas of soft material at the panel edges are assumed to be the result of silicone resin "bleed-out" in this case caused by vacuum induced air flow and possibly lower pressure due to bleeder fabric bridging. Dressing of the panel removed the majority of the soft surface areas. However, in one corner of the panel an area approximately 3 x 5 inches remained where the soft material extended below the cell surface.

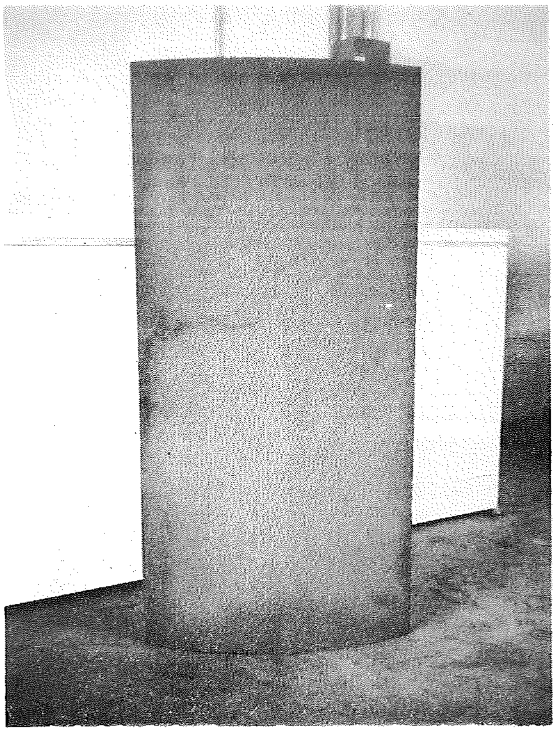


Figure 22. Discoloration After Dressing of Low-Density Phenolic/Nylon Panel

The panel was then subjected to further processing in an effort to repair the uncured areas. The soft material was removed by blowing pressurized air over the affected areas. New material was mixed and the voided areas filled. The panel was repositioned into the mold and subjected to a second cure cycle using vacuum pressure only. After the cure cycle, the new material exhibited the same soft characteristic as was noted after the initial cure.

At this point experimental samples of material were prepared and processed in an attempt to determine the reason for this problem. With emphasis placed on the quality of material mixing, several samples were unsuccessfully produced when cured at 180°F. However, a cure temperature of 250°F would harden the material whereas 180°F would result in a soft surface condition. It is undetermined at this time whether the problem is related only to cure temperature or to the rate of heating although the latter is suspected as the masking tape provided a heat block while the heating of the edges is retarded due to the heat sink of the mold side rails.

The full size panel was subjected to a second repair with a cure cycle of four (4) hours at 250°F and twenty (20) hours at 180°F under vacuum pressure. With the exception of one area at the corner of the panel which was adjacent to the vacuum outlet, the repair material exhibited a cured condition.

Two additional problems were observed after curing the ablation material in both curved elastomeric panels. One was the appearance of a dark, charred area approximately five (5) inches in diameter, on the ablative surface of the low density panel. Directly opposite this area on the face sheet side was a smaller area that also appeared charred or scorched. This area is located at one of the center attachment holes. It is felt that this condition resulted from a minor air leak through the sealed drill bushing hole in the mold base plate during cure. This leakage caused a continuous flow of oxygen which resulted in partial combustion of the ablation material. Upon boring of the panel attachment hole at this point it was observed that the ablation material had been burned. The burned area was evident as a conical shaped void in the ablation material. The void was approximately 1½ inch in diameter at the face sheet and tapered over 1½ inch in height to the 3/4 inch diameter of the attachment hole. As had been observed in earlier pre-production testing, the phenolic Microballoons will burn at temperatures as low as 210°F when exposed to air over a prolonged period of time. The second problem, observed in the high density panel, was the crushing of the honeycomb core in one quadrant of the panel. The maximum amount of the honeycomb cell collapse was ½ inch. This condition occurred during the initial autoclave pressure/cure cycle. Although the bare compressive strength rating for the OX type honeycomb core used is 160 psi nominal with a minimum of 105 psi, the filled panel collapsed at 100 psi autoclave pressure. It is felt that the reason for this failure can be related to the distortion of the overexpanded cells discussed earlier in this section.

The condition of poor edge fill or voided edges was typical of all the elastomeric panels. The primary reason for this again was the apparent loss of pressure at the panel edges due to the bridging of the bleeder fabric and vacuum bag. Since the manufacturing process was designed to produce net edges, these voided edge cells could not be trimmed away. Another factor is that the cutting of the honeycomb panel resulted in only partial cells in some areas of the edges. The reduced cell size created a higher ratio of frictional resistance to cross sectional area which produced the same problem that made filling of ¼ inch cell unsatisfactory.

Warpage occured in all heat shield panels. The amount of warpage depended on the panel material composition and configuration.

In all flat panels, the warpage was concave in the length and width directions on the ablative surface side of the panel except for the high-density elastomeric panel. In the latter case, the warpage was convex in the length direction. The warpage, as measured from a straight edge resting on the panel edges to the center of the panel surface, was as follows:

	Amount of Warp (inches)	
Panel (flat)	Length	Width
Low-Density Phenolic/Nylon	.000	.108
High-Density Phenolic/Nylon	.037	.048
Low-Density Elastomeric	.012	.015
High-Density Elastomeric	.024 convex	.223

The warpage of the curved panels was observed primarily in the width direction. This was apparent as an increase of the 24 inch radius of the panels to a somewhat larger curvature. Warpage in the length direction was noted to be concave as described above for the flat panels. The warpage, measured as described above for the length direction and with radius templates for the panel curvature, was as follows:

	Amount of Warp (inches)	
Panel	Length	Radius
Low-Density Phenolic/nylon	.000	24-25
High-Density Phenolic/nylon	.024	24-25
Low-Density Elastomeric	.045	24-25
High-Density Elastomeric	.012	25-28

It is felt that warping of the panels can be attributed to any of several different reasons depending on individual panel configuration and materials. These are: cure temperature, ablation material thermal expansion and/or shrinkage, the presence of a face sheet on one side only, and the honeycomb matrix type and ribbon direction. However, specific causes could not be established within the scope of this effort.

Warpage of the elastomeric material is quite sensitive to cure temperature. In the higher density material, one (1) foot square x two (2) inch thick panels cured at 250°F produced as much as 3/16 inch of warpage. By reducing the cure temperature, this condition was less severe, but not completely eliminated. The influence of cure temperature was much lower on the low density elastomeric composition in which the liquid silicone resin content was only 20 percent.

The high shrinkage factor of the phenolic resin with the thermal expansion of the nitrogen filled phenolic Microballoons during cure and subsequent contraction of the cured material contributed to warping of the phenolic/nylon panels.

G. Drilling Heat Shields and Machining Plugs

The heat shield attachment holes were located by using the hole pattern incorporated in the mold base plate. Before drilling, the panels were placed in the mold cavity and clamped down to remove any warpage.

Using a 9/32 inch diameter drill, six (6) pilot holes were drilled through each panel. The panel was then removed from the tool. The 3/4 inch diameter clearance holes in the ablative compound material were produced in a mill using a piloted flat-bottomed end mill. Both the drill and end mill were hi-speed steel designs. Abrasion of the ablation material was observed in all panels. The high-density phenolic/nylon material produced the worst abrasion but it was not severe enough to warrant the use of carbide tools. Abrasiveness of the low-density phenolic/nylon and elastomeric materials was minimal.

During the manufacture of the heat shields, a six (6) inch square x two (2) inch thick panel was produced from each of the four (4) material systems. The panels were processed in the same manner as the respective full-scale heat shields except that the face sheet was excluded. Each panel was used to fabricate twelve (12) plugs for the attachment holes, six (6) for each heat shield panel of the same material and density. With the exception of the high-density phenolic/nylon panel, all of the 11/16 inch diameter x 2 inch long plugs were machined by means of a diamond hole saw.

Due to the abrasiveness of the high-density phenolic/nylon material, machining by using the diamond hole saw was unsuccessful for this material. The diamond cutting surface tended to load with the phenolic and nylon particles thereby reducing cutting ability and generating excessive heat. An attempt was made to turn the plugs in a lathe using a single point cutting tool. This resulted in excessive chipping of the material. The plugs were finally produced by turning in a lathe and grinding to size with a diamond wheel. Because of the single point effect obtained with this method, the diamond cutting surface was self-cleaning and functioned satisfactorily. The completed heat shields are shown in Figure 23 to 30 inclusive.

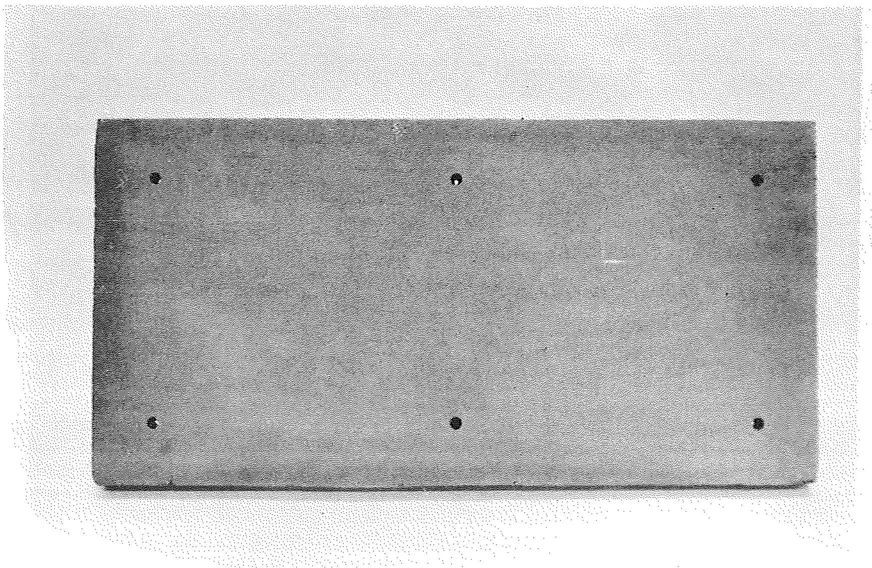


Figure 23. Low-Density Phenolic/Nylon
Flat Heat Shield-Completed

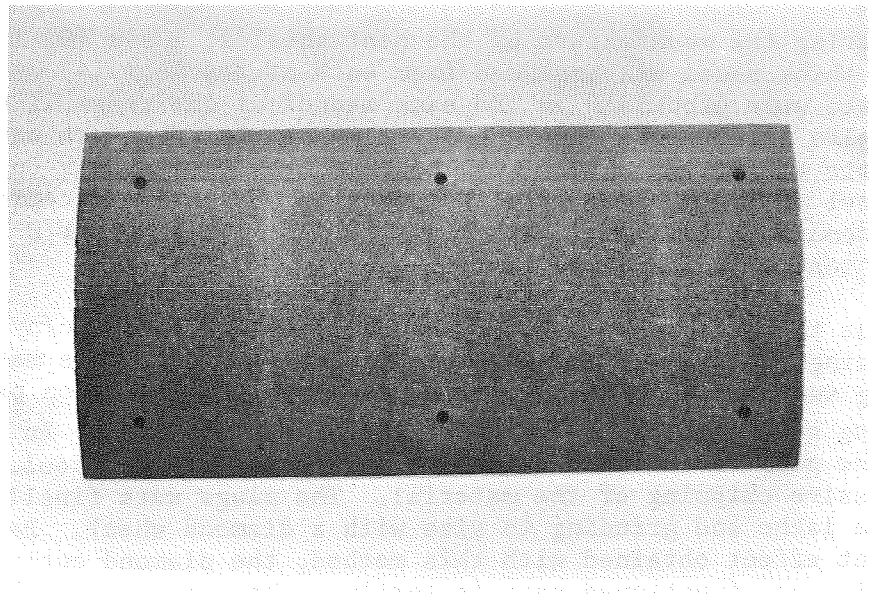


Figure 24. Low-Density Phenolic/Nylon Curved Heat Shield-Completed

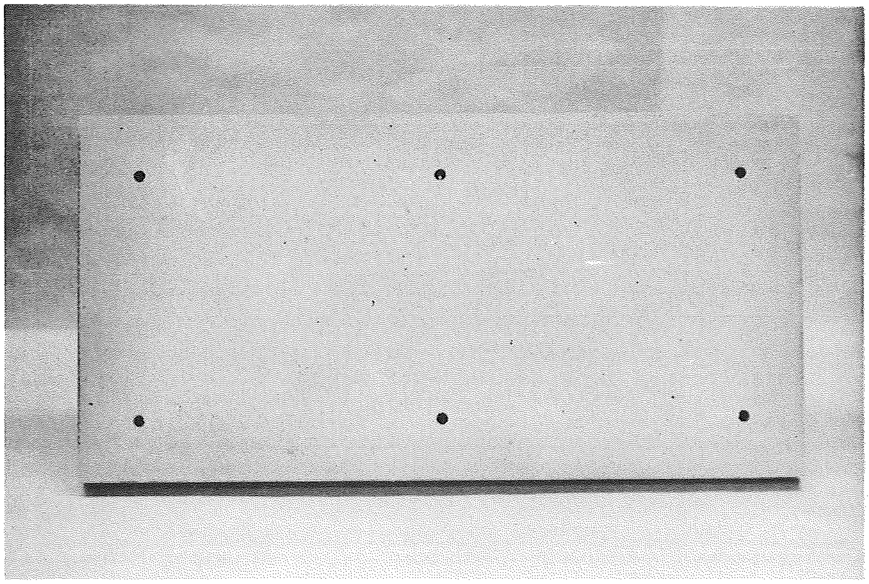


Figure 25. High-Density Phenolic/Nylon Flat Heat Shield-Completed

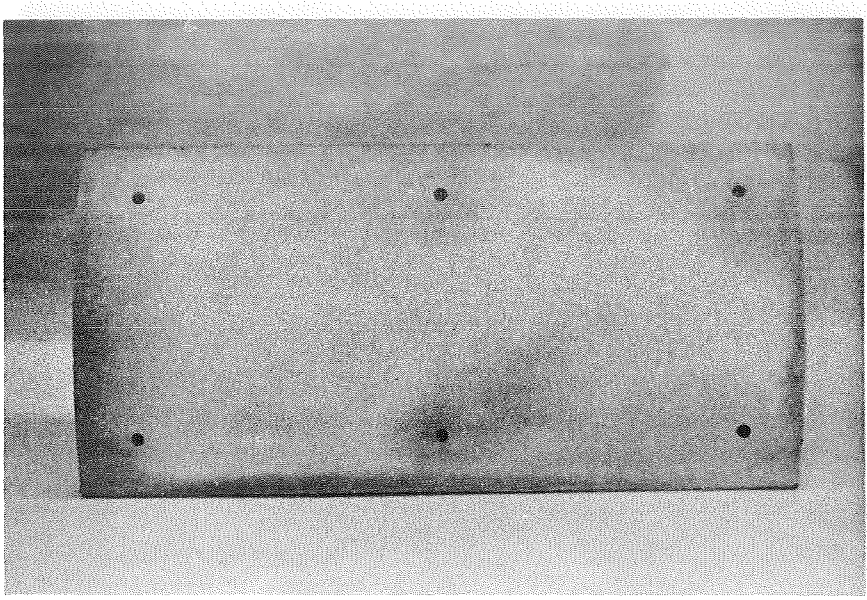


Figure 26. High-Density Phenolic/Nylon Curved Heat Shield-Completed

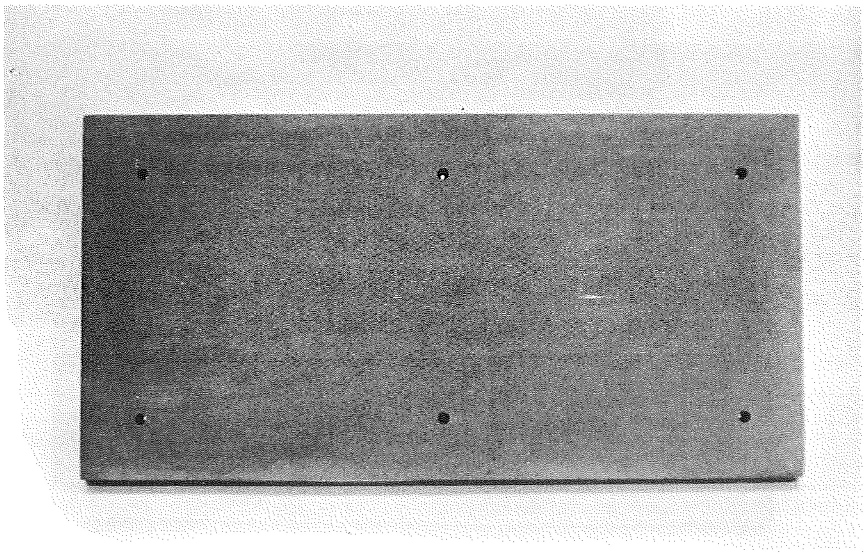


Figure 27. Low-Density Elastomeric Flat Heat hield-Completed

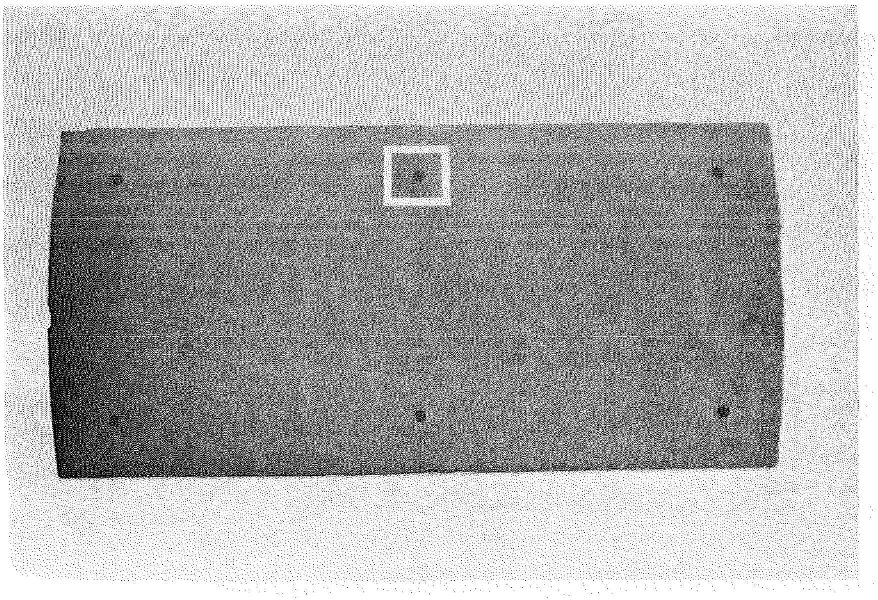


Figure 28. Low-Density Elastomeric Curved Heat Shield Completed (indicated attachment hole is location of burned ablation material)

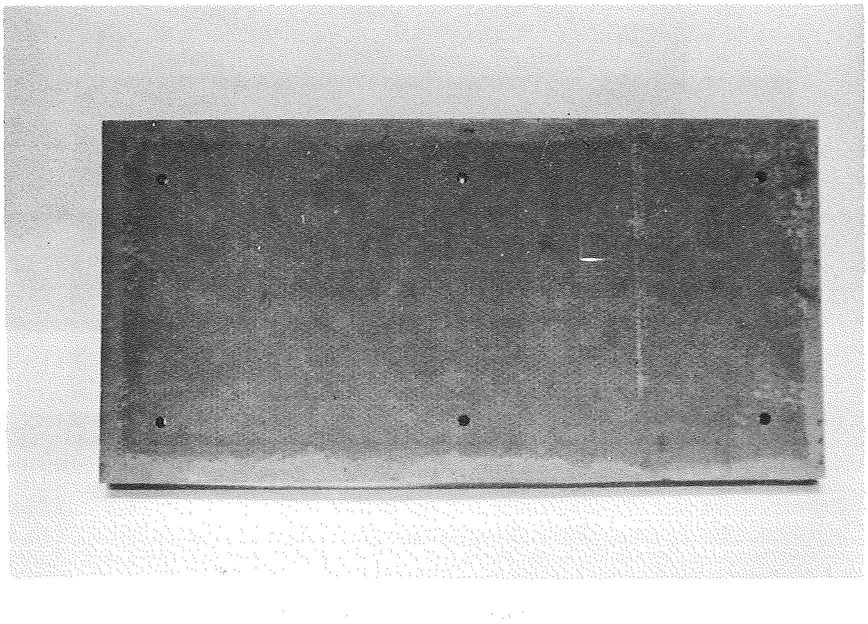


Figure 29. High-Density Elastomeric Flat Heat Shield-Completed

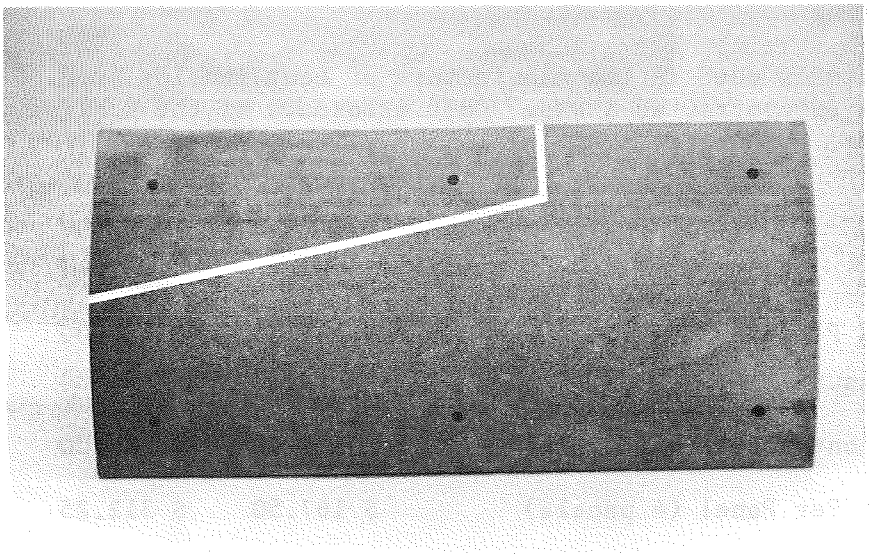


Figure 30. High-Density Elastomeric Curved Heat Shield-Completed (lined upper left section is area of crushed core)

III. COST ANALYSIS AND ESTIMATES

A. Tooling

The tools used in the manufacture of heat shields (ref. Section I) were produced as subcontracted items. Cost breakdown of the tooling is as follows:

	Cost	
Tool	Flat	Curved
Mold Plate	$ 645.00	$1205.00
Pressure Plate	25.00	44.00
Subcontracted Cost	$ 670.00	$1249.00
Cost Per Panel (4 panels)	$ 167.50	$ 312.25

B. Analysis of Fabricated Heat Shields

Tables 4 through 7 present a detailed cost breakdown of material and labor costs required to produce the heat shield panels fabricated under this contract.

All costs shown reflect only the deliverable panels and do not include materials and labor expended for process development or engineering assistance in manufacturing. The panel costs include 1) the costs of those materials which fall in a minimum order category shown as an amortized cost for the applicable number of heat shield units and 2) the cost of material waste resulting from trim loss when cutting the required size honeycomb from the as-received honeycomb sheet.

The amortized costs of minimum order materials are as follows:

Material	Cost Amortized by Units
Narmco 500/120 Epoxy prepreg	$210.00 ÷ 8 = $26.25
BRP-5549 Phenolic	29.50 ÷ 4 = 7.38

The Narmco 500/120 epoxy prepreg material was used in all eight (8) heat shield panels whereas the BRP-5549 phenolic was used only in the four (4) phenolic/nylon panels. Amortization units are therefore eight (8) and four (4) respectively.

TABLE 4.

COST ANALYSIS - LOW - DENSITY PHENOLIC/NYLON HEAT SHIELD

Material	Quantity	Unit Cost	Cost/Panel	
			Flat	Curved
Narmco 500/120 Epoxy prepreg	(amortized cost)		26.25	26.25
NP¼-4.0 Honeycomb	12.0 ft^2	9.73/9.97	116.76	119.64
BRP-5549 Phenolic	(amortized cost)		7.38	7.38
Polypenco 66-D Nylon	1.91 lb.	3.99	7.62	7.62
BJO-0930 Microballoons	8.93 lb.	1.21	10.81	10.81
SC-1008 Phenolic resin	1.10 lb.	1.37	1.51	1.51
Shop aids			2.50	2.50
Total Material Cost			$172.83	$175.71

Manufacturing Operation	Elapsed Hours/Panel		Labor Hours/Panel	
	Flat	Curved	Flat	Curved
Bond honeycomb to face sheet	6.5	8.0	4.5	5.2
Trim face sheet and coat with resin	2.5	2.8	1.0	1.3
Dry microballoons	3.0	3.0	0.5	0.5
Mix ablative compound	2.5	2.5	2.5	2.5
Fill honeycomb panel	2.8	3.5	5.5	7.0
Pressurize and cure	27.0	27.0	4.0	4.5
Dress ablative surface	2.0	2.5	2.0	2.5
Spray coat with resin	2.0	2.0	0.5	0.5
Bore attachment holes	1.0	2.0	1.0	2.0
Machine plugs	0.3	0.3	0.3	0.3
Total Elapsed Hours	49.6	53.6		
Total Labor Hours			21.8	26.3

	Flat	Curved
Tooling Cost	$ 167.50	$ 312.25
Total Unit Cost (Excluding Fee)	$ 662.88	$ 890.24

TABLE 5.

COST ANALYSIS - HIGH - DENSITY PHENOLIC/NYLON HEAT SHIELD

Material	Quantity	Unit Cost	Cost/Panel Flat	Cost/Panel Curved
Narmco 500/120 Prepreg	(amortized cost)		26.25	26.25
NP¼-4.0 Honeycomb	12.0 ft^2	9.73/9.97	116.76	119.64
BRP-5549 Phenolic	(amortized cost)		7.38	7.38
Polypenco 66-D Nylon	15.0/14.0 lb.	3.99	59.85	55.85
SC-1008 Phenolic resin	1.10	1.37	1.51	1.51
Shop aids			2.50	2.50
Total Material Cost			$214.25	$213.13

Manufacturing Operation	Elapsed Hours/Panel Flat	Elapsed Hours/Panel Curved	Labor Hours/Panel Flat	Labor Hours/Panel Curved
Bond honeycomb to face sheet	6.5	8.0	4.5	5.2
Trim face sheet and coat with resin	2.5	2.8	1.0	1.3
Mix ablative compound	2.2	2.2	2.2	2.2
Fill honeycomb panel	3.0	4.3	6.0	8.5
Pressurize and cure	27.0	27.0	4.0	4.5
Dress ablative surface	5.0	2.5	5.0	2.5
Bore attachment holes	1.5	2.5	1.5	2.5
Machine plugs	2.3	2.3	2.3	2.3
Total Elapsed Hours	50.0	51.6		
Total Labor Hours			26.5	29.0
Tooling Cost			$ 167.50	$ 312.25
Total Unit Cost (Excluding Fee)			$ 768.41	$ 966.80

TABLE 6.

COST ANALYSIS - LOW - DENSITY ELASTOMERIC HEAT SHIELD

Material	Quantity	Unit Cost	Cost/Panel Flat	Cost/Panel Curved
Narmco 500/120 Prepreg	(amortized cost)		26.25	26.25
HRP3/8-3.2 Honeycomb	12.0 ft^2	8.65	103.80	-
HRP-OX3/8-2.7 Honeycomb	10.0 ft^2	11.68	-	116.80
Sylgard 182 Silicone resin with hardener	2.89/3.30 lb.	5.40	15.61	17.82
BJO-0930 Microballoons	11.56/13.26 lb.	1.21	13.99	16.04
SC-1008 Phenolic resin	.67 lb.	1.37	.92	.92
Shop aids			2.50	2.50
Total Material Cost			$163.07	$180.33

Manufacturing Operation	Elapsed Hours/Panel Flat	Elapsed Hours/Panel Curved	Labor Hours/Panel Flat	Labor Hours/Panel Curved
Bond honeycomb to face sheet	7.5	9.8	5.5	7.3
Trim face sheet and coat with resin	3.5	3.8	1.0	1.3
Dry microballoons	3.0	3.0	0.5	0.5
Mix ablative compound	2.0	2.0	2.0	2.0
Fill honeycomb panel	3.5	4.3	7.0	8.5
Pressurize and cure	27.0	27.0	4.0	4.5
Dress ablative surface	2.0	5.0	2.0	5.0
Bore attachment holes	1.5	2.5	1.5	2.5
Machine plugs	0.3	0.3	0.3	0.3
Total Elapsed Hours	50.3	57.7		
Total Labor Hours			23.8	31.9

	Flat	Curved
Tooling Cost	$ 167.50	$ 312.25
Total Unit Cost (Excluding Fee)	$ 675.74	$ 963.63

TABLE 7.

COST ANALYSIS - HIGH - DENSITY ELASTOMERIC HEAT SHIELD

			Cost/Panel	
Material	Quantity	Unit Cost	Flat	Curved
Narmco 500/120 Epoxy prepreg	(amortized cost)		26.25	26.25
HRP3/8-3.2 Honeycomb	12.0 ft^2	8.65	103.80	-
HRP-OX3/8-2.7 Honeycomb	10.0 ft^2	11.68	-	116.80
Sylgard 182 Silicone resin with hardener	20.80/22.30	5.40	112.32	120.42
BJO-0930 Microballoons	10.25/11.00	1.21	12.40	13.31
SC-1008 Phenolic resin	.67 lb.	1.37	.92	.92
Shop aids			2.50	2.50
Total Material Cost			$258.19	$280.20

Manufacturing Operation	Elapsed Hours/Panel		Labor Hours/Panel	
	Flat	Curved	Flat	Curved
Bond honeycomb to face sheet	7.5	9.8	5.5	7.3
Trim face sheet and coat with resin	3.5	3.8	1.0	1.3
Dry microballoons	3.0	3.0	0.5	0.5
Mix ablative compound	2.0	2.0	2.0	2.0
Fill honeycomb panel	3.8	4.5	7.5	9.0
Pressurize and cure	27.0	27.0	4.0	4.5
Dress ablative surface	2.0	2.5	2.0	2.5
Bore attachment holes	1.5	2.5	1.5	2.5
Machine plugs	0.3	0.3	0.3	0.3
Total Elapsed Hours	50.6	55.4		
Total Labor Hours			24.3	29.9
Tooling Cost			$ 167.50	$ 312.25
Total Unit Cost (Excluding Fee)			$ 793.09	$1056.19

C. Cost Estimates - Heat Shield Panels

The following text and tables define the tooling and manufacturing approach and estimated unit costs for producing various sizes and quantities of heat shield panels and tooling.

The panel thickness for all heat shields is two (2) inches. Except as noted, the heat shields are of a flat configuration.

Estimated material costs are based on current supplier prices. The labor costs are based on experience obtained through manufacture of the panels described in Section II.

Due to the minimum order purchase for some materials and the varying material waste factor depending on the heat shield quantity and size, all of the following estimated costs cannot be accurately related to a standard learning curve.

All costs shown for any quantity, heat shield type and configuration are estimated on a stand-alone basis. There is no combining of quantities or heat shield types for purposes of cost reduction for individual items.

1. Tooling configuration

The tooling used to produce the phenolic/nylon heat shields would basically be the same as that described in Section I. The only difference would be the incorporation of a pneumatic device to produce the proper vibration or shock amplitude and frequency for settling the powder compound.

Tooling for the elastomeric system would also remain the same except for the addition of a male/female filling mold. This tool would be designed to accept a pre-calculated charge of the elastomeric composition and to produce an even distribution and compaction of the material in the mold cavity prior to filling the honeycomb cells.

A separate drill jig would also be required for producing the panel hole pattern instead of being a part of the mold base plate as described in Section I.

2. Manufacturing approach

The cost estimates for the phenolic/nylon panels reflect a change from 1/4 to 3/8 inch cell honeycomb. This change was made to facilitate core filling and to reduce the cost of the honeycomb material. The filling technique, with the exception of the vibration and shock produced by the pneumatic impact device, would remain unchanged.

Filling the elastomeric panels would be accomplished by a totally different approach. As will be discussed in Section IV, the hand troweling method is undesirable. The new filling technique would distribute, uniformly and without voids, the pre-calculated material charge within the filling mold cavity. This would be accomplished in a hydraulic press by closing the male punch of the mold onto the material in the female cavity. Filling would then be accomplished by positioning the honeycomb panel in an inverted attitude onto the material and then again closing the mold thereby pushing the honeycomb cells into the elastomeric compound. After filling, the panel would be removed, positioned onto a curing tool, and cured as required using vacuum pressure only.

All panels would be manufactured with ½ inch overstock on all edges and trimmed to net dimensions after filling and curing the ablative compound.

Except as stated above, the estimates shown in Table 8 through 21 are based on the same manufacturing approach as that described in Section II.

D. Cost Estimates - Space Shuttle Flights

The following costs are shown as square footage prices for the four (4) ablation material systems covered in this report. Each flight is considered to consist of approximately eight thousand (8,000) square feet of ablative heat shield and a total heat shield weight of twenty-five thousand (25,000) pounds.

The square footage prices are based on a proportional average of the estimated prices for the heat shield panels described in the previous section. This average is derived by considering that one space shuttle flight will consist of heat shield panels of which fifty (50) percent are flat (or slightly curved) with an area of twenty-four (24) square feet per panel, thirty (30) percent are curved with an area of fifteen (15) square feet per panel, and twenty (20) percent are double-curved with an area of eight (8) square feet per panel. Based on this and a panel thickness of two (2) inches the square foot prices, excluding tooling, are as follows:

	Price Per Square Foot (Excluding Fee) Number of Flights		
Ablation Material System	1	10	100
Low-Density Phenolic/nylon	$ 36.60	$ 31.00	$ 26.50
High-Density Phenolic/nylon	46.60	39.50	33.80
Low-Density Elastomeric	36.20	30.70	26.20
High-Density Elastomeric	62.20	52.80	45.10

A summary of the unit heat shield prices excluding tooling and fee is shown in Table 22.

The cost of tooling required to produce heat shields for a space shuttle flight is also based on a percentage of panels by size and configuration as described above except that panels which are classified as nearly flat will be considered to be curved. Therefore, the estimated proportion of tooling to produce flat panels is twenty (20) percent, large size curved panels is thirty (30) percent, medium size curved panels is thirty (30) percent, and doubly-curved panels is twenty (20) percent.

Of the tooling allocated by configurations as described above, it is estimated that individual tools will be required for fifty (50) percent of the flat panels, seventy (70) percent of the curved panels, and one hundred (100) percent of the doubly-curved panels. The total tooling required is tabulated as follows:

Panel Type Configurations/Size	Percent of Total Vehicle Area	Percent Individual Tools	Total No. of Tools
Flat/24 ft^2	20	50	34
Curved/24 ft^2	30	70	70
Curved/15 ft^2	30	70	112
Doubly-curved/8 ft^2	20	100	200

Based on the above analysis, the cost of tooling to produce heat shields for a space shuttle vehicle is as follows:

Type Tooling (Quantity)	Average Cost Per Tool		Extended Tooling Cost	
	Phenolic/ Nylon	Elastomeric	Phenolic/Nylon	Elastomeric
Impact Device and Mounting Fixture (26)	$2,250.00	--------	$ 58,500.00	--------
24 ft^2 Flat Mold (34)	715.00	$1,080.00	24,310.00	$36,720.00
24 ft^2 Curved Mold (70)	1,305.00	2,000.00	91,350.00	140,000.00
15 ft^2 Curved Mold (112)	1,070.00	1,720.00	119,840.00	192,640.00
8 ft^2 Doubly-curved Mold (200)	2,690.00	3,770.00	538,000.00	754,000.00
Trim and Drill Fixtures (416)	409.00	409.00	170,144.00	170,144.00
Total Tooling Cost for Phenolic/ Nylon System			$1,002,144.00	
Total Tooling Cost for Elastomeric System				$1,293,504.00

TABLE 8.

ESTIMATE - TWO (2) x FOUR (4) FOOT LOW-DENSITY PHENOLIC/NYLON HEAT SHIELD

	Flat Panel		Curved Panel	
	Quantity		Quantity	
	10	100	10	100
Material Cost Per Panel	$ 137.54	$ 94.35	$ 137.54	$ 94.35
Total Manufacturing Cost Per Panel (Excluding Fee)	377.09	236.41	417.18	262.00
Subcontracted Tooling Cost Per Panel	68.00	19.10	82.00	28.80
Total Unit Selling Price (Excluding Fee)	$ 456.69	$ 258.76	$ 513.18	$ 295.70

TABLE 9.

ESTIMATE - TWO (2) x FOUR (4) FOOT HIGH-DENSITY PHENOLIC/NYLON HEAT SHIELD

	Flat Panel		Curved Panel	
	Quantity		Quantity	
	10	100	10	100
Material Cost Per Panel	$ 188.38	$ 130.51	$ 188.38	$ 130.51
Total Manufacturing Cost Per Panel (Excluding Fee)	439.02	285.40	482.74	313.21
Subcontracted Tooling Cost Per Panel	68.00	19.10	82.00	28.80
Total Unit Selling Price (Excluding Fee)	$ 518.62	$ 307.75	$ 578.74	$ 346.91

TABLE 10.

ESTIMATE - TWO (2) x FOUR (4) FOOT LOW-DENSITY ELASTOMERIC HEAT SHIELD

	Flat Panel		Curved Panel	
	Quantity		Quantity	
	10	100	10	100
Material Cost Per Panel	$ 158.14	$ 109.25	$ 158.14	$ 109.25
Total Manufacturing Cost Per Panel (Excluding Fee)	401.20	243.37	423.05	256.73
Subcontracted Tooling Cost Per Panel	53.00	13.80	192.00	35.20
Total Unit Selling Price (Excluding Fee)	$ 463.20	$ 259.52	$ 647.75	$ 297.91

TABLE 11.

ESTIMATE - TWO (2) x FOUR (4) FOOT HIGH-DENSITY ELASTOMERIC HEAT SHIELD

	Flat Panel		Curved Panel	
	Quantity		Quantity	
	10	100	10	100
Material Cost Per Panel	$ 290.02	$ 233.47	$ 290.02	$ 233.47
Total Manufacturing Cost Per Panel (Excluding Fee)	555.50	388.71	577.35	402.07
Subcontracted Tooling Cost Per Panel	53.00	13.80	192.00	35.20
Total Unit Selling Price (Excluding Fee)	$ 617.50	$ 404.86	$ 802.05	$ 443.25

TABLE 12.

ESTIMATE - THREE (3) x FIVE (5) FOOT LOW-DENSITY PHENOLIC/NYLON HEAT SHIELD CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$ 824.50	$ 245.81	$ 165.03
Total Manufacturing Cost Per Panel (Excluding Fee)	1754.08	572.27	357.17
Subcontracted Tooling Cost Per Panel	1000.00	100.00	24.20
Total Unit Selling Price (Excluding Fee)	$2924.08	$ 689.27	$ 385.49

TABLE 13.

ESTIMATE - THREE (3) x FIVE (5) FOOT HIGH-DENSITY PHENOLIC/NYLON HEAT SHIELD CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$ 937.20	$ 324.18	$ 237.69
Total Manufacturing Cost Per Panel (Excluding Fee)	1944.63	678.54	456.66
Subcontracted Tooling Cost Per Panel	1000.00	100.00	24.20
Total Unit Selling Price (Excluding Fee)	$3114.63	$ 795.54	$ 484.98

TABLE 14.

ESTIMATE - THREE (3) x FIVE (5) FOOT LOW-DENSITY ELASTOMERIC HEAT SHIELD CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$ 900.20	$ 271.96	$ 191.87
Total Manufacturing Cost Per Panel (Excluding Fee)	1812.29	585.88	361.41
Subcontracted Tooling Cost Per Panel	850.00	85.00	19.00
Total Unit Selling Price (Excluding Fee)	$2807.29	$ 685.38	$ 383.64

TABLE 15.

ESTIMATE - THREE (3) x FIVE (5) FOOT HIGH-DENSITY ELASTOMERIC HEAT SHIELD CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$1354.50	$ 524.40	$ 418.58
Total Manufacturing Cost Per Panel (Excluding Fee)	2343.83	881.23	626.66
Subcontracted Tooling Cost Per Panel	850.00	85.00	19.00
Total Unit Selling Price (Excluding Fee)	$3338.83	$ 980.73	$ 648.89

TABLE 16.

ESTIMATE - FOUR (4) x SIX (6) FOOT LOW-DENSITY PHENOLIC/NYLON HEAT SHIELD FLAT OR SLIGHTLY CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$ 905.28	$ 331.16	$ 256.49
Total Manufacturing Cost Per Panel (Excluding Fee)	2061.11	738.68	518.29
Subcontracted Tooling Cost Per Panel	1110.00	111.00	28.00
Total Unit Selling Price (Excluding Fee)	$3360.11	$ 868.58	$ 551.05

TABLE 17.

ESTIMATE - FOUR (4) x SIX (6) FOOT HIGH-DENSITY PHENOLIC/NYLON HEAT SHIELD FLAT OR SLIGHTLY CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$1084.78	$ 456.33	$ 371.25
Total Manufacturing Cost Per Panel (Excluding Fee)	2283.69	891.93	660.57
Subcontracted Tooling Cost Per Panel	1110.00	111.00	28.00
Total Unit Selling Price (Excluding Fee)	$3582.69	$1021.83	$ 693.33

TABLE 18.

ESTIMATE - FOUR (4) x SIX (6) FOOT LOW-DENSITY ELASTOMERIC HEAT SHIELD FLAT OR SLIGHTLY CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$ 934.78	$ 352.60	$ 277.92
Total Manufacturing Cost Per Panel (Excluding Fee)	2013.46	737.30	505.98
Subcontracted Tooling Cost Per Panel	1090.00	109.00	23.50
Total Unit Selling Price (Excluding Fee)	$3288.46	$ 864.80	$ 533.48

TABLE 19.

ESTIMATE - FOUR (4) x SIX (6) FOOT HIGH-DENSITY ELASTOMERIC HEAT SHIELD FLAT OR SLIGHTLY CURVED PANELS

	Quantity		
	1	10	100
Material Cost Per Panel	$1668.28	$ 776.41	$ 660.96
Total Manufacturing Cost Per Panel (Excluding Fee)	2871.66	1233.16	954.14
Subcontracted Tooling Cost Per Panel	1090.00	109.00	23.50
Total Unit Selling Price (Excluding Fee)	$4146.66	$1360.66	$ 981.64

TABLE 20.

ESTIMATE - TWO (2) x FOUR (4) FOOT DOUBLE-CURVATURE HIGH-DENSITY PHENOLIC/NYLON HEAT SHIELD

	Quantity		
	1	10	100
Material Cost Per Panel	$ 820.54	$ 289.72	$ 197.44
Total Manufacturing Cost Per Panel (Excluding Fee)	2097.33	662.08	441.44
Subcontracted Tooling Cost Per Panel	2800.00	280.00	51.00
Total Unit Selling Price (Excluding Fee)	$5373.33	$ 989.68	$ 501.11

TABLE 21.

ESTIMATE - TWO (2) x FOUR (4) FOOT DOUBLE-CURVATURE HIGH-DENSITY ELASTOMERIC HEAT SHIELD

	Quantity		
	1	10	100
Material Cost Per Panel	$1112.13	$ 410.26	$ 317.27
Total Manufacturing Cost Per Panel (Excluding Fee)	2347.66	777.31	539.51
Subcontracted Tooling Cost Per Panel	4200.00	420.00	60.00
Total Unit Selling Price (Excluding Fee	$7261.66	$1268.71	$ 609.71

TABLE 22.

SUMMARY - UNIT SELLING PRICES (EXCLUDING TOOLING AND FEE) OF HEAT SHIELD PANELS

Panel Configuration	Quantity	Cost ($/ft^2)			
		Phenolic/Nylon		Elastomeric	
		Low-Density	High-Density	Low-Density	High-Density
2' x 4' x 2" Flat	1	$ 61.92	$ 75.11	$ 63.53	$ 78.20
	10	47.14	54.88	50.15	69.44
	100	29.55	35.68	30.42	48.59
2' x 4' x 2" Curved	1	72.25	81.82	81.42	92.99
	10	52.15	60.34	52.88	72.17
	100	32.75	39.15	32.09	50.26
3' x 5' x 2" Curved	1	116.94	129.64	120.82	156.26
	10	38.15	45.24	39.06	58.75
	100	23.81	30.44	24.09	41.78
4' x 6' x 2" Flat or Slightly Curved	1	85.88	95.15	83.89	119.65
	10	30.78	37.16	30.72	51.38
	100	21.60	27.52	21.08	39.76
2' x 4' x 2" Double-Curvature	1		262.17		293.46
	10		82.76		97.16
	100		55.18		67.44
Costs to cover 8000 ft^2 of Vehicle	1 Flight	36.60	46.60	36.20	62.20
	10 Flights	31.00	39.50	30.70	52.80
	100 Flights	26.50	33.80	26.20	45.10

IV. CONCLUSIONS AND RECOMMENDATIONS

The fabrication cost of replaceable ablative heat shield panels was determined from actual experience of producing eight evaluation panels. Production cost estimates were prepared by applying learning curve factors to the labor expenditures and obtaining material prices from suppliers. Tooling estimates include recommended improvements and changes in the manufacturing methods. To increase the confidence in the estimated production costs, a pilot lot of panels should be manufactured and corresponding adjustments made in the estimates.

Fabricating the face sheet and honeycomb panels by the labor saving one-step cure and primary bond was successful for both the 1/4 and 3/8 inch cell size core.

Mixing and sifting the ablation materials was successfully accomplished with commercially available equipment.

Filling the ¼ inch cell size honeycomb with the powder materials was successfully accomplished by bulk loading and panel vibration. To effect further labor savings through reduced filling time, 3/8 inch cell size honeycomb is recommended for future production.

The hand troweling method of filling the elastomeric ablation materials into honeycomb cells was unsatisfactory. The ¼ inch cell core could not be filled without residual voids. Although experimental 3/8 inch cell size panels were successfully filled, the operation is tedious and a reliable void-free fill cannot be assured. A change is recommended to the method of material precompaction in a female mold and pressing the honeycomb into the material in a hydraulic press.

As a result of poor edge filling, a change is recommended to fabricate the panels with ½ inch overstock on all edges which would be trimmed off after completion of the panel cure.

Warpage was experienced on all evaluation panels. This condition was caused mainly by shrinkage of the ablation material and the differential thermal expansion and contraction of the panel constituents. In an attempt to eliminate panel warpage, additional research is recommended to determine the optimum compaction pressure and cure temperature of the ablation material. Bonding the face sheet to the honeycomb after filling and curing the ablation material should also be investigated. This would eliminate the condition of one surface of the panel being placed in lateral restraint with the attendant warpage forces during processing of the ablation material. A corollary benefit would be the simple means of visual inspection of the honeycomb filling. However, a problem area would be the necessity to qualify the bond strength of the face sheet to the core.

As a cost reduction item, the study of the feasibility of ½ inch cell size honeycomb is recommended for both types of ablation materials. This would reduce the filling time and void incidence. The unknown at this time is the

quality of
step cure

Anot
bility of
comparable
tially lower
cost. Howev
core to act as an effective reinforcing matrix
the ablation material must be investigated.