NASA CR-112135
(MCR-72-188)



Final Report

# INVESTIGATION OF FORMING CURVED ABLATIVE PANELS FROM FLAT PANELS FOR SPACE SHUTTLE

By Huel H. Chandler

Prepared under Contract No. NAS1-10793 by
MARTIN MARIETTA CORPORATION
Denver, Colorado 80201

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## FOREWORD

This report is submitted in accordance with the requirements of the statement of work for Contract NAS1-10793, which was sponsored by NASA-Langley Research Center.

The report is the result of a team effort in close cooperation with the NASA Technical Monitor, Mr. Claud Pittman. The Martin Marietta Aerospace effort was managed by Mr. Daniel V. Sallis and directed by Mr. Huel H. Chandler.

CONTENTS



LIST OF ILLUSTRATIONS



LIST OF TABLES

FINAL REPORT

# INVESTIGATION OF FORMING CURVED ABLATIVE PANELS FROM FLAT PANELS FOR SPACE SHUTTLE

by Huel H. Chandler
Martin Marietta Corporation

## SUMMARY

The purpose of this study was to determine the feasibility of reforming flat ablative panels to a curved configuration. The study indicated that if the panels could be shaped to a radius of 2.54 m (100 in.) then 88.7% of the surface area of the orbiter could be covered, and that if they could be shaped to a radius of 3.81 m (150 in.) then 77.2% of the surface could be covered.

Two basic approaches were followed to determine the best method for forming the flat panels to a curved shape. The first was to determine if partially cured panels could be formed, allowing the forming heat cycle to complete the curing of the ablator. The second method was to form fully cured flat panels into the desired curvature through a secondary heat cycle.

The first method proved to be unfeasible because of the rapid cure of the ablator resin at an elevated temperature. The ablative material cured before the phenolic resin coating on the honeycomb core. The phenolic resin is used to bond the ablative matrix to the reinforcing core. Without a bond established, the panels failed when a bending load was applied.

The second method, that of using fully cured panels, proved that panels could be reshaped into a curved configuration. However, the amount of springback was not predictable.

Various temperature cycles were investigated to reduce the springback and to achieve the smallest radius of curvature. The cycle that worked the best consisted of a low-temperature hold to relax the residual strains, followed by a high-temperature heat treatment to increase the bending set. This cycle was also used for the six large test panels made and delivered to NASA-Langley.

Measurements made on the panels during storage indicated that they continued to straighten out over time. This was attributed to residual stresses locked into the panels that had not been fully relaxed by the heat cycle.

Cost analyses indicated that large savings could be realized by using this method to form curved panels. The savings are due to the larger number of panels that can be made to one configuration; i.e., by using large flat panels to produce stock sheets. The savings were estimated to be $\$275/m^2$ ($\$25.61/ft^2$) for a lot of 100 panels.

At the present time, the method cannot be recommended for production due to the inconsistency of the process and the residual stress in the panels. If these problems can be overcome through formulation changes or other bending cycles then the method is attractive.

## INTRODUCTION

The radii of curvature of the Shuttle Orbiter are relatively large. If it is possible to bend flat ablative panels to these contours rather than form the curved panels directly, then large cost savings should be realized. These savings would come from being able to fabricate large flat sheets of ablative material, which could later be machined to the desired thickness and cut to the desired peripheral dimensions. Then the panels could be reformed to the desired curvature.

To determine if this could be accomplished, a flat ablative panel was heated and bent over a mandrel. A permanent set was introduced into the panel even though springback occurred.

This study was funded: to determine if there were better ways of reforming ablative panels; to determine the effect of panel thickness and reinforcement on the amount of curvature; to determine the degree of consistency of the process; and to estimate the cost savings that could be realized.

## ORBITER RADIUS OF CURVATURE

The majority of the orbiter surface area has large radii of curvature. To determine the surface area that could be covered using curved panels formed from previously made flat panels, a drawing showing the surface contours of the GIII Orbiter was prepared. Figure 1 depicts a simplified form of the drawing.

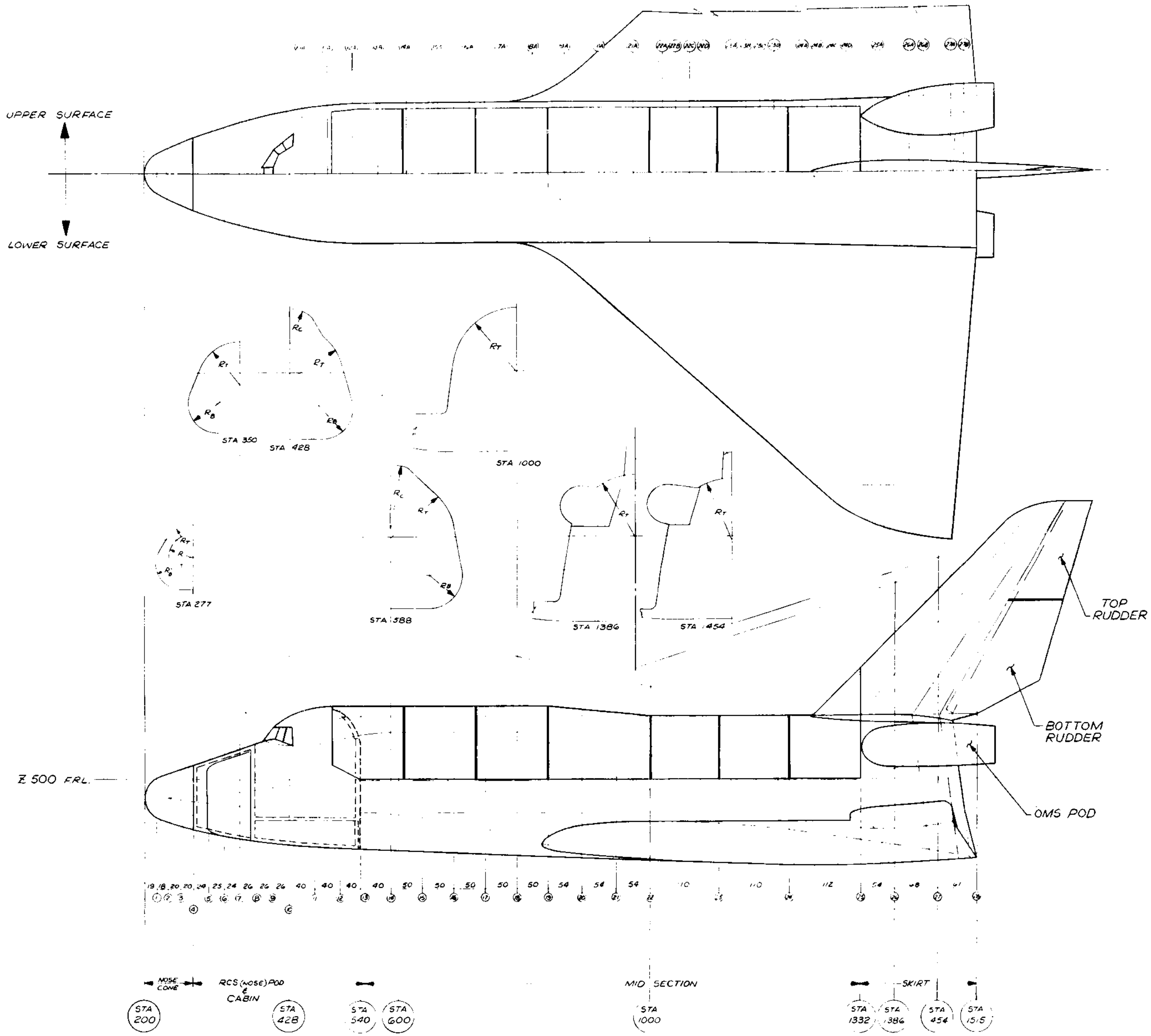



Figure 1.- Surface Contours of the GIII Orbiter

(ALL SURFACES SHOWN. ALL RADII IN METERS)

BODY

NOSE CONE

| AREA | $M^2$ | R | $R_B$ | $R_T$ |
|---|---|---|---|---|
| $S_{0-1}$ | 2 6 | 89 | | |
| $S_{1-2}$ | 2 8 | 1.02 | | |
| $S_{2-3}$ | 3 5 | | .99 | 1 14 |
| $S_{3-4}$ | 4 2 | | 1 02 | 1 22 |
| TOTAL | 13 1 | | | |

TOTAL SURFACE AREA - 13 1 $M^2$
42 % CIRCULAR CAP
46 % DOUBLE CONTOURED
12 % SINGLE CONTOURED
100 %

CABIN + RCS (NOSE) POD

| AREA | $M^2$ | $R_B$ | $R_T$ | $R_C$ |
|---|---|---|---|---|
| $S_{4-5}$ | 5 6 | 1 14 | 1 37 | |
| $S_{5-6}$ | 6.7 | 1 24 | 1 52 | |
| $S_{6-7}$ | 7 7 | 1 29 | 1.65 | |
| $S_{7-8}$ | 8 5 | 1 32 | 1 80 | |
| $S_{8-9}$ | 9 2 | 1.34 | 1 93 | 64 |
| $S_{9-10}$ | 10 5 | 1 40 | 2 08 | 1 35 |
| $S_{10-11}$ | 17 2 | 1 45 | 2 29 | 1 60 |
| $S_{11-12}$ | 17 8 | 1 47 | 2 46 | 1.98 |
| $S_{12-13}$ | 18 1 | 1 50 | 2 54 | 2 34 |
| TOTAL | 101 2 | | | |

TOTAL SURFACE AREA = 101 2 $M^2$
64.8 % DOUBLE CONTOURED
35.2 % SINGLE CONTOURED
100.0 %

MID-SECTION

| AREA | $M^2$ | $R_B$ | $R_T$ | $R_C$ |
|---|---|---|---|---|
| $S_{13-14}$ | 18 6 | 1 47 | 2 56 | 2 54 |
| $S_{14-15}$ | 23.0 | 1 42 | 2 59 | 2.54 |
| $S_{15-16}$ | 24 0 | 1 32 | 2 59 | 2.54 |
| $S_{16-17}$ | 24 3 | 1.12 | 2 59 | 2.54 |
| $S_{17-18}$ | 23 9 | 91 | 2 59 | 2.54 |
| $S_{18-19}$ | 23 4 | 61 | 2.59 | 2 54 |
| $S_{19-20}$ | 24 0 | .36 | 2 59 | 2 39 |
| $S_{20-21}$ | 23 1 | 23 | 2 59 | 2.29 |
| $S_{21-22}$ | 23 3 | .08 | 2 59 | 1 14 |
| $S_{22-23}$ | 47 0 | — | 2 59 | — |
| $S_{23-24}$ | 47 3 | — | 2 59 | — |
| $S_{24-25}$ | 50 8 | — | 2 59 | — |
| TOTAL | 353 6 | | | |

TOTAL SURFACE AREA = 353 6 $M^2$
41.4 % SINGLE CONTOURED
13.8 % DOUBLE CONTOURED
44.8 % FLAT
100.0 %

SKIRT

| AREA | $M^2$ | $R_T$ |
|---|---|---|
| $S_{25-26}$ | 25.5 | 2.59 |
| $S_{26-27}$ | 32 5 | 2 59 |
| $S_{27-28}$ | 21 1 | 2 59 |
| TOTAL | 79 1 | |

TOTAL SURFACE AREA = 79.1 $M^2$
22.5 % SINGLE CONTOURED
77.5 % FLAT
100.0 %

BODY - OMS PODS = 603 - 56 = 547 $M^2$

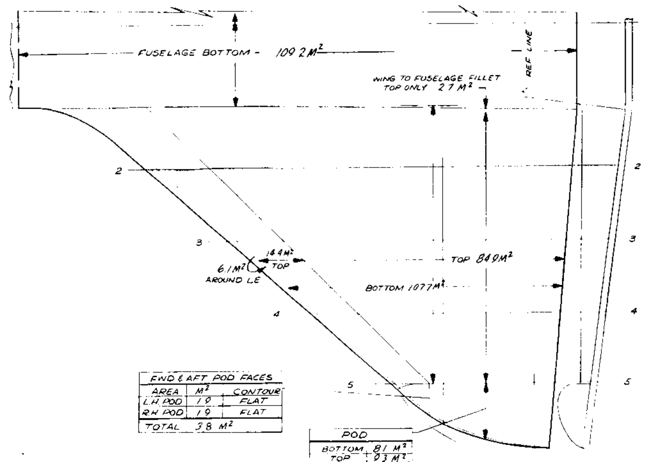
| | |
|---|---|
| NOSE CONE $S_{WET}$ | 13.2 |
| CABIN $S_{WET}$ | 101.2 |
| MID-SECTION $S_{WET}$ | 353 6 |
| SKIRT $S_{WET}$ | 79 1 |
| TOTAL BODY - OMS | 547 1 |

27.8 % SINGLE CONTOURED
41.6 % DOUBLE CONTOURED
30.6 % FLAT
100.0 %

FIN

| | |
|---|---|
| TOP RUDDER | 12.9 |
| BOTTOM RUDDER | 21 7 |
| VERTICAL TAIL | 58.8 |
| TOTAL FIN | 93 4 |

TOTAL SURFACE AREA = 93 4 $M^2$
27.2 % SINGLE CONTOURED
72.8 % FLAT
100.0 %




FWD & AFT POD FACES

| AREA | $M^2$ | CONTOUR |
|---|---|---|
| L.H. POD | 1 9 | FLAT |
| R.H. POD | 1 9 | FLAT |
| TOTAL | 3 8 $M^2$ | |

POD
BOTTOM 8 1 $M^2$
TOP 9 3 $M^2$
FWD & AFT ENDS 1 0 $M^2$


WING

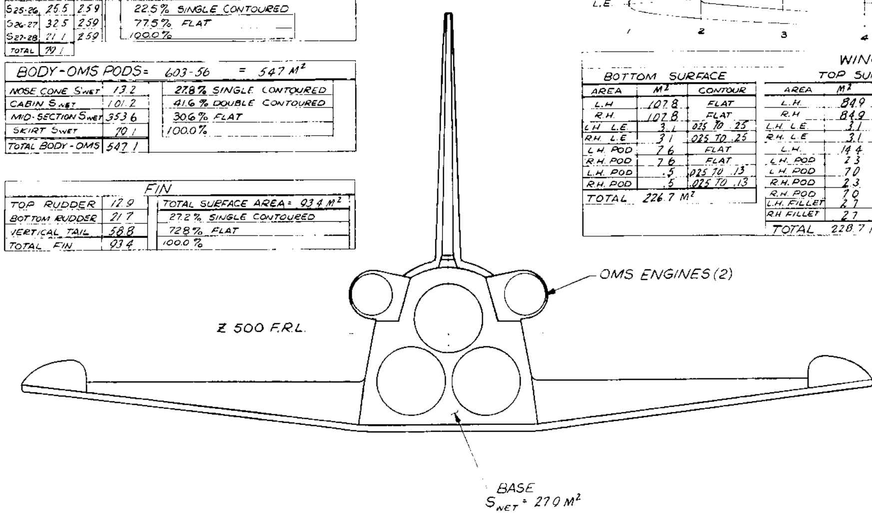
BOTTOM SURFACE

| AREA | $M^2$ | CONTOUR |
|---|---|---|
| L.H | 107.8 | FLAT |
| R.H. | 107 8 | FLAT |
| L.H L.E. | 3 1 | .025 TO .25 |
| R.H. L.E | 3 1 | .025 TO .25 |
| L.H. POD | 7 6 | FLAT |
| R.H. POD | 7 6 | FLAT |
| L.H. POD | .5 | .025 TO .13 |
| R.H. POD | .5 | .025 TO .13 |
| TOTAL | 226.7 $M^2$ | |

TOP SURFACE

| AREA | $M^2$ | CONTOUR |
|---|---|---|
| L.H. | 84.9 | FLAT |
| R.H | 84.9 | FLAT |
| L.H. L.E. | 3 1 | .13 TO .51 M R |
| R.H. L.E | 3.1 | .13 TO .51 M R |
| L.H. | 14 4 | 3.81 TO 6.35 M R |
| L.H. POD | 2 3 | .13 TO .51 M R |
| L.H. POD | 7 0 | 1.27 TO 2.54 M R |
| R.H. POD | 2.3 | .13 TO .51 M R |
| R.H. POD | 7 0 | 1.27 TO 2.54 M R |
| L.H. FILLET | 2 7 | .13 TO .51 M R |
| R.H FILLET | 2 7 | .13 TO .51 M R |
| TOTAL | 228.7 $M^2$ | |

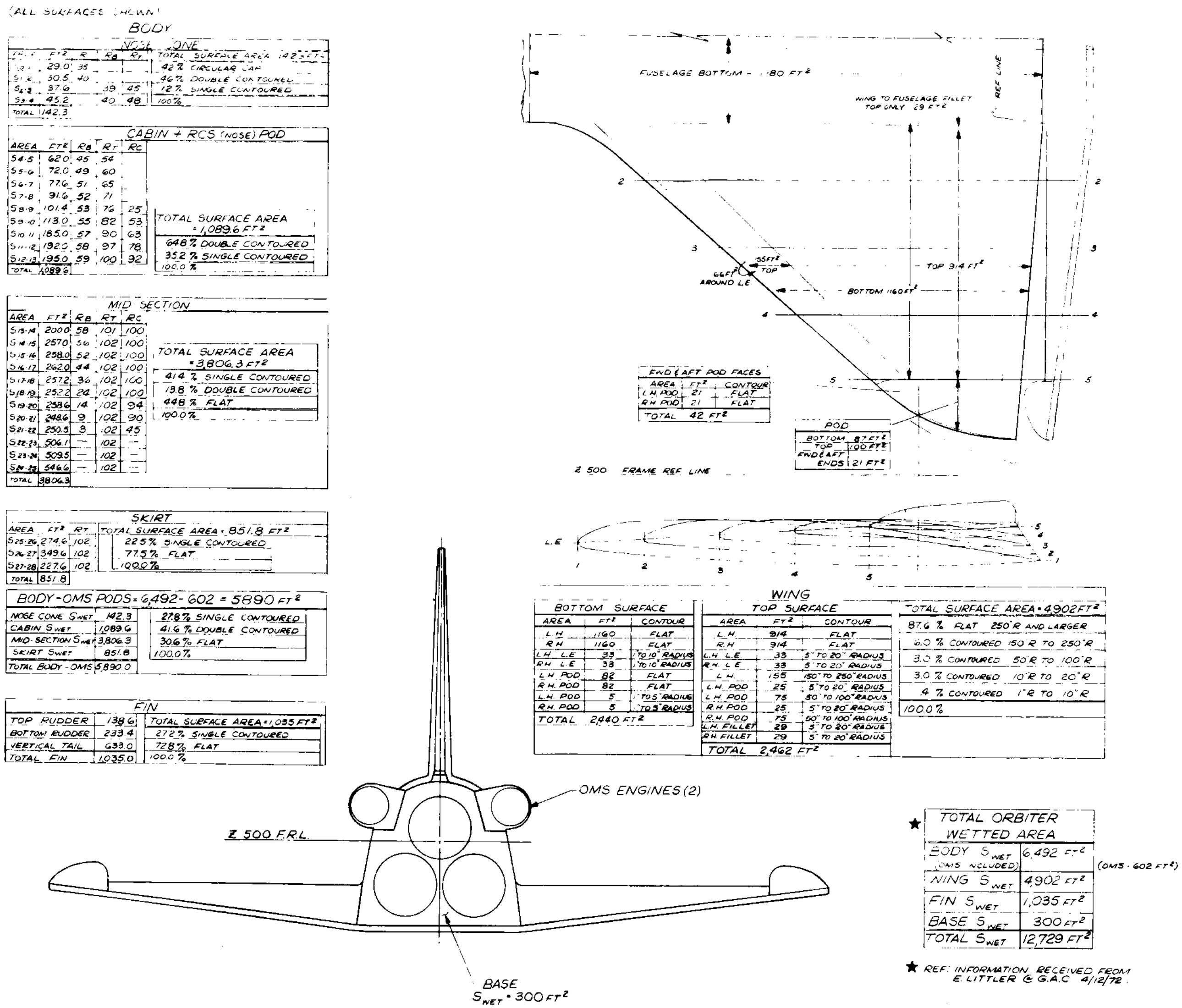
TOTAL SURFACE AREA = 455.4 $M^2$
87.6 % FLAT 6 35 M R
6.0 % CONTOURED 3.81 TO 6.35 M R
3.0 % CONTOURED 1.27 TO 2.54 M R
3.0 % CONTOURED .25 TO .51 M R
.4 % CONTOURED .02 TO .25 M R
100.0 %




TOTAL ORBITER WETTED AREA

| | |
|---|---|
| BODY $S_{WET}$ (OMS INCLUDED) | 603 1 $M^2$ (OMS - 55 9 $M^2$) |
| WING $S_{WET}$ | 455.4 $M^2$ |
| FIN $S_{WET}$ | 96 2 $M^2$ |
| BASE $S_{WET}$ | 27 0 $M^2$ |
| TOTAL $S_{WET}$ | 1182.6 $M^2$ |

Figure 1.- Continued




BODY

| NOSE CONE | | | | | TOTAL SURFACE AREA 142.3 FT² |
|---|---|---|---|---|---|
| AREA | FT² | R | $R_B$ | $R_T$ | |
| $S_{0-1}$ | 29.0 | 35 | | | 42% CIRCULAR CAP |
| $S_{1-2}$ | 30.5 | 40 | | | 46% DOUBLE CONTOURED |
| $S_{2-3}$ | 37.6 | | 39 | 45 | 12% SINGLE CONTOURED |
| $S_{3-4}$ | 45.2 | | 40 | 48 | 100% |
| TOTAL | 142.3 | | | | |

| CABIN + RCS (NOSE) POD | | | | | |
|---|---|---|---|---|---|
| AREA | FT² | $R_B$ | $R_T$ | $R_C$ | |
| $S_{4-5}$ | 62.0 | 45 | 54 | | |
| $S_{5-6}$ | 72.0 | 49 | 60 | | |
| $S_{6-7}$ | 77.6 | 51 | 65 | | |
| $S_{7-8}$ | 91.6 | 52 | 71 | | |
| $S_{8-9}$ | 101.4 | 53 | 76 | 25 | TOTAL SURFACE AREA = 1,089.6 FT² |
| $S_{9-10}$ | 113.0 | 55 | 82 | 53 | 64.8 % DOUBLE CONTOURED |
| $S_{10-11}$ | 185.0 | 57 | 90 | 63 | 35.2 % SINGLE CONTOURED |
| $S_{11-12}$ | 192.0 | 58 | 97 | 78 | 100.0 % |
| $S_{12-13}$ | 195.0 | 59 | 100 | 92 | |
| TOTAL | 1,089.6 | | | | |

| MID SECTION | | | | | |
|---|---|---|---|---|---|
| AREA | FT² | $R_B$ | $R_T$ | $R_C$ | |
| $S_{13-14}$ | 200.0 | 58 | 101 | 100 | |
| $S_{14-15}$ | 257.0 | 56 | 102 | 100 | TOTAL SURFACE AREA = 3,806.3 FT² |
| $S_{15-16}$ | 258.0 | 52 | 102 | 100 | 41.4 % SINGLE CONTOURED |
| $S_{16-17}$ | 262.0 | 44 | 102 | 100 | 13.8 % DOUBLE CONTOURED |
| $S_{17-18}$ | 257.2 | 36 | 102 | 100 | 44.8 % FLAT |
| $S_{18-19}$ | 252.2 | 24 | 102 | 100 | 100.0 % |
| $S_{19-20}$ | 258.6 | 14 | 102 | 94 | |
| $S_{20-21}$ | 248.6 | 9 | 102 | 90 | |
| $S_{21-22}$ | 250.5 | 3 | 102 | 45 | |
| $S_{22-23}$ | 506.1 | — | 102 | — | |
| $S_{23-24}$ | 509.5 | — | 102 | — | |
| $S_{24-25}$ | 546.6 | — | 102 | — | |
| TOTAL | 3806.3 | | | | |

| SKIRT | | | |
|---|---|---|---|
| AREA | FT² | $R_T$ | TOTAL SURFACE AREA = 851.8 FT² |
| $S_{25-26}$ | 274.6 | 102 | 22.5 % SINGLE CONTOURED |
| $S_{26-27}$ | 349.6 | 102 | 77.5 % FLAT |
| $S_{27-28}$ | 227.6 | 102 | 100.0 % |
| TOTAL | 851.8 | | |

| BODY - OMS PODS = 6,492 - 602 = 5890 FT² | | |
|---|---|---|
| NOSE CONE $S_{WET}$ | 142.3 | 27.8 % SINGLE CONTOURED |
| CABIN $S_{WET}$ | 1,089.6 | 41.6 % DOUBLE CONTOURED |
| MID-SECTION $S_{WET}$ | 3,806.3 | 30.6 % FLAT |
| SKIRT $S_{WET}$ | 851.8 | 100.0 % |
| TOTAL BODY - OMS | 5,890.0 | |

| FIN | | |
|---|---|---|
| TOP RUDDER | 138.6 | TOTAL SURFACE AREA = 1,035 FT² |
| BOTTOM RUDDER | 233.4 | 27.2 % SINGLE CONTOURED |
| VERTICAL TAIL | 633.0 | 72.8 % FLAT |
| TOTAL FIN | 1,035.0 | 100.0 % |

| END & AFT POD FACES | | |
|---|---|---|
| AREA | FT² | CONTOUR |
| L.H. POD | 21 | FLAT |
| R.H. POD | 21 | FLAT |
| TOTAL | 42 FT² | |

| POD | |
|---|---|
| BOTTOM | 87 FT² |
| TOP | 100 FT² |
| FWD & AFT ENDS | 21 FT² |

WING

| BOTTOM SURFACE | | |
|---|---|---|
| AREA | FT² | CONTOUR |
| L.H. | 1160 | FLAT |
| R.H. | 1160 | FLAT |
| L.H. L.E. | 33 | 1" TO 10" RADIUS |
| R.H. L.E. | 33 | 1" TO 10" RADIUS |
| L.H. POD | 82 | FLAT |
| R.H. POD | 82 | FLAT |
| L.H. POD | 5 | 1" TO 5" RADIUS |
| R.H. POD | 5 | 1" TO 5" RADIUS |
| TOTAL | 2,440 FT² | |

| TOP SURFACE | | |
|---|---|---|
| AREA | FT² | CONTOUR |
| L.H. | 914 | FLAT |
| R.H. | 914 | FLAT |
| L.H. L.E. | 33 | 5" TO 20" RADIUS |
| R.H. L.E. | 33 | 5" TO 20" RADIUS |
| L.H. | 155 | 150" TO 250" RADIUS |
| L.H. POD | 25 | 5" TO 20" RADIUS |
| L.H. POD | 75 | 50" TO 100" RADIUS |
| R.H. POD | 25 | 5" TO 20" RADIUS |
| R.H. POD | 75 | 50" TO 100" RADIUS |
| L.H. FILLET | 29 | 5" TO 20" RADIUS |
| R.H. FILLET | 29 | 5" TO 20" RADIUS |
| TOTAL | 2,462 FT² | |

| TOTAL SURFACE AREA = 4902 FT² |
|---|
| 87.6 % FLAT 250"R AND LARGER |
| 6.0 % CONTOURED 150"R TO 250"R |
| 3.0 % CONTOURED 50"R TO 100"R |
| 3.0 % CONTOURED 10"R TO 20"R |
| .4 % CONTOURED 1"R TO 10"R |
| 100.0 % |

| ★ TOTAL ORBITER WETTED AREA | | |
|---|---|---|
| BODY $S_{WET}$ (OMS INCLUDED) | 6,492 FT² | (OMS - 602 FT²) |
| WING $S_{WET}$ | 4,902 FT² | |
| FIN $S_{WET}$ | 1,035 FT² | |
| BASE $S_{WET}$ | 300 FT² | |
| TOTAL $S_{WET}$ | 12,729 FT² | |

★ REF: INFORMATION RECEIVED FROM E. LITTLER @ G.A.C. 4/12/72.

**Figure 1.- Concluded**

Table I summarizes the results of this part of the study. As can be seen from the table, 88.7% of the heat shield has a radius of curvature larger than 2.54 m (100 in.) and 77.2% has a radius larger than 3.81 m (150 in.)

## ROOM-TEMPERATURE BENDING TESTS

Room-temperature bending tests were run to determine the minimum bending radius that could be used and to determine the amount of pressure required to force the panels against the bending mandrels.

All of the SS-41 (see ref. 1) test panels used in this study were first made into 0.46x0.46-m (18x18-in.) billets and later cut into 10x30-cm (4x12-in.) specimens. Both 9-mm (3/8-in.) hexagonal core and two-directional-bending core were used for reinforcement. The billets were cured for 16 hr at 394°K (250°F) under a vacuum pressure of $8.3 \times 10^{-4}$ $N/m^2$ (12 psia). A series of bending mandrels were made by rolling 6.4-mm (1/4-in.) thick aluminum plate to radii of 2.54 m (100 in.), 1.27 m (50 in.), 0.64 m (25 in.), and 0.38 m (15 in.), and wooden picture frames were fabricated to fit over the mandrels. These picture frames were approximately one-half as thick as the panels and were used to prevent the vacuum bag from pulling in between the mandrel and the test panel. Electrical contacts were placed on the ends of the panel to indicate when the panel was fully in contact with the mandrel. Figure 2 depicts the test setup; the picture frame has been removed for clarity.

TABLE I. - CURVATURE DISTRIBUTION BY AREA

| | Base heat shield | | Fin | | Wing | | Body | | Total | | Percent of Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $m^2$ | $ft^2$ | $m^2$ | $ft^2$ | $m^2$ | $ft^2$ | $m^2$ | $ft^2$ | $m^2$ | $ft^2$ | |
| Contour 0- to 1.27-m (0- to 50-in.) radius | | | | | 23.2 | 250 | 24.3 | 262 | 47.6 | 512 | 4.0 |
| Contour 1.27-m to 2.54-m (50-in. to 100-in.) radius | | | | | 13.9 | 150 | 72.3 | 778 | 86.2 | 928 | 7.3 |
| Contour 2.54-m to 3.81-m (100-in. to 150-in.) radius | | | | | | | 137.3 | 1478 | 137.3 | 1478 | 11.5 |
| Contour 3.81-m to 6.35-m (150-in. to 250-in.) radius | | | | | 14.4 | 153 | | | 14.4 | 155 | 1.2 |
| Flat - 6.35-m (250-in.) radius & larger | 27.9 | 300 | 96.2 | 1035 | 400.6 | 4312 | 369.2 | 3974 | 893.8 | 9621 | 76.0 |
| | 27.9 | 300 | 96.2 | 1035 | 452.1 | 4867 | 603.1 | 6492 | 1179.3 | 12 694 | 100.0 |

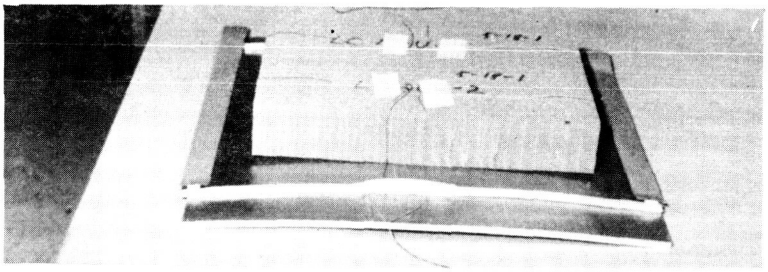


Figure 2.- Ablative Panels on Bending Mandrel, Contacts Installed

The panels were vacuum-bagged and the amount of vacuum pressure or vacuum pressure plus autoclave pressure was recorded when the ends of the panel contacted the mandrels. All bends were made in the long [30-cm (12-in.)] direction. The specimens were cut from the billets in such a manner as to provide core ribbons running both parallel and perpendicular to the bend direction. Table II gives the results of this study.

## PARTIAL CURING

We originally believed that if the ablative material was only partially cured, it would be simpler to form the panel to a curved shape. We also felt that the cure would be completed in the curving operation. To test this approach, panels of SS-41 material without core were prepared and cured at 366°K (200°F) and 394°K (250°F) for periods varying between 15 minutes and 16 hr. Hardness and flexural strength tests were run on the samples after their cure cycle. The tests indicated that full properties were achieved after 4 hr at 394°K (250°F) or 6 hr at 366°K (200°F), and that a cure sufficient to handle and machine the panels was achieved after 2 hr at 366°K (200°F) or 1 1/2 hr at 394°K (250°F).

Two lots of the SS-41 material were prepared. One lot was used for cure times up to 2 hr; the second lot, for cures from 2 hr to 16 hr. For some unknown reason the first lot had a higher flexural strength than the second lot. This can be seen in figures 3 thru 6.

Further study of the partial cure method was stopped at this point since the method was considered impractical. The resin system used in the ablators, GE 655, cures in about 1.5 hr (see figs. 5 and 6). However, the phenolic resin on the honeycomb core, which bonds the ablator matrix to the core, has not had time to cure and form a complete bond. When the panels are bent, the ablator debonds at the cell walls. To overcome these

TABLE II.- ROOM-TEMPERATURE BEND - 30.5x10.2-cm (12x4-in.) PANELS WITH HEXAGONAL CORE REPLACEMENT

| Panel thickness | | Ribbon direction | Radius | | Make circuit | | Comments |
|---|---|---|---|---|---|---|---|
| cm | in. | | m | in. | N/m$^2$ | psia | |
| 5.0 | 2 | Parallel to curve | 2.54 | 100 | 4.4 x $10^{-4}$ | 6.4 | |
| 5.0 | 2 | Parallel to curve | 2.54 | 100 | 4.5 | 6.6 | |
| 5.0 | 2 | Perpendicular to curve | 2.54 | 100 | 5.2 | 7.5 | |
| 5.0 | 2 | Perpendicular to curve | 2.54 | 100 | 3.8 | 4.0 | |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | 11.0 x $10^{-4}$ | 16.0 | Would not bend to curve under full vacuum. |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | 11.4 | 16.5 | |
| 5.0 | 2 | Perpendicular to curve | 1.27 | 50 | 14.5 | 21.0 | |
| 5.0 | 2 | Perpendicular to curve | 1.27 | 50 | 9.6 | 14.0 | |
| 5.0 | 2 | Parallel to curve | 0.64 | 25 | | | 42.7 N/m$^2$ x $10^{-4}$ (62 psia) applied. No contact. Cracked. |
| 5.0 | 2 | Parallel to curve | .64 | 25 | | | 68.9 N/m$^2$ x $10^{-4}$ (100 psia) applied. No contact. Cracked. |
| 5.0 | 2 | Perpendicular to curve | .64 | 25 | | | 42.7 N/m$^2$ x $10^{-4}$ (62 psia) applied. No contact. Cracked. |
| 5.0 | 2 | Perpendicular to curve | .64 | 25 | | | |
| 5.0 | 2 | Parallel to curve | 0.38 | 15 | | | 42.7 N/m$^2$ x $10^{-4}$ (62 psia) applied. Cracked. |
| 5.0 | 2 | Perpendicular to curve | .38 | 15 | | | Cracked. |
| 2.5 | 1 | Parallel to curve | 2.54 | 100 | 0.69 x $10^{-4}$ | 1.0 | |
| 2.5 | 1 | Parallel to curve | 2.54 | 100 | .69 | 1.0 | |
| 2.5 | 1 | Perpendicular to curve | 2.54 | 100 | .69 | 1.0 | |
| 2.5 | 1 | Perpendicular to curve | 2.54 | 100 | .69 | 1.0 | |
| 2.5 | 1 | Parallel to curve | 1.27 | 50 | 1.7 x $10^{-4}$ | 2.5 | |
| 2.5 | 1 | Parallel to curve | 1.27 | 50 | 2.5 | 3.7 | |
| 2.5 | 1 | Perpendicular to curve | 1.27 | 50 | 1.1 | 1.6 | |
| 2.5 | 1 | Perpendicular to curve | 1.27 | 50 | 1.7 | 2.5 | |
| 2.5 | 1 | Parallel to curve | 0.64 | 25 | 34.5 x $10^{-4}$ | 50.0 | |
| 2.5 | 1 | Parallel to curve | .64 | 25 | 10.3 | 15.0 | |
| 2.5 | 1 | Perpendicular to curve | .64 | 25 | 6.3 | 9.2 | |
| 2.5 | 1 | Perpendicular to curve | .64 | 25 | 6.0 | 8.7 | |
| 2.5 | 1 | Parallel to curve | 0.38 | 15 | | | 31.8 N/m$^2$ x $10^{-4}$ (46 psia) applied. Cracked. |
| 2.5 | 1 | Perpendicular to curve | .38 | 15 | | | 3.5 N/m$^2$ x $10^{-4}$ (5 psia). Cracked. |

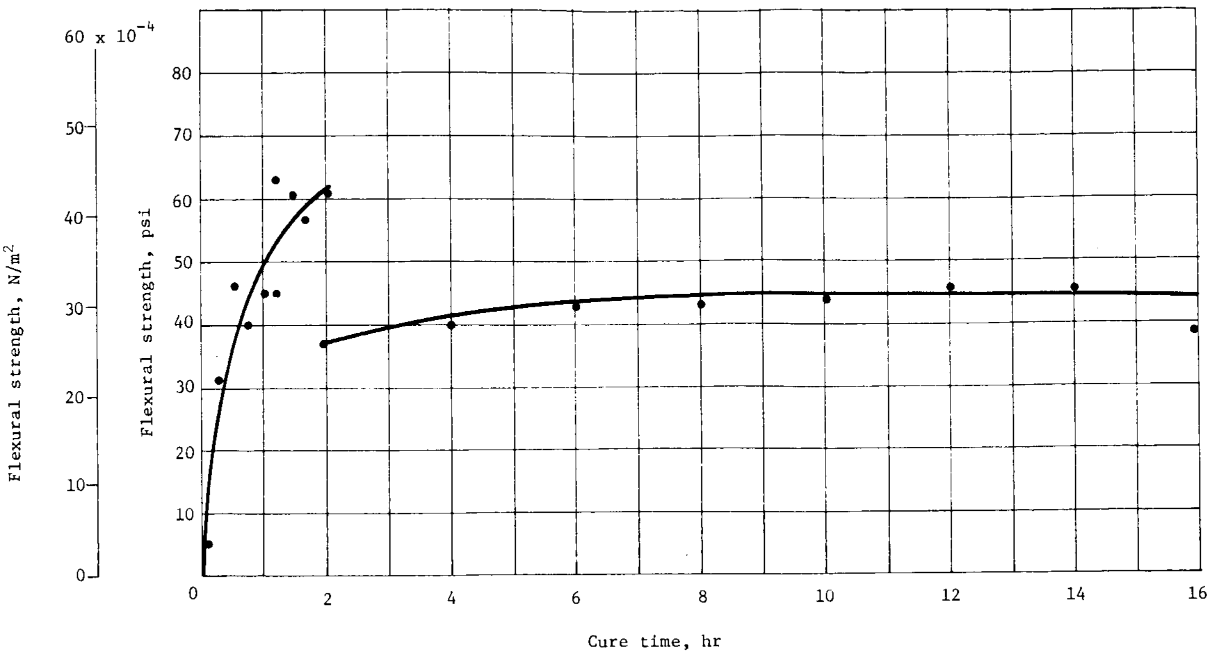



Figure 3.- Flexure Strength at 366°K (200°F)

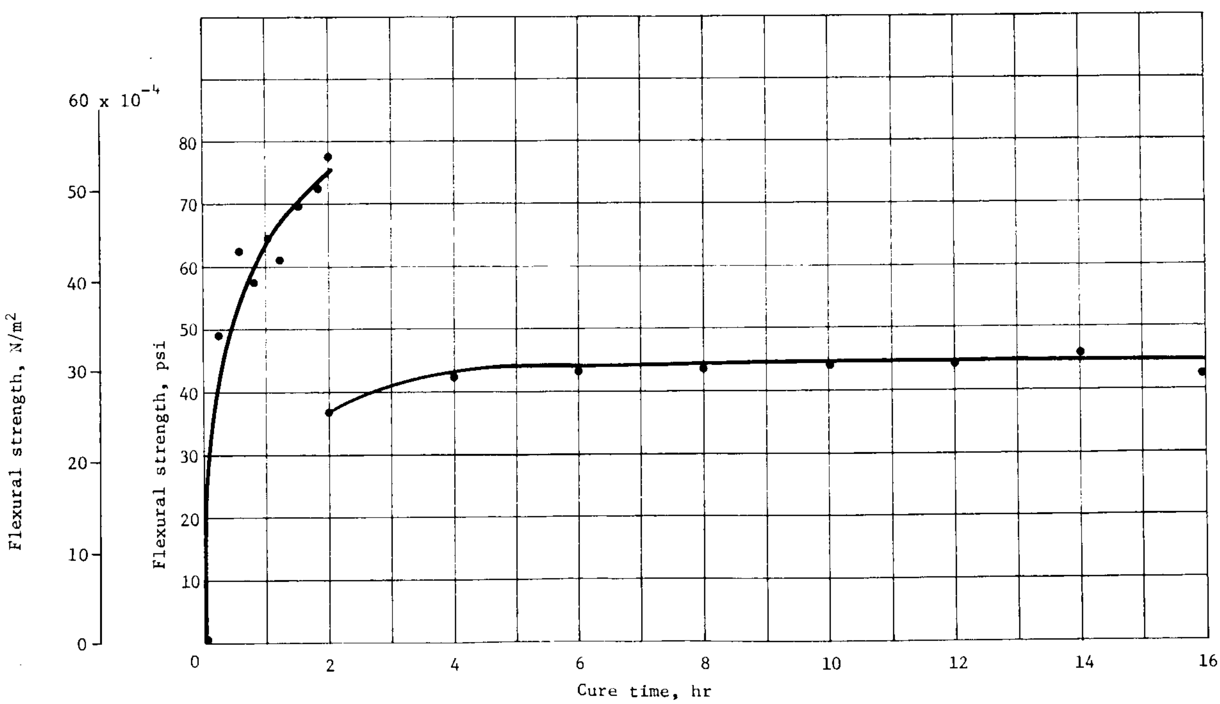



Figure 4.- Flexure Strength at 394°K (250°F)

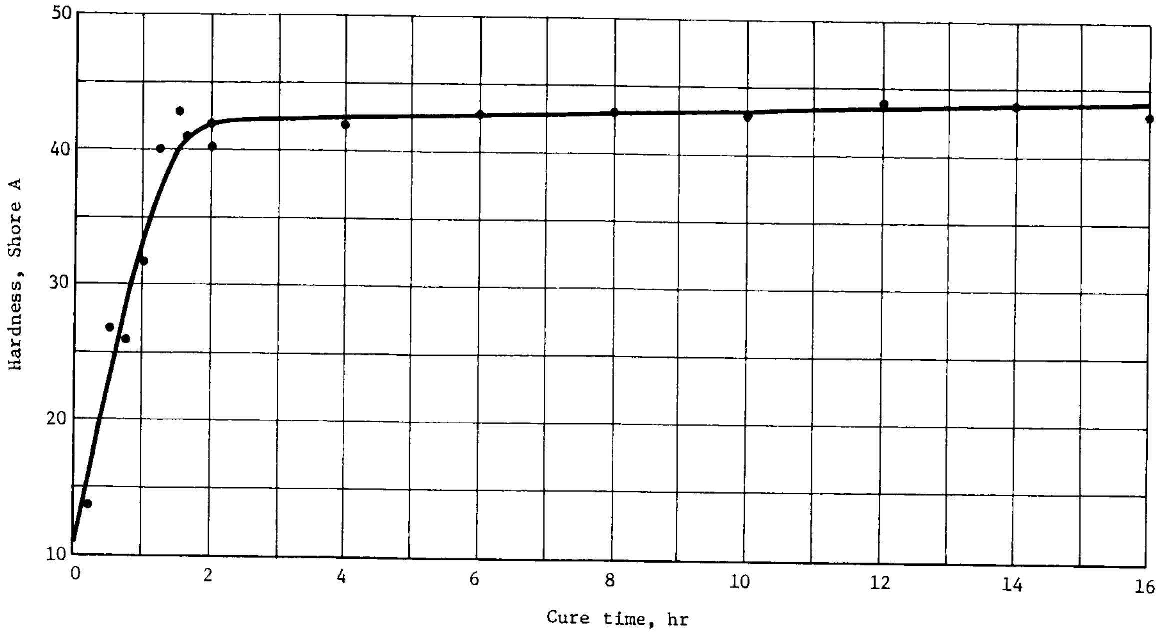



Figure 5.- Hardness after Cure at 366°K (200°F)

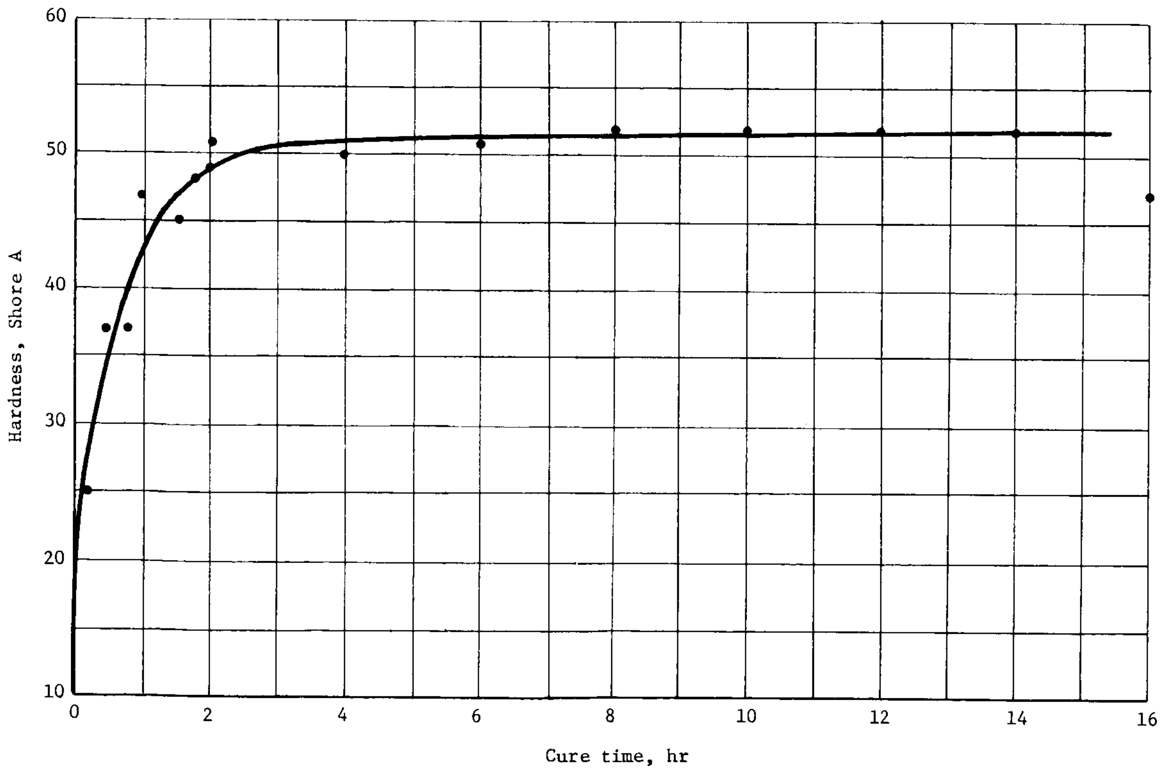



Figure 6.- Hardness after Cure at 394°K (250°F)

difficulties it would be necessary either to change the ablator resin system to give a slower cure rate or to develop a two-step curing system.

## HOT BENDING TEST

Flat ablative panels were fabricated for these tests using a method identical to that used for the room-temperature bending specimens. The same bending mandrels were used. Heat was applied using an autoclave (see fig. 7).

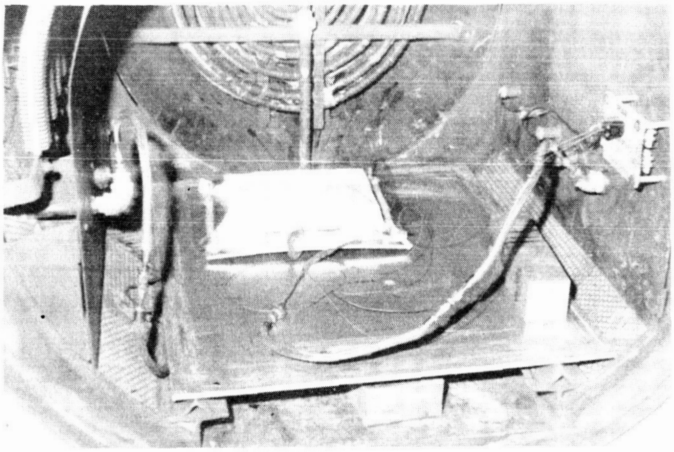


Figure 7.- Panels in Autoclave

After the panels were placed over the mandrels and vacuum-bagged, the assembly was placed in an autoclave and the bag was evacuated. Additional pressure was then applied where necessary. The heat was then started. The relaxation cycle began when the panel reached the test temperature.

The first series of tests consisted of a 2-hr heat cycle at 436°K (325°F) using panels reinforced with hexagonal honeycomb core. Table III gives the results of these tests. Another series of tests was run using two-directional core in place of the standard core. Table IV gives the results of these latter tests.

Several conclusions were drawn from these tests:

TABLE III.- 2-hr HEAT SOAK AT 436°K (325°F) WITH HEXCEL CORE - 30.5x10.2-cm (12x4-in.) PANELS

| Panel thickness | | Ribbon direction | Radius | | Make circuit | | Deflection set radius after 2 hr | | Comments |
|---|---|---|---|---|---|---|---|---|---|
| cm | in. | | m | in. | $N/m^2$ | psia | m | in. | |
| 5.0 | 2 | Parallel to curve | 2.54 | 100 | | | 5.03 | 198 | |
| 5.0 | 2 | Parallel to curve | 2.54 | 100 | $4.1 \times 10^{-4}$ | 6.0 | 5.26 | 207 | |
| 5.0 | 2 | Perpendicular to curve | 2.54 | 100 | 4.6 | 6.0 | 5.26 | 207 | |
| 5.0 | 2 | Perpendicular to curve | 2.54 | 100 | 3.4 | 5.0 | 5.59 | 220 | |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | | | | | Cracked. |
| 5.0 | 2 | Perpendicular to curve | 1.27 | 50 | | | 2.92 | 115 | |
| 5.0 | 2 | Perpendicular to curve | 1.27 | 50 | | | | | Cracked. |
| 2.5 | 1 | Parallel to curve | 2.54 | 100 | $0.69 \times 10^{-4}$ | 1.0 | 5.03 | 198 | |
| 2.5 | 1 | Parallel to curve | 2.54 | 100 | .69 | 1.0 | 4.88 | 198 | |
| 2.5 | 1 | Perpendicular to curve | 2.54 | 100 | .69 | 1.0 | 4.24 | 167 | |
| 2.5 | 1 | Perpendicular to curve | 2.54 | 100 | .90 | 1.3 | 4.16 | 164 | |
| 2.5 | 1 | Parallel to curve | 1.27 | 50 | $3.7 \times 10^{-4}$ | 5.3 | 2.29 | 90 | Slight cracking. |
| 2.5 | 1 | Parallel to curve | 1.27 | 50 | 3.3 | 4.8 | 2.34 | 92 | Slight cracking. |
| 2.5 | 1 | Perpendicular to curve | 1.27 | 50 | -- | -- | -- | -- | Cracked. |
| 2.5 | 1 | Perpendicular to curve | 1.27 | 50 | -- | -- | -- | -- | Cracked. |
| 2.5 | 1 | Perpendicular to curve | 0.64 | 25 | -- | -- | -- | -- | Cracked. |
| 2.5 | 1 | Perpendicular to curve | .64 | 25 | -- | -- | -- | -- | Cracked. |

TABLE IV.- 2-hr HEAT SOAK AT 436°K (325°F) WITH CORE BENT IN TWO DIRECTIONS - 30.5x10.2-cm (12x4-in.) PANELS

| Panel thickness | | Ribbon direction | Radius | | Make circuit | | Initial deflection-set radius | | Comments |
|---|---|---|---|---|---|---|---|---|---|
| cm | in. | | m | in. | $N/m^2$ | psia | m | in. | |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | $32.4 \times 10^{-4}$ | 47.0 | 2.41 | 95 | Cracked. |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | 42.7 | 62.0 | 2.26 | 89 | Cracked. |
| 5.0 | 2 | Parallel to curve | 2.54 | 100 | $3.8 \times 10^{-4}$ | 5.5 | 3.83 | 151 | |
| 5.0 | 2 | Perpendicular to curve | 2.54 | 100 | 2.4 | 3.5 | 3.68 | 145 | |
| 5.0 | 2 | Parallel to curve | 1.27 | 50 | $22.1 \times 10^{-4}$ | 32.0 | 1.68 | 66 | Cracked. |
| 5.0 | 2 | Perpendicular to curve | 1.27 | 50 | 28.3 | 41.0 | 1.75 | 69 | Cracked. |
| 2.5 | 1 | Parallel to curve | 1.27 | 50 | $2.4 \times 10^{-4}$ | 3.5 | 2.26 | 89 | |
| 2.5 | 1 | Perpendicular to curve | 1.27 | 50 | 2.8 | 4.0 | 2.29 | 90 | Cracked after test. |

1) The springback was nonreproducible;

2) The 5.08-cm (2-in.) thick panels could be bent cold to a 1.27-m (50-in.) radius. When heat was applied the panels cracked. This was attributed to the fact that the material's allowable strain properties decrease as the temperature increases. This is typical of this class of materials;

3) Springback was larger than desired;

4) Failures occurred more frequently with the two-directional core than with the hexagonal core.

Figure 8 shows the bent 5.08-cm (2-in.) thick panel. Figure 9 shows the bent 2.54-cm (1.0-in.) thick panel.

A third series of tests, using a 2.54-m (100-in.) radius mandrel, was run to determine if a higher bending temperature, 464°K (375°F), would reduce the springback. Table V gives the results of this test. A slightly better bend was achieved, but the springback was still larger than desired.

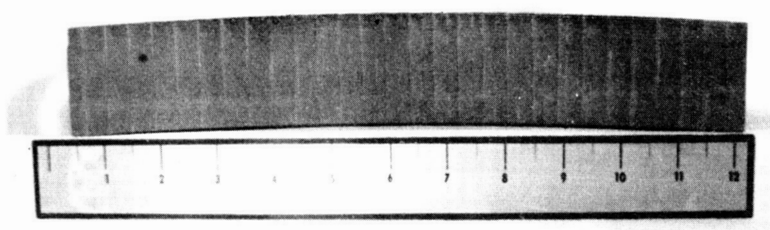


Figure 8.- Bent 5.08-cm (2-in.) Thick Panel

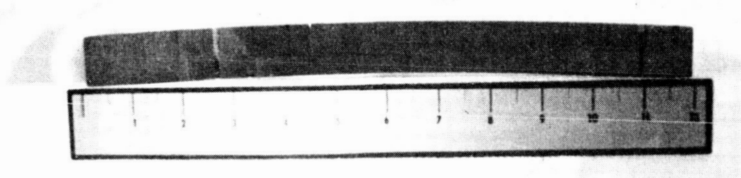


Figure 9.- Bent 2.54-cm (1.0-in.) Thick Panel

TABLE V.- HOT BEND TEST - 2 hr AT 464°K (375°F)

| Panel thickness | | Mandrel radius | | Core type | Ribbon direction | Radius formed | |
|---|---|---|---|---|---|---|---|
| cm | in. | m | in. | | | m | in. |
| 5.08 | 2.0 | 2.54 | 100 | Hexcel | Parallel to curvature | 4.28 | 175 |
| 5.08 | 2.0 | 2.54 | 100 | Hexcel | Perpendicular to curvature | 4.12 | 168 |

In the next series of tests we used a smaller bending radius, 1.27 m (50 in.), and held the temperature at 394°K (250°F) for a longer time. This was to determine if we could keep the actual strain below the allowable strain and produce a better set. Table VI gives the results of these tests.

Despite this approach, we were still exceeding the strain limit. The panels cracked. During the previous tests we had noted that when the panels were bent perpendicular to the ribbon direction less cracking occurred. As a result, we made a new mandrel with a 1.65-m (65-in.) radius and repeated the test using this mandrel, changing the bending direction with respect to the core ribbons. Table VII gives the results of these tests.

As shown in the table, this eliminated cracking of the panels, but the data scatter was still large and an insufficient set occurred. By this point, time was running out and the large deliverable hardware had to be committed to fabrication. Therefore, a best-guess fabrication method was established and fabrication was begun. The curing cycle was derived from the following considerations:

1) The panels could be bent on a 1.65-m (65-in.) radius using a 4-hr cure at 394°K (250°F);

2) The core ribbon should be perpendicular to the bending direction;

3) The panels bent at 394°K (250°F) did have a permanent set, and we assumed that some of the residual strain had been relieved;

4) Using a higher-temperature cycle would increase the set.

## FABRICATION OF LARGE PANELS

Under this contract we were to fabricate six large-scale panels (see fig. 10) to determine if there were any problems associated with scaling and to determine the repeatability of the process. Six flat panels, each 0.457 m (18 in.) square, were fabricated using hexagonal core reinforcement, filled with SS-41 ablative material, and cured for 16 hr at 394°K (250°F) under vacuum pressure. After being cured, two of the panels were machined to a thickness of 5.08 cm (2 in.); the other four, to a thickness of 2.54 cm (1 in.). A picture frame was then made to accommodate the larger panels.

TABLE VI.- HOT BEND TEST - 4 hr AT 394°K (250°F)

| Panel thickness | | Mandrel radius | | Core type | Ribbon direction | Radius formed | | Comments |
|---|---|---|---|---|---|---|---|---|
| cm | in. | m | in. | | | m | in. | |
| 5.1 | 2 | 1.27 | 50 | Hexcel | Perpendicular to curvature | 3.13 | 128 | |
| 5.1 | 2 | 1.27 | 50 | Hexcel | Parallel to curvature | 3.08 | 126 | Cracked. |
| 5.1 | 2 | 1.27 | 50 | Two-directional | Perpendicular to curvature | 4.01 | 164 | Cracked. |
| 5.1 | 2 | 1.27 | 50 | Hexcel | Perpendicular to curvature | 2.18 | 89 | Cracked. |
| 2.54 | 1 | 1.27 | 50 | Hexcel | Parallel to curvature | 3.97 | 162 | Cracked. |
| 2.54 | 1 | 1.27 | 50 | Hexcel | Perpendicular to curvature | 3.83 | 156 | Cracked |

TABLE VII.- HOT BEND TEST WITH NEW MANDREL - 4 hr AT 394°K (250°F)

| Panel thickness | | Mandrel radius | | Core type | Ribbon direction | Radius formed | | Comments |
|---|---|---|---|---|---|---|---|---|
| cm | in. | m | in. | | | | | |
| 5.12 | 2 | 1.65 | 65 | Two-directional | Perpendicular to curvature | 6.2 | 253 | |
| 5.12 | 2 | 1.65 | 65 | Hexcel | Perpendicular to curvature | 6.89 | 281 | |
| 5.12 | 2 | 1.65 | 65 | Hexcel | Perpendicular to curvature | 4.01 | 164 | |
| 5.12 | 2 | 1.65 | 65 | Hexcel | Perpendicular to curvature | 4.64 | 189 | |

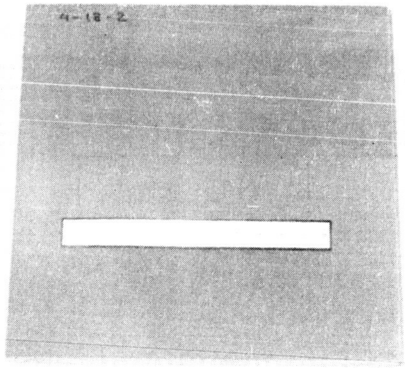


Figure 10.- Large [0.46x0.46-m (18x18-in.)] Panels

The following procedure was used for bending and measuring all six panels:

1) The panel was placed in the tool and vacuum-bagged;

2) The panel was then placed in the autoclave, and the bag was evacuated;

3) Next, the autoclave was pressurized to $42.7 \times 10^4$ N/m$^2$ (62 psia), which includes $8.3 \times 10^4$ N/m$^2$ (12.0 psia) from the evacuated vacuum bag, and then heated to 394°K (250°F). (The cure cycle started once the panel reached the desired temperature);

4) The panel was held under the desired pressure and heat for 4 hr, then cooled to 356°K (150°F) under pressure and removed to measure the deflection;

5) After measuring the deflection, the panel was rebagged and repressurized;

6) The autoclave was heated to 436°K (325°F) and held at that temperature for 1 hr;

7) The panel was then cooled to 356°K (150°F) under pressure and removed to remeasure its deflection;

8) The deflection was again measured 2 hr later.

(NOTE: The panels were removed from the autoclave after the 394°K (250°F) cure only to obtain additional data. The normal cycle would be to go directly to 436°K (325°F) without a cool-down and rebagging operation.)

After 2 weeks the radius of curvature of the panels was remeasured to determine if there had been any change. (During this period the panels were laying on flat shelves and were not supported under their curved surface.) A change in the dimension was noted. The panels were then packaged so that they were fully supported over the curved surface and were then stored. Approximately 1 1/2 months after being bent the panels were again remeasured. The results of these measurements are given in table VIII.

TABLE VIII.- 0.46x0.46-m (18x18-in.) LARGE-PANEL BEND TEST - 1.65-m (65-in.) RADIUS MANDREL

| Panel thickness | | Radius after 4 hr at 394°K (250°F) | | Initial radius after 1 hr at 436°K (325°F) | | Radius after 2 hr | | Radius after 2 weeks | | Radius after 1½ months | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| cm | in. | m | in. | m | in. | m | in. | m | in. | m | in. |
| 2.5 | 1 | 6.09 | 240 | 3.48 | 137 | 3.99 | 157 | 4.11 | 162 | 4.54 | 179 |
| 2.5 | 1 | 5.76 | 227 | 3.32 | 131 | 3.99 | 157 | 5.03 | 198 | 5.26 | 207 |
| 2.5 | 1 | -- | -- | 2.56 | 101 | 2.76 | 109 | 3.61 | 142 | 3.56 | 140 |
| 2.5 | 1 | 4.32 | 170 | 2.97 | 117 | 3.02 | 119 | 4.11 | 162 | 4.34 | 171 |
| 5.0 | 2 | 4.98 | 196 | 3.12 | 123 | 3.22 | 127 | 3.61 | 142 | 4.99 | 197 |
| 5.0 | 2 | 4.16 | 164 | 2.74 | 108 | 3.02 | 119 | 3.28 | 129 | 3.5 | 138 |

The large panels had varying rates of springback and continued to straighten out up to the time they were shipped. Whether the panels were supported or not did not appear to prevent them from straightening. This phenomenon is attributed to locked-in stresses present in the curved panels. Apparently, the heat cycles that were used did not completely relax the panels.

It is also worth noting that there was no deflection perpendicular to the bending direction. Unfilled honeycomb core, when bent in one direction, also tends to bow up in the other direction. However, no evidence of this bowing was found with either the small samples or the large panels.

Longer curing times at higher final temperatures might produce a sharper radius of curvature. However, since autoclave pressure is required for the 5.08-cm (2-in.) thick panels, this would tie up expensive capital equipment.

# COST ANALYSIS

Taking flat stock panels and forming them into curved panels has several advantages. One advantage is that a larger number of stock flat panels can be made for later custom forming. This would reduce cost by moving the accumulated average cost further along a given learning curve. A second advantage is that the thickness may be machined in a flat configuration rather than in a curved configuration.

On the negative side, essentially the same curved tooling is required whether the panel is cured to a given curvature or later formed to the curvature. Furthermore, on thick sections, autoclave pressure is required to bend the panels to the desired radius. And finally, an additional step of heat-treating the panel to introduce a curvature is required.

To estimate the cost of fabricating curved panels from flat stock sheets we modified the cost estimates used in two previous NASA contracts, NAS1-10793 (ref. 1) and NAS1-9946 (ref. 2). The following steps were taken to arrive at the estimates. Figure 11 shows this calculation.

1) The cost of fabricating curved panels by curing them in a curved configuration was arrived at by applying the cost factors from reference 1 to the cost computed for curved panels under reference 2. This procedure updates the cost estimates for curved panels to reflect the latest figures.

2) The time saved due to using simpler machining operations for flat panels was found to be 24 minutes per panel. The added time for bending was found to be 63 minutes. The net time (cost) increase required to fabricate a curved panel instead of a flat panel is therefore 39 minutes.

3) The cost per unit area per run time was then computed for a 100-panel lot. This cost was then multiplied by the additonal 39 minutes required, which gives the cost differential for fabricating curved panels.

4) Next the unit cost for 1000 flat panels was added to the delta cost of bending the panels (based on a 100-unit lot).

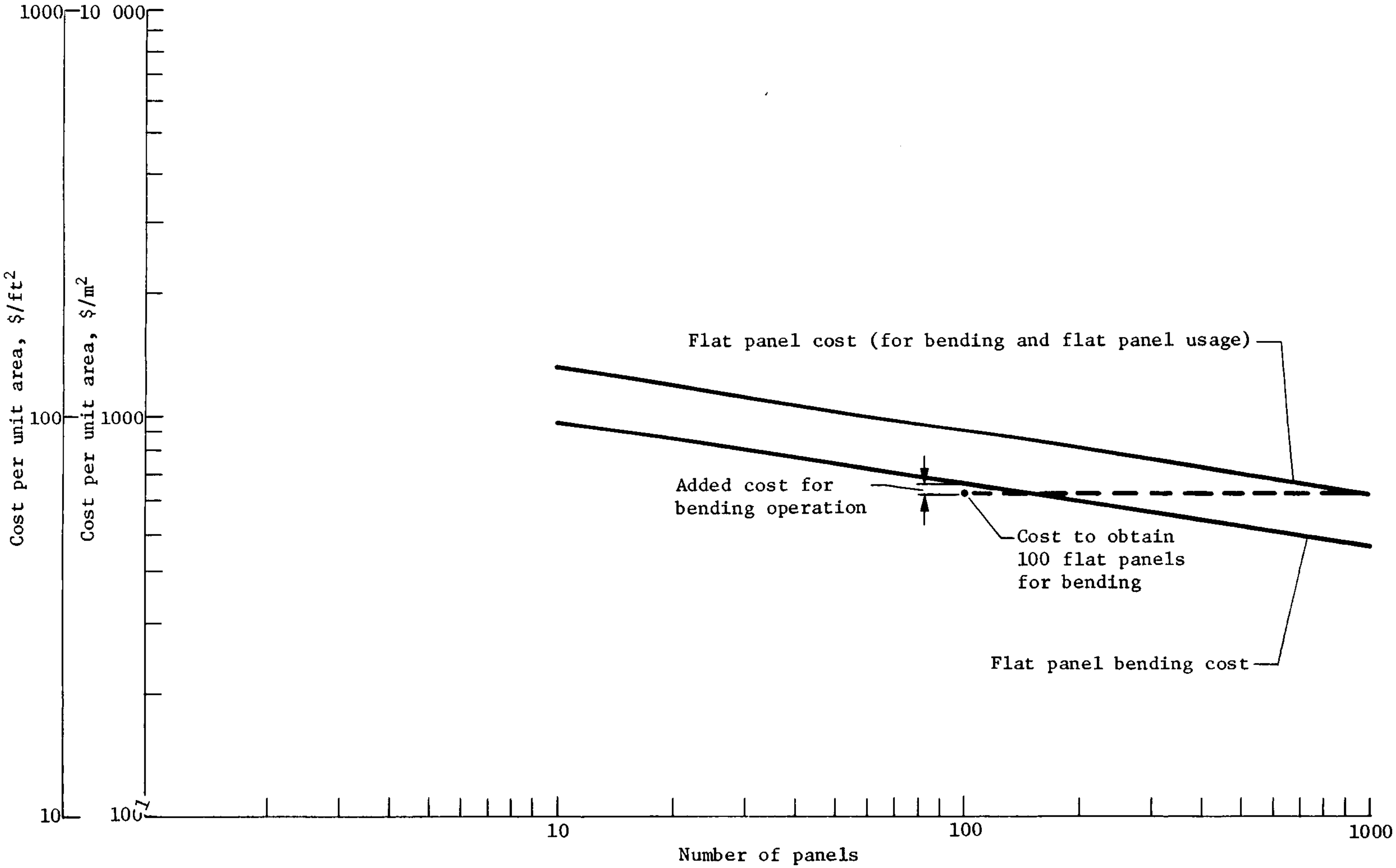



Figure 11.- Cost per Unit Area for Various Numbers of Panels

5) The above figure is now the estimated cost for fabricating one curved panel in lots of 100.

6) The cost for forming curved panels from flat panels (Item 4) was subtracted from the cost of fabricating curved panels computed using the old method (Item 1) to arrive at a net saving.

7) To determine the per-panel cost for lots of 10 and 1000 panels, the unit cost arrived at for a 100-panel lot was adjusted using the same factor applied to the flat panels estimated in reference 1.

Table IX gives the results of the cost analysis conducted under this study. The real savings are realized by being able to make larger amounts of flat panels. The cost differential for an equal number of panels made by the old process vs the new process indicates that fabrication costs would be higher for fabricating and bending the flat panels than for forming the curved panels directly.

TABLE IX.- PANEL COST PER UNIT AREA FOR CURVED PANELS

| Process | Number of panels | | | | | |
|---|---|---|---|---|---|---|
| | 10 | | 100 | | 1000 | |
| | $\$/m^2$ | $\$/ft^2$ | $\$/m^2$ | $\$/ft^2$ | $\$/m^2$ | $\$/ft^2$ |
| Old method | 1362 | 126.68 | 939 | 87.35 | 660 | 61.35 |
| Flat panel bending | 963 | 89.54 | 664 | 61.74 | 466 | 43.36 |
| Saving | 399 | 37.14 | 275 | 25.61 | 194 | 17.99 |

The above costs are for 0.61-m x 1.22-m x 5.08-cm (2-ft x 2-ft x 2-in.) panels.

## CONCLUSIONS

The following conclusions were made during the study.

1) The Shuttle Orbiter TPS has a large radius of curvature over most of the surface panels. Seventy six percent of the surface area has a radius of 6.35 m (250 in.) or larger.

2) Panels can be bent at room temperature to a smaller radius then when hot. A strain is introduced into the panel when it is bent. When the panel is heated to set the bend, a failure will occur. The allowable strain of the ablative material decreases with a rise in temperature.

3) The procedure in which partially cured panels are bent and the bending temperature cycle is allowed to complete the panel cure proved to be unfeasible. The resin system used in the ablator material cured before the phenolic resin coating on the honeycomb core. The phenolic resin is used to bond the ablator matrix to the reinforcing core. Without a bond established, the panels failed when a bending load was applied.

4) There is considerable scatter in the amount of springback. We are not sure why this variable springback occurs from panel to panel.

5) The cure cycles investigated still left locked-in residual stresses in the panels. These residual stresses cause the panels to continue to straighten out over time after the bending cycle.

6) A substantial cost savings can be realized by bending flat panels instead of forming curved panels directly. A large number of similar flat panels could then be fabricated for a given ship.

7) The process is not recommended at this time due to unknown process variables and residual stresses in the panels.

Martin Marietta Corporation
Denver, Colorado 80201
September 1, 1972

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2. Chandler, Huel H.: *Low-Cost Ablative Heat Shields for Space Shuttles*. NASA CR-111800. Martin Marietta Aerospace, Denver, Colorado, October 1970.