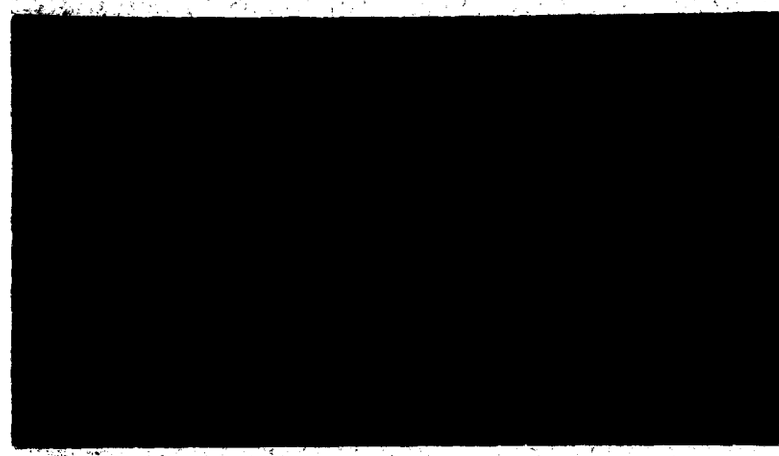

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DEVELOPMENT OF LIGHTWEIGHT GRAPHITE/POLYIMIDE SANDWICH PANELS PHASES III, IV AND V

H400-12-1-12

October 1972

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Prepared by

HERCULES INCORPORATED
SYSTEMS GROUP
Bacchus Works
Magna, Utah

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas

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Date October 1972

DEVELOPMENT OF LIGHTWEIGHT GRAPHITE/POLYIMIDE SANDWICH PANELS PHASES III, IV AND V

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FOREWORD

This report covers the work performed in Phases III, IV and V of National Aeronautics and Space Administration (NASA) Contract NAS 9-11368 during the period of 1 June 1971 through 1 August 1972. The work was performed under the sponsorship of the NASA Manned Spacecraft Center R&D Procurement Branch. The program is administered under the direction of Mr. T. J. Dunn, Technical Monitor.

The work was performed by the Composite Materials Development Department, Hercules Incorporated, Bacchus Works, Magna, Utah.

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ABSTRACT

Work performed in the last three phases of the program is reported. Specific elements include:

(1) Face Sheet Processing

(2) Honeycomb Core Manufacture

(3) Face Sheet-to-Core Bonding Development

(4) Sandwich Panel Fabrication and Testing

Resin cure studies were a major portion of this effort since processing problems traced to the polyimide matrix resin had to be resolved before quality core and face sheets could be fabricated.

Honeycomb core fabrication and testing were conducted by Hexcel Corporation. A total of four graphite/polyimide resin composite cores were fabricated, tested, and reported.

A polyimide adhesive selection and development program resulted in the use of Whittaker Thermadite 17 as the core-to-face sheet bonding adhesive. Composite beams were assembled with this and tested at temperatures from 172°K (-150°F) to 588°K (600°F).

Two sandwich panels weighing .48 and .58 lb/sq ft, respectively (excluding foamed edge closure), were designed and fabricated which meet the support structure loads for the shuttle orbiter thermal protection system.

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DEVELOPMENT OF LIGHTWEIGHT GRAPHITE/POLYIMIDE HONEYCOMB

A. INTRODUCTION

The payload potential of any large re-entry vehcile is sensitive to the weight of its thermal protection system. One thermal protection system being studied by NASA/MSC utilizes an external insulation which is supported by a stiff lightweight substructure as shown in Figure 1. Studies run by several contractors concluded that a sandwich panel employing fiberglass core and high modulus graphite composite face sheets offered a decided weight advantage over titanium corrugation, titanium sandwich, and other combinations of metal face sheets on fiberglass core. A study run by TRW[1] concluded that the minimum weight panel in every condition utilized the minimum weight fiberglass core presently available. It was further concluded that the development of a lightweight core, less than 2.0 lbs/cu ft, with a small cell size would produce substantial additional weight savings.

In the design application being considered, that is a simply supported sandwich panel under a distributed load, there are two primary sandwich core parameters which control the final design of the structure. The first is the shear allowable, F_s', of the core material. The second is the product of the core elastic compressive (E_c) and shear modulus (G_c) values to the 1/3 power. The latter function is of importance in maintaining face sheet stability. The structural efficiencies of various core materials can then be compared as in Figure 2 by plotting specific strength F_s'/ρ_c' versus specific stiffness $(E_c' G_c')^{1/3}/\rho_c'$. The advantage of graphite composite is evident.

The core properties shown on Figure 2 for non-graphite material are based upon measured core properties. The core properties presented for the various graphite core stock materials were predicted using composite properties and empirical equations developed from metal core[2] with correction coefficients developed to be more consistant with fiberglass composite core performance. Thus, although the analytical structural advantage of graphite composite was evident, demonstration of these values had not been obtained, particularly at low core densities and temperatures up to 588°K (600°F). The demonstration of the anticipated structural advantage of graphite composite and the development of the tools and techniques necessary to produce extremely lightweight honeycomb sandwich panels, therefore, became the objective of this program.

The program was conducted in five phases as follows:

Phase I - Materials Selection
Phase II - Thin Gage Material Manufacture
Phase III - Fabrication Studies
Phase IV - Design and Manufacture of Panels
Phase V - Panel Testing and Design Allowables Determination

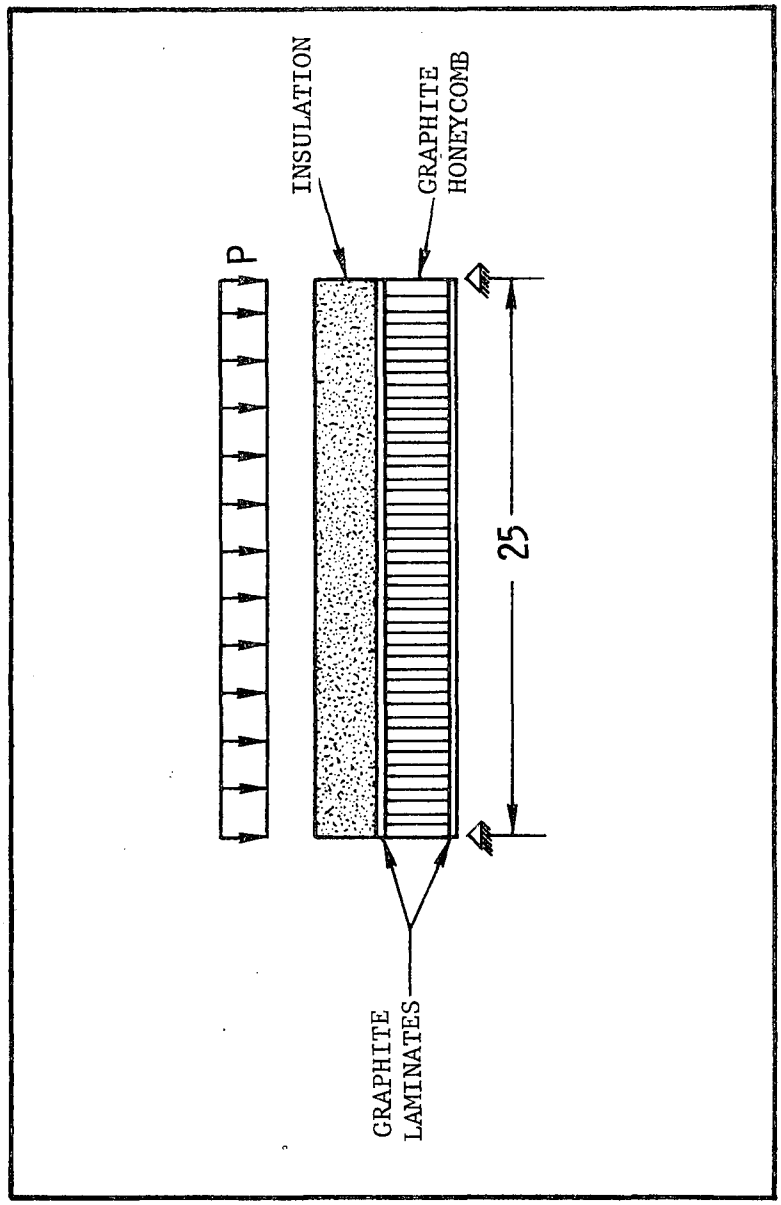

Figure 1. Panel Configuration

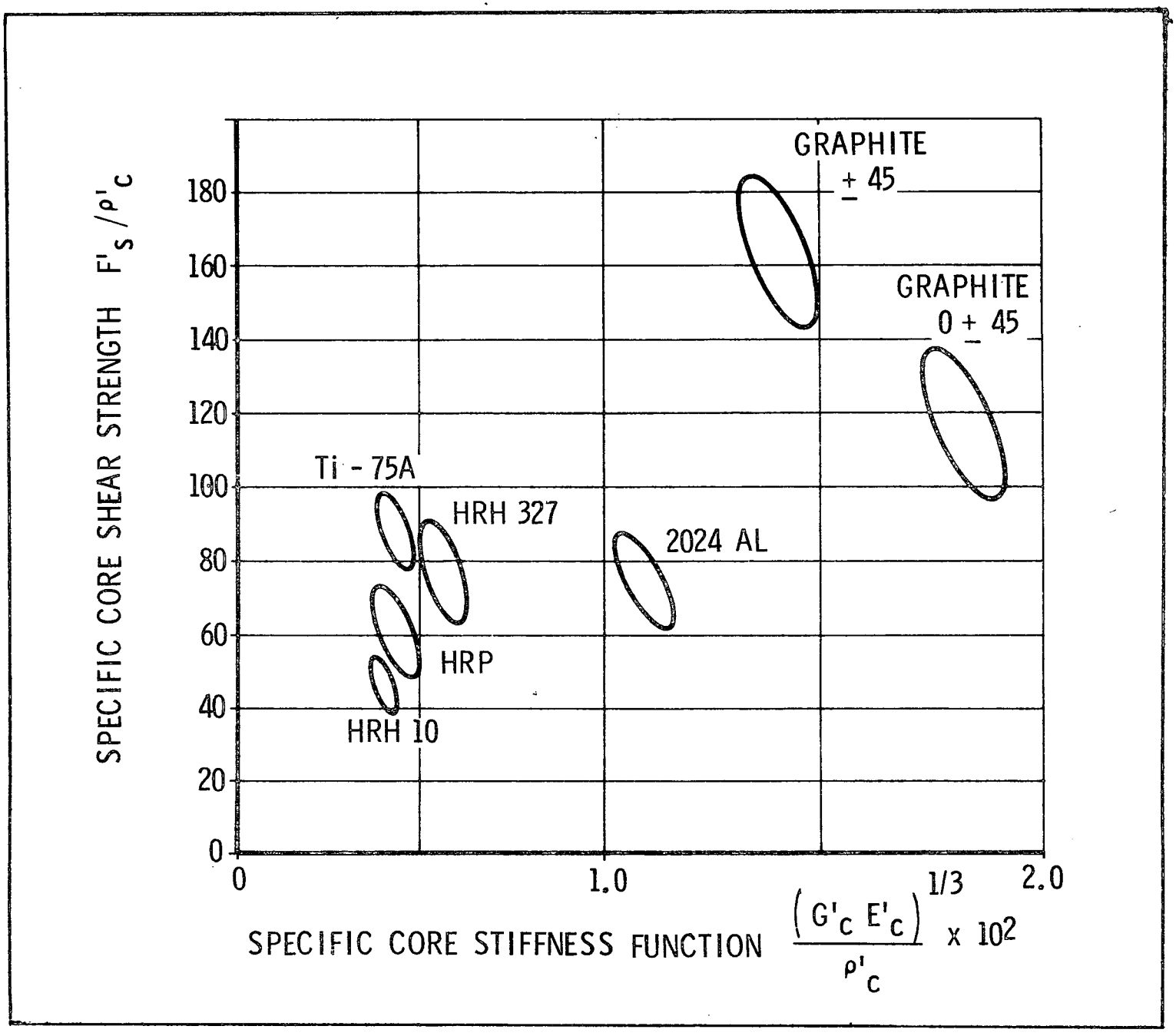

Figure 2. Structural Efficiency of Honeycomb Core Materials

Reports covering the work conducted in Phase I[3] and Phase II[4] were issued at the ends of the respective phases. This report covers the work accomplished during Phases III, IV, and V.

The materials selected, as reported in the Phase I report, were Hercules HM-S fiber for the face sheets and HT-S fiber for the sandwich core with Monsanto RS6234 (Skybond 710) polyimide resin matrix. A $\pm$ 45° orientation using unidirectional prepreg was selected for the core laminate orientation because of superior properties and a potential lower cost. Forms such as random mat and oriented mat did not offer significant cost reduction and produce less optimum properties.

The process by which thin gage prepreg material was fabricated is reported in the Phase II report.

B. RESIN CURE STUDIES

Resin cure studies were a significant portion of the Phase III effort since processing problems traced to the polyimide matrix resin had to be resolved before quality core and face sheet subcomponents could be fabricated. The problem manifests itself as a formulation of dry, granular particles of resin during the cure cycle instead of a continuous polymer. This condition is referred to as precipitation and was of large enough importance to warrant a section of this report.

The matrix resin, Monsanto RS6234, is a heat reactive aromatic system which is thermally cured to a cross-linked polyimide. The first lots of prepreg produced at Hercules were autoclave cured under a vacuum following a General Dynamics/Convair developed autoclave cure cycle[5], shown below, for evaluation in the Phase I material evaluation program. Although these plates showed evidence of slight precipitation, the phenomenon was overlooked when respectable mechanical properties were obtained.

General Dynamics Cure Cycle for RS6234

Vacuum bag and pull vacuum on lamination for 30 minutes.
Place in autoclave.
Heat to 352°K (175°F) at 1.7°K (3°F)/minute under full vacuum.
Hold at 352°K (175°F) for 30 minutes.
Heat to 394°K (250°F) at 1.7°K (3°F)/minute under full vacuum.
Hold at 394°K (250°F) for 30 minutes.
Apply 100 psi.
Heat to 453°K (350°F) at 1.7°K (3°F)/minute.
Hold at 453°K (350°F) for 60 minutes.
Cool to 338°K (150°F). Release pressure and vacuum.

The first real evidence of the precipitation problem occurred when Hexcel Corporation, the honeycomb core processor, tried to corrugate some trial lots of thin (.002 in.) prepreg with a one step/no vacuum cure cycle. The elimination of vacuum in the final cure is desirable to reduce the cost of core fabrication.

Hexcel obtained dull red patches in the laminates they processed without vacuum. A program was initiated to solve this problem.

A series of webs was fabricated in order to develop a press cure procedure which did not use vacuum in the final cycle. The general procedure for these webs was to place the prepreg on preheated platens, allow sufficient time for the solvent to flash off and immediately close and pressurize the mold. Temperature from 394°K (250°F) to 588°K (600°F) were evaluated using flash times from 30 seconds up to 30 minutes. Ethanol and xylene solvents were driven off by this method. A third solvent, n-methyl-2-pyrrolidone or NMP, does not boil off until about 477°K (400°F) without vacuum. At the higher "drying" temperatures, the resin reaction occurs faster than the NMP evaporation causing the resin to "coagulate" in the solution. The formation of these particles in the presence of the solvent causes a dull red dust, whereas good resin is generally clear or very dark. Upon microscopic examination, the precipitant appears granular, is easily removed by scraping, and, in the extreme case, contains thermal shrinkage cracks, a sign of its very poor strength. When heated to over 533°K (500°F), the precipitant changes from a dull red to a dull yellow-gold color. Cure pressures in excess of 900 psi merely pack the hardened granules closer together.

Although these initial trials were generally unsuccessful, a key factor in the processing was found to be timely removal of the NMP solvent.

Members of the Monsanto high temperature resin group were consulted at the Bircham Bend Plant in Springfield, Massachusetts. Dr. Irving Serlin, Dr. Albert Markhart and others reviewed the prepregging procedure to prevent possible premature formation of precipitation. The following potential problems were noted: (1) Straining of the resin for prepregging could be a problem as particles of a proprietary "flow control" material may be inadvertently removed. This solid additive is present in 2 to 4 weight percent in order to reduce flow at high temperatures. (2) Staging of the resin for one-half hour at 366°K (200°F) to 377°K (220°F) is acceptable as long as the prepreg is uncovered. The resin should not be heated above 324°K (125°F) in a covered condition where no provision has been made to bleed off volatiles.

The next area of discussion was on heat-up rates and curing. Dr. Serlin preferred a one-step cure cycle which is in direct contrast to General Dynamics/Convair's developed cycle. He recommended going from room temperature to 373°K (212°F) with only partial vacuum (5-in.) to maximize ethanol removal and minimize xylene loss. In this temperature range, the polyamic acid polymer is formed slowly and the retention of xylene maintains flowability of the resin. Flow is maintained up to 393°K (248°F). At 373°K (212°F) and above, rapid chain growth occurs; and it is time to remove all the ethanol and xylene as they are no longer required. So, apply full vacuum at 408°K (275°F) (one hour into the cure) while still maintaining a rapid heat-up rate. Flow is controlled after the xylene is drawn off because the proprietary solid is present and prevents excessive flow as the resin heats up. The NMP, which is still

present, holds the formed polyamic acid in solution during the chain formation since the resin in this form is still soluble in NMP. As the imidization begins to occur rapidly (approximately 423°K (302°F)), it is necessary to get the NMP out as the polyimide will precipitate if NMP is present. A hold between 393°K (248°F) and 453°K (350°F), or the application of pressure too soon, would cause problems by allowing the polyamic acid to imidize in the presence of solvent resulting in precipitation. By rushing through the temperature range of 408°K (275°F) to 453°K (350°F) under full vacuum, the majority of the NMP is boiled off before much of the acid is formed into polyimide. This is assured by holding at 453°K (350°F) for five minutes before applying 100 psi. Full vacuum and pressure are maintained at 453°F (350°F) until the cure is complete (two hours) and cooled to 339°K (150°F).

Water does not affect the cure (hydrolysis) and was proved to Monsanto's satisfaction by adding 10 percent water to the resin. Good laminates were obtained by Serlin with the water contaminated resin. However, aluminum/polyethylene/paper sheets should be used for bagging prepreg to keep in the solvents (xylene) and keeping out moisture which may cause problems in other ways (wrinkling of the release paper for example).

Unsuccessful attempts were made to precipitate 6234 from solution; however, the resin was found to be soluble in both acetone and methyl alcohol. Heating diluted 6234 at reduced viscosities (330 cps) showed considerable solvent retention below 408°K (275°F) and heating small samples of resin at temperatures above 408°K (275°F) resulted in a "dry, crusty (brittle) material". Figure 3 shows weight losses with continued heating of RS6234/graphite prepreg. Initial values of resin, solvent and fiber content were 44, 26, and 30 percent, respectively.

After consulting other processors of RS6234 and reviewing the experimental cure data generated by both Hercules and Hexcel, a special laminating process applicable only to very thin laminates was developed. Since release of volatiles was so critical and use of vacuum objectionable to Hexcel, a compromise technique was formulated. Sheets of heavy porous Armalon were placed next to the surfaces of the prepreg to provide a gas path for the volatiles to escape. This passage was purposely substantially porous to remain open throughout the cure. A moderate temperature drying step prior to processing under vacuum reduced the initial prepreg volatile content from 22 percent to less than 12 percent. The dried prepreg is then sandwiched between the porous sheets and cured with heat and pressure. Hexcel slightly modified this cure process to make it more amenable to their equipment. The final procedure developed for fabrication of honeycomb webs is given below:

(1) Heat flash prepreg in oven for 10 minutes at 366°K (200°F) sandwich prepreg between porous Armalon).

(2) Vacuum bag in oven. (Heat for 25 minutes from room temperature toward 394°K (250°F). Shut off heaters after

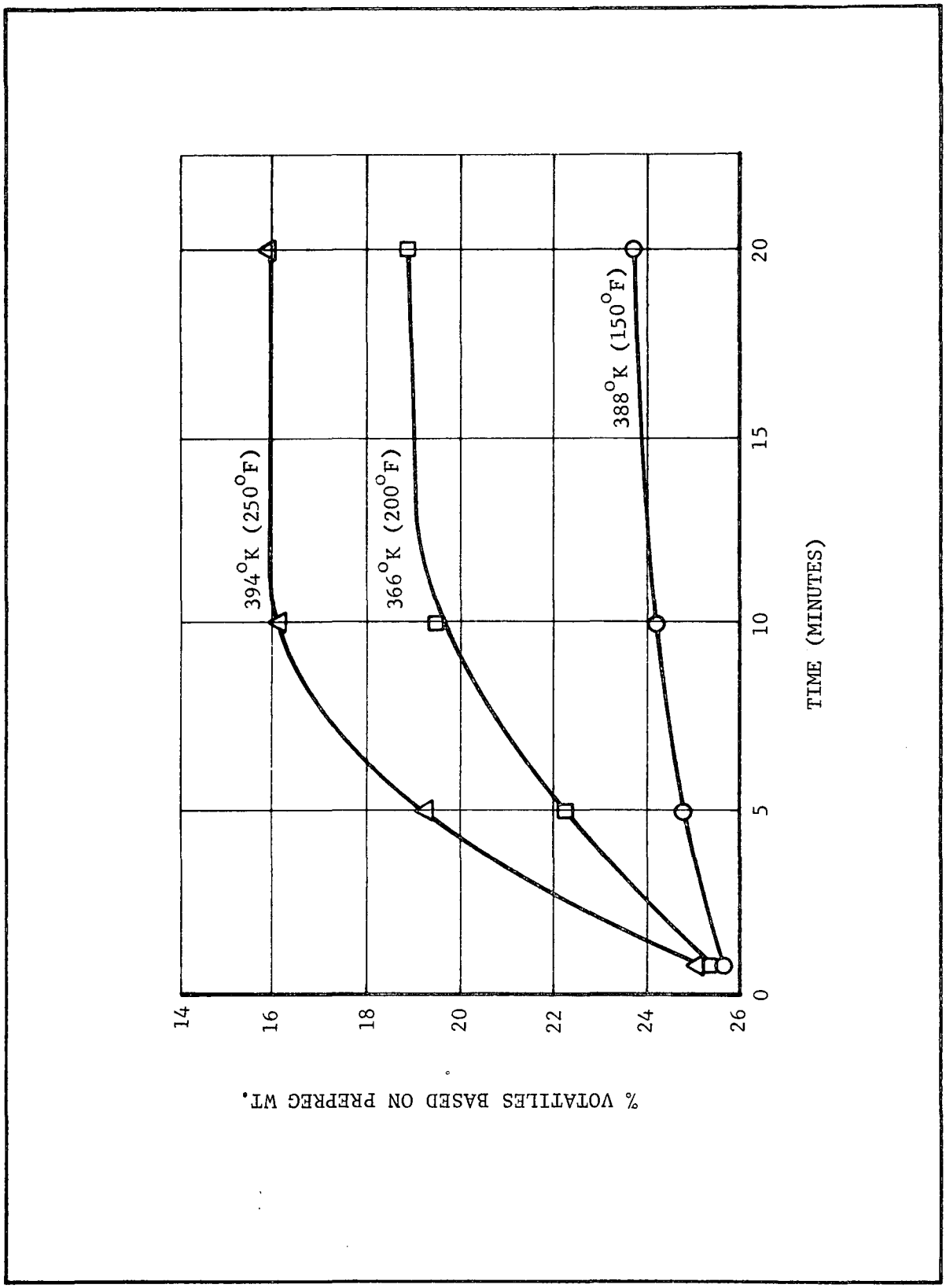

Figure 3. Prepreg Volatiles Content Versus Oven Drying Time and Temperature

25 minutes. Temperature should be near 394°K (250°F) at this time.)

(3) Corrugate plies being careful not to exceed 408°K (275°F).

(4) Press cure without vacuum in corrugated platens.

Several thin laminates were successfully cured with reduced per-ply thicknesses and without visible precipitation by incorporating the "non-vacuum" cure cycle. A temperature of 402°K (265°F) appeared to be a limiting drying temperature. Excessive temperatures resulted in either premature resin reactions or excessive xylene loss (and thus poor flow/compaction during cure). The maximum laminate thickness whereby good resin could be obtained without vacuum appears to be .010 in. The cross plied honeycomb webs were well within this limitation.

At this point in the program, an informal report was generated by General Dynamics/Convair regarding the RS6234 precipitation problem. This report gives several explanations for the causes of the precipitation and a description of the apparent chemical reactions occurring during the cure. It asserted that measurable changes in the acid equivalent number (AEN) of the resin influence the precipitation behavior of the resin and that values around 540 were desirable. However, at the meeting with Dr. Serlin, Mr. Lavin, Dr. Markhart and Mr. Morris at Monsanto, Hercules was told that the AEN was not a critical value in controlling 6234 resin.

Samples of the two remaining lots of RS6234 resin were sent to Ferro Corporation for AEN tests. Lot #3409 gave a value of 565.7 and Lot #3506 gave 577.8. Although the test data indicate an excessive AEN for both lots, thin laminates cured using this matrix resin were visibly free of precipitation; thus, the acid equivalent number was not inserted as a requirement on purchases of resin for thin laminates.

1. Microscopy

Regular microscopic examination at 1500X of precipitated 6234 resin failed to reveal the nature of the precipitation in early composites. At these higher magnifications, visual clarity degenerates to a point where conclusions become difficult.

The Scanning Electron Microscope (SEM) was, therefore, used throughout the program to assist in evaluations of resins and adhesives. Visual records of these studies were made with both the SEM and other conventional microscopic equipment.

Several samples of the precipitated composite were prepared for SEM examination at the University of Utah SEM laboratory. Prior to examining the precipitated resin, a sample of good matrix resin was photographed (Figure 4). Note the clean fractures and adhesion of the matrix resin (BP-907 epoxy) to the HM-S fibers indicating good resin strength

and consistency. The second SEM recording (Figure 5) is of an HT-S/P13N composite taken at the Hercules Research Center. Note that here again good matrix to fiber bonds can be found along with clean matrix fractures.

Figures 6 and 7 are SEM records of a delaminated composite with precipitated RS6234 resin. Note the granular appearance of the matrix. These grains would appear as dust particles as the surface is disturbed, such as by scratching with a needle.

Figure 8 is an SEM record of non-precipitated HT-S/6234 composite showing the improved matrix resin obtained after adjustments were made in the cure method.

C. FACE SHEET DEVELOPMENT

Face sheet development consisted of two parts. The first was cure cycle evaluation and the second testing of mechanical properties.

The subject panel is simply supported at a 25-in. span; thus, the major face sheet design stress is unidirectional tension and compression. The second major design consideration is that the face sheet must have sufficient thickness and modulus to resist intercell buckling. Design trade-offs discussed in Section D showed that thicknesses between .007 and .014 would provide minimum weight panels.

Since the stresses are uniaxial, the face sheet layup calls for a high percentage of 0° plies with a small percentage of 90's to prevent handling damage and to resist transverse stresses from the Poisson's effects in the thin foils. Hercules HM fiber was used for the face sheets because inner cell buckling was expected to be the primary failure mode.

1. Cure Cycle Evaluation

The problems of resin precipitation occurring with the cure of laminates has been discussed in the previous section on resin cure studies. It was not as serious a problem with face sheets since they could be cured in an autoclave or press while pulling a vacuum on the laminate.

Some changes in the General Dynamics cure cycle were required in order to maximize the removal of volatile reaction products. These changes were to insert heavier layers of release material between the bleeder material and the laminate and to perforate the base plate and the caul plate. The complete layup sequence is shown in Figure 9. Following the layup sequence of Figure 9 and the time-temperature pressure sequence described in Section B, excellent test laminates were fabricated using 2, 3, 5, 6 and 9 plies of prepreg material. Table I summarizes the panels fabricated with HM-S/6234 for testing. Tests included coupon tensile testing, sandwich beam testing, and face sheet-to-core flatwise tensile tests.

Figure 4. SEM of HM-S/BP-907 Showing
Non Precipitated Matric Formation, 1250X

Figure 5. SEM of HT-S/P13N Showing
Non Precipitated Matrix Formation, 5000X

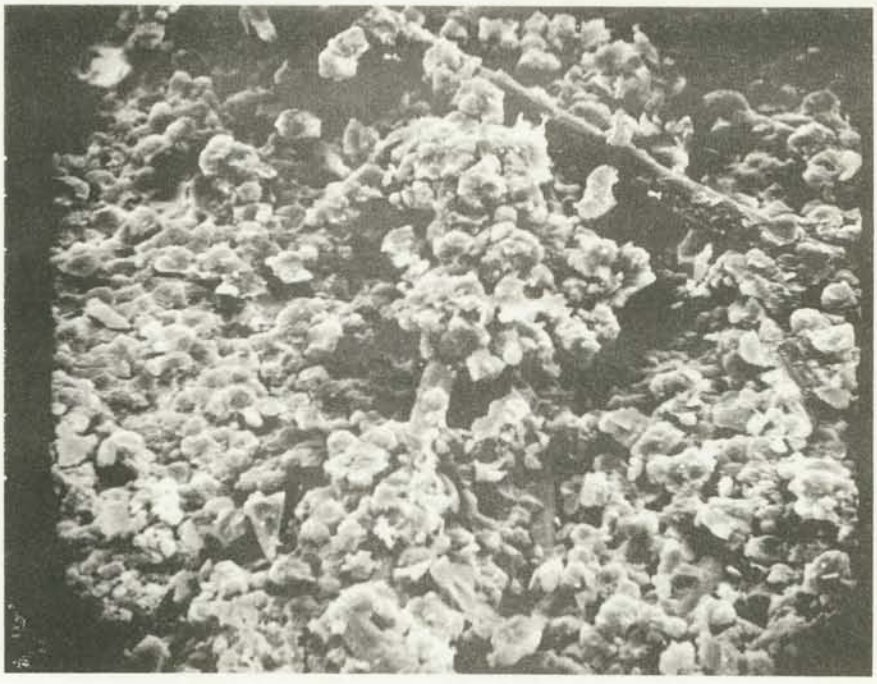

Figure 6. SEM of HT-S/6234 Showing Precipitated Matrix Formation, 500X

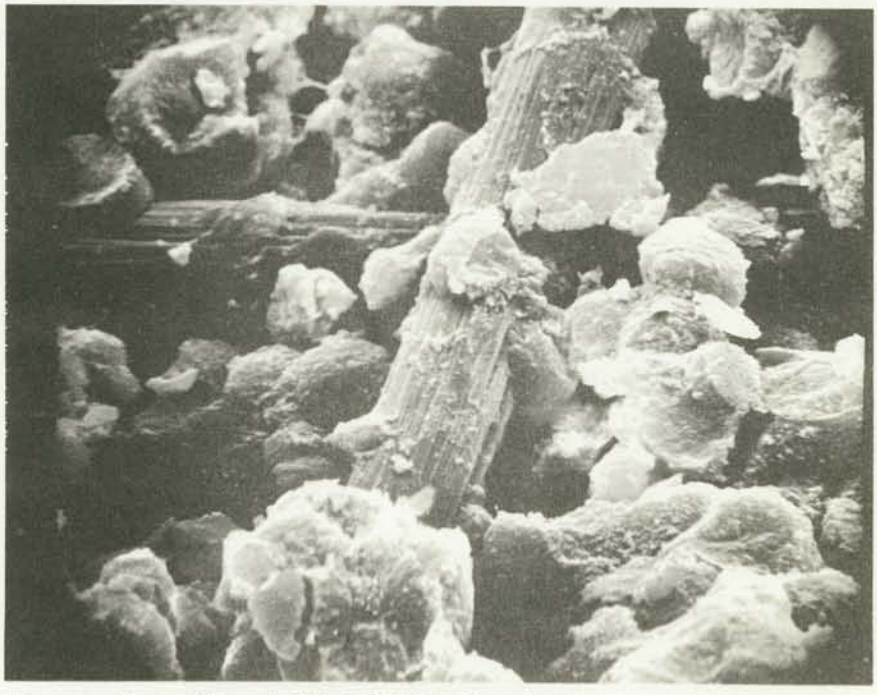

Figure 7. SEM of HT-S/6234 Showing Precipitated Matrix Formation, 2060X

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Figure 8. SEM of HT-S/6234 Showing
Non Precipitated Matrix Formation, 2500X

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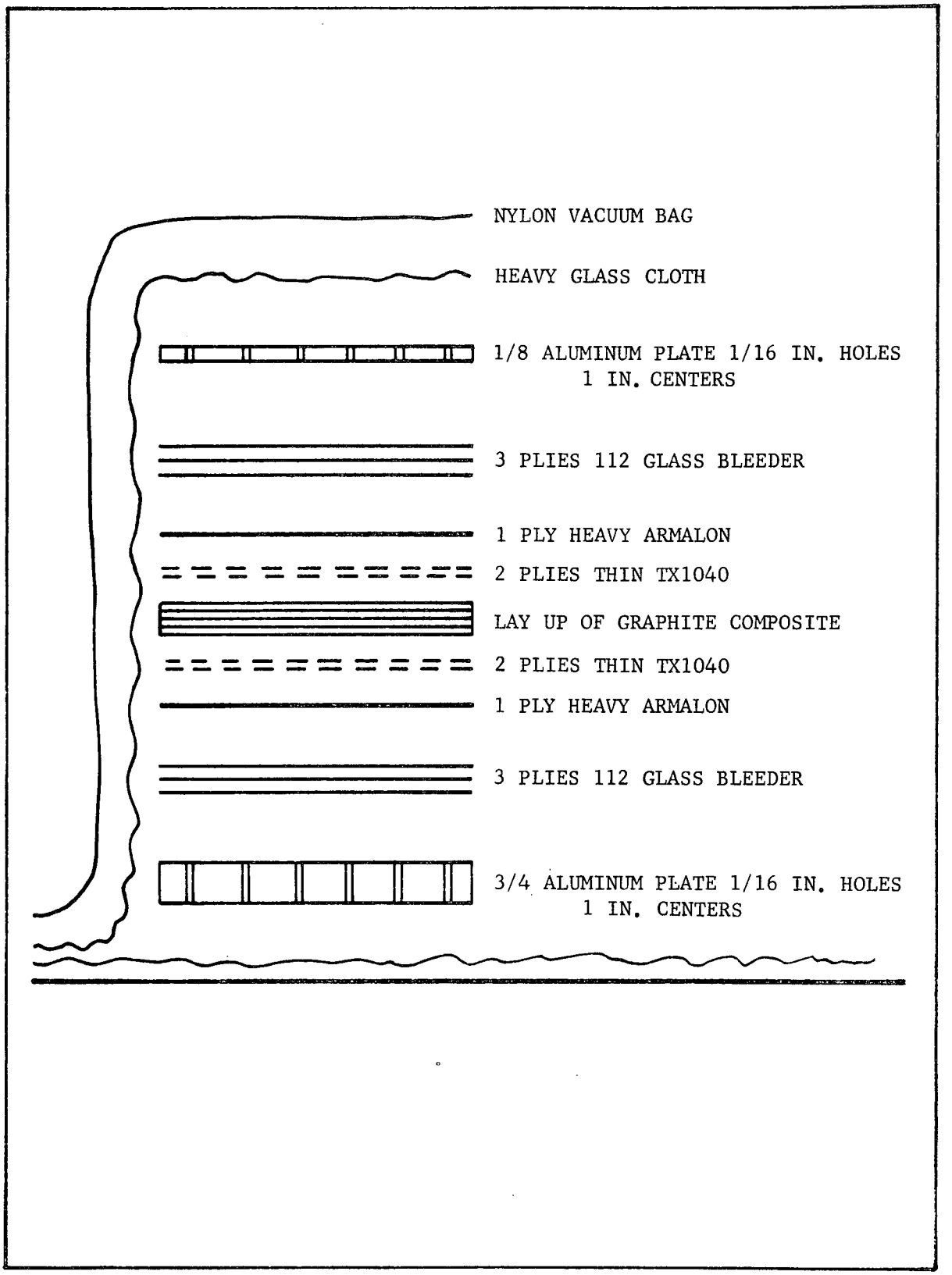

Figure 9. Layup of Graphite/Polyimide Laminates

TABLE I

SUMMARY OF HM-S/6234 FACE SHEET TEST LAMINATES

Panel	Panel Size (in.)	Ply Orientation	Per Ply Thickness (in.)	Test
132	6 x 24	$[0]_2$	0.0025	Tensile Test
133	4 x 12	45, -45, -45, 45	0.0023	Tensile Test
135	6 x 24	0, 0, 90, 0, 0	0.0022	Tensile Test
136	6 x 24	0, 0, 90, 0, 0	0.0024	Tensile Test
137	6 x 24	0, 0, 90, 0, 0	0.0020	Tensile Test
147	6 x 24	0, 90, 0	0.0023	Tensile Test
148	6 x 24	0, 90, 0	0.0027	Tensile Test
149	6 x 24	0, 90, 0	0.0025	Tensile Test
159	7 x 7	0, 0, 90, 0, 0	0.0016	2 in. x 2 in. Flatwise Tensile
160	7 x 7	0, 0, 90, 0, 0	0.0020	2 in. x 2 in. Flatwise Tensile
161	7 x 7	0, 0, 90, 0, 0	0.0018	2 in. x 2 in. Flatwise Tensile
162	7 x 7	0, 0, 90, 0, 0	0.0016	2 in. x 2 in. Flatwise Tensile
164	3 x 10	0, 0, 90, 0, 0	0.002	Post Cure Study
165	3 x 10	0, 0, 90, 0, 0	0.002	Post Cure Study
166	3 x 10	0, 0, 90, 0, 0	0.0022	Post Cure Study
171	7 x 9	0, 0, 90, 0, 0	0.0024	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
172	7 x 9	0, 0, 90, 0, 0	0.0022	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
173	7 x 9	$[0]_5$	0.0022	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
174	7 x 9	$[0_{.5}$	0.0020	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
175	7 x 9	$[0]_3$	0.0017	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
178	7 x 9	0, 90, 0, 0, 90, 0	0.0013	Tensile Test
179	7 x 9	0, 90, 0, 0, 90, 0	0.0013	Tensile Tests
180	7 x 9	0, 0, 90, 0, 0	0.0016	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
189	7 x 9	0, 0, 90, 0, 0, 0, 90, 0, 0	0.0012	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets
190	7 x 9	0, 0, 90, 0, 0, 0, 90, 0, 0	0.0012	1-1/2 in. x 8 in. Honeycomb Panel Face Sheets

All test samples were post cured per the following schedule:

Post Cure Schedule

Time (Hr)	Temperature (°K)	(°F)
2	479	400
2	505	450
2	533	500
2	561	550
4	588	600
4	616	650

The rise time between each step was 30 minutes with a one hour initial rise time to 479°K (400°F).

2. Face Sheet Testing

Tensile tests were conducted on candidate face sheet laminates. The test specimen was straight sided 1/2-in. x 9-in. Scotchply 1002 end tabs were used at 298°K (77°F) and DuPont Pyralin Type 3S-501 glass polyimide end tabs were used at 533°K (500°F). End tabs were attached to the specimen with Eastman 910 adhesive for room temperature tests and Micro Measurements M Bond 610 for 533°K (500°F) tests.

Initial coupon tensile tests on HM-S/6234 unidirectional plates of two-ply 0.004 in. thickness containing 37 percent volume of fiber yielded a value of 37,240 psi. This is 50 percent of the value obtained from standard gage material at the same fiber volume.

Degradation was not unexpected as it had been reported by Penton[6] on graphite and by Hertz[7], Young[8], Kimball[9], and others on fiberglass; however, the magnitude of degradation was much larger than expected. The problem results from three primary causes:

(1) Surface roughness is a larger percentage of the measured thickness.

(2) Damage to the edges of thin gage material occurs during machining.

(3) Manufacturing flaws are comparatively larger than in thicker cross sections.

To evaluate this effect more carefully, 5, 10, and 20 ply laminates were constructed from one lot of HT-S/3002 epoxy prepreg containing 0.85 tows per inch. The epoxy resin was selected for the study to achieve more flow and higher fiber volumes.

The results shown on Table II reveal that thin gage material produced no degradation at the 0.032 in. thickness although fiber volume was still low. As the number of plies decreased, fiber volume tended to drop and apparent property degradation increased. It was found that the results of Table II, when reduced by a constant, could be superimposed directly on curves presented by Hertz[7] for fiberglass. Thus, the degradation of unidirectional HT-S can be predicted by equations developed for fiberglass.

Following the above evaluation, further testing of laminates with HM-S/6234 thin gage material containing 0° and 90° orientations was conducted to obtain design values for sandwich face sheets. Face sheets were produced with ply thickness values as low as 0.0012 in. and total face sheet thicknesses of 0.008 to 0.013 in. All laminates were bagged and cured in an autoclave while pulling vacuum on the laminate.

The results shown on Table III were used in the design of the two sandwich panels which were delivered to NASA/Houston. The magnitude of property degradation was apparently reduced in these tests possibly because of the crossplied layup which reduced axial splitting and improved load transfer. A maximum degradation of 13 percent is shown.

No results are shown for three ply 0°, 90°, 0° laminates. These specimens were damaged during machining when the diamond wheel used for cutting picked up the adhesive on the double-faced tape being used to hold the specimens in place. As the wheel pulled the sticky adhesive upward, the cut edges of the specimens chipped. Since design calculations indicated three-ply laminates would not be of sufficient thickness, additional test specimens were not fabricated.

Compressive properties of the face sheet material were obtained on sandwich beams 1.5-in. wide by 9-in. long consisting of graphite face sheets on graphite core. These results are described in Section G of this report.

D. CORE DEVELOPMENT

Hexcel Corporation, Dublin, California, had the responsibility for transforming graphite/polyimide prepreg, supplied by Hercules, into finished honeycomb blocks. Hexcel conducted tests on the incoming webs, fabricated and tested the honeycomb.

A total of four graphite composite cores was fabricated and tested by Hexcel Corporation. Approximately 1/2 cu ft of core in blocks 6-1/2 in. thick x 23 in. long x 7-1/2 in. wide was fabricated for each of the first three cores and one cubic foot for the fourth core. A summary of these cores is given in Table IV. Hercules HT-S fiber was used in three of the four cores. Hercules Type A-S fiber was used in Core IV to evaluate spreadability of the tow and, thus, more uniform fiber distribution. Type A-S has a less rigorous processing history compared with HT-S and is

TABLE II

EFFECT OF GAGE UPON TENSILE STRENGTH OF HT/3002 GRAPHITE COMPOSITE

No. of Plies	Thickness (in.)	Strength (psi)	Fiber Volume (%)	Apparent Degradation (psi)	Apparent Degradation (%)
20	0.032	141,600	45.9	0	0
		137,100			
		149,700			
		(142,800)			
10	0.017	109,500	43.1	11,700	12
		123,800			
		132,700			
		(122,000)			
5	0.009	84,700	40.8	46,000	36
		78,500			
		74,800			
		(79,333)			

( ) Indicates Average Value

TABLE III

TENSILE STRENGTH OF HM-S/6234 FACE SHEET TEST LAMINATES

Ply Orientation (Degrees)	Temp (^{o}K)	Thickness (in.)	Strength (psi)	Modulus (psi x 10^{6})	Elongation (%)
0, 0, 90, 0, 0	298 (77^{o}F)	0.008	44,370	12.4	0.35
		0.007	53,529	14.4	0.39
		0.008		12.2	0.37
		(0.0076)	(48,950)	(13.0)	(0.37)
0, 90, 0, 0, 90, 0	298 (77^{o}F)	0.008	62,120	13.7	0.45
		0.008	59,640	14.4	0.41
		0.009	48,000	12.3	0.39
		0.009	33,200	10.3	0.35
		0.009	42,530		0.43
		(0.0086)	(49,100)	(13.7)	(0.41)
0, 0, 90, 0, 0, 0, 90, 0, 0	298 (77^{o}F)	0.013	43,750	13.7	0.36
		0.012	56,735	15.6	0.35
		0.011	54,110	14.1	0.38
		0.013	40,530	13.4	0.30
		(0.0128)	(46,572)	(13.7)	(0.35)
0, 0, 90, 0, 0, 0, 90, 0, 0	533 (500^{o}F)	0.010	69,200	18.2	0.38
		0.011	75,820	14.9	0.50
		0.011	57,820	15.0	0.38
		0.011	65,970	16.2	0.41
		0.013	64,232	14.8	0.42
		(0.011)	(66,610)	(15.8)	(0.42)

( ) Indicates Average Value

TABLE IV

GRAPHITE CORE FABRICATION SUMMARY

S/N	Cell Size (in.)	Web Material	Weight (lb/ft^3)	Web Thickness (in.)	Fiber Volume (%)
I	1/4	$\pm$45 HT-S/6234	3.6	0.0047	32
II	3/8	$\pm$45 HT-S/6234	2.7	0.0049	35
III	3/8	$\pm$45 A-S/6234	2.3	0.0046	37
IV	3/8	$\pm$45 HT-S/6234	1.9	0.0046	37

less likely to be tangled. Essentially equivalent performance was obtained with A-S and HT-S fiber, however.

1. Core Fabrication

There are two primary methods of fabricating honeycomb core from single sheets. These methods are (1) the expansion process and (2) the corrugation process. In the expansion process, all node bonds are made simultaneously on flat, raw material sheets, stacked and bonded flat (primary or secondary cure). The block is subsequently expanded to form the honeycomb core. This method is unsuitable for existing graphite/polyimide prepreg because of web delamination and potential damage to the fiber.

Thus, the corrugation process was used exclusively for all core made on the program. A schematic of this process is shown in Figure 10. The advantages of the corrugation process are (1) minimal damage to the fibers, (2) high reliability, (3) low scrap rates, and (4) better compaction of the web sheets by completely curing the individual webs at a desired pressure. Manufacture of the first three cores was accomplished in the same manner. With Core IV, the processing was changed to achieve web cure and node bond in one step. The following paragraphs describe the process.

a. Prepreg Predrying

The first step in core fabrication is the preparation of the graphite/polyimide prepreg for processing. The protective release paper is removed from each surface of the prepreg, and the prepreg placed in a forced draft oven for a 10-minute heat cycle at 366°K (200°F) (optimized during cure studies).

This preliminary flash cycle (which reduces solvent levels from 20-25 percent to below 12 percent) is followed by a vacuum drying cycle. A layer of thin TX1040 teflon-coated porous scrim cloth is placed on both surfaces of each sheet. Four or five of these plies are stacked on each side of a vacuum manifold. Vent plies are placed between each layer of scrim-covered prepreg. A nylon vacuum bag is placed over the well-vented layup, and the assembly heated up to 394°K (250°F). The temperature was dropped off immediately after reaching temperature on the first and second core. It was held for 15 minutes on the third core because of a higher solvent level in that lot of prepreg (26 percent solvent).

The vacuum bag is removed immediately from the prepreg to afford rapid cooling and the prepreg is then corrugated.

b. Corrugation

The corrugator consists of a 3-ft long conditioning box within which a conveyor system passes the thin sheets at such a rate that

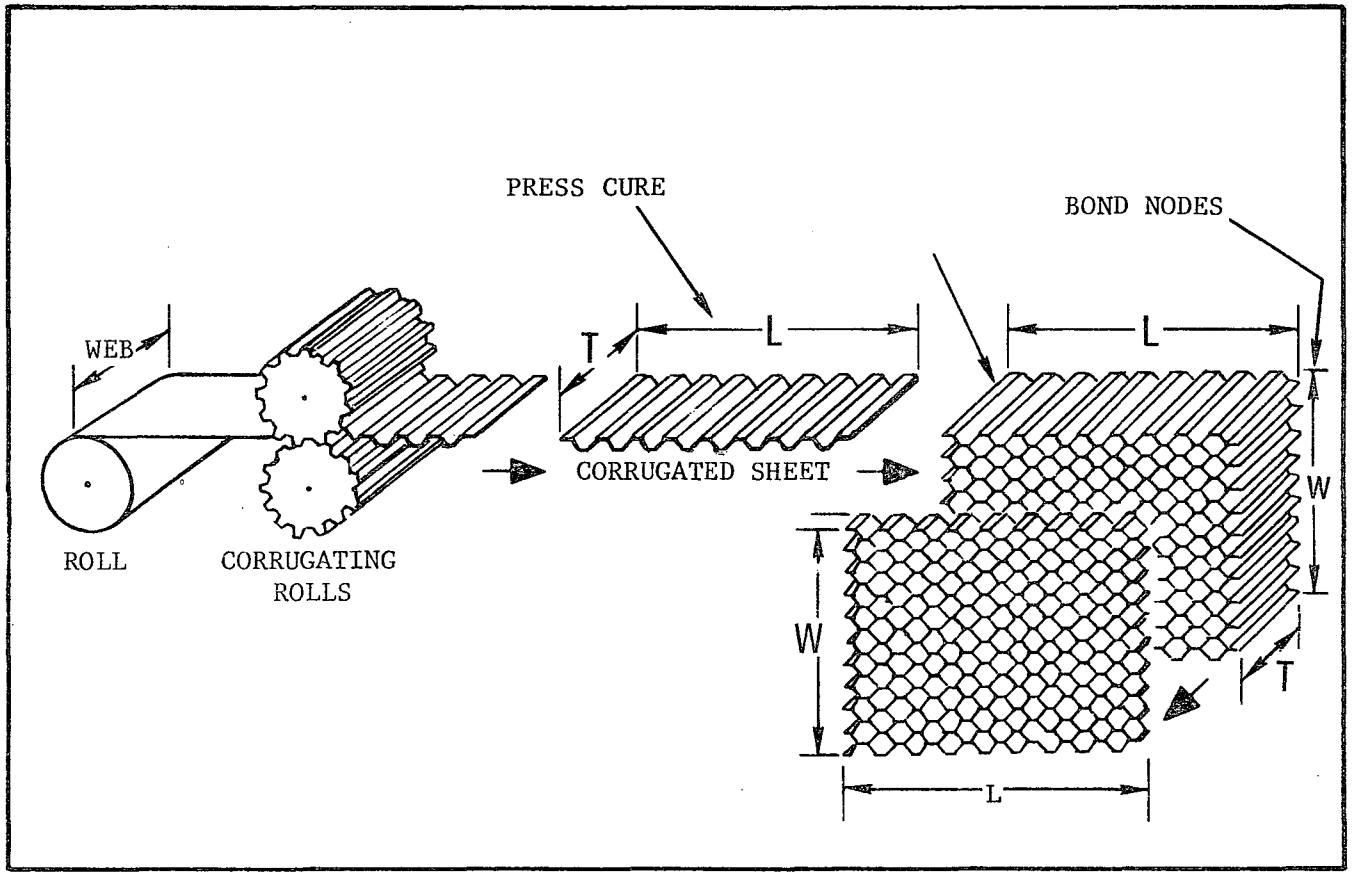

Figure 10. Corrugation Process Of Honeycomb Manufacture

a temperature of 408°K (275°F) is reached when the softened prepreg goes through the meshing corrugator teeth. The two corrugator rolls are about 7 in. wide and 3 in. in diameter. A rapid feed rate of about 1 ft/sec prevents over-staging of the resin. Little flow into the TX1040 occurred during this process step.

c. Final Cure

The corrugated sheets are stacked in a platen press with matched die corrugated steel plates attached to both the top and bottom heated platens. Between 12 and 24 webs are cured simultaneously. The plies are pressure cured (100 psi) at 453°K (350°F). Approximately two hours are required to reach cure temperature throughout the stack and a minimum of one hour at temperature assures sufficient curing of the resin to permit bonding of the core nodes and post cure without the need for external support. The temperature gradient throughout the stack is carefully monitored at a minimum of every other ply and at each station and measured every ten minutes throughout the cure cycle.

d. Node Bond and Splicing

Node bond adhesive is applied to the mating surfaces of each corrugated sheet, positioned in a bonding fixture, and then cured to form the core block. HX-856, a high solids content version of Monsanto Skybond 703 polyimide, was the node bond adhesive used by Hexcel.

Very little mechanical pressure was required to hold the webs during the adhesive cure. Clips of excessive width were inadvertently used for bonding the first half of Core II causing damage to the webs and incomplete expansion of the cells. Modification of the tooling to achieve a better fit eliminated the problem. Node adhesive weight varied between .25 and .4 lb/cu ft. Typical appearance of a fabricated block is shown in Figure 11.

A major improvement was gained in the processing of Core IV. The corrugated sheets were stacked in such a way that the prepreg was in contact at the nodes during the final cure. Thus, the node bond and web cure was achieved in one step elminating the additional weight. A twist, resulting from thermal stresses caused by the unbalanced ply layup (two ply $\pm$ 45°) was observed in the cured webs of all cores. This twist was still evident in finished core blocks particularly in narrow thin slabs as shown in Figure 12. On Core I, the more numerous node bonds associated with 1/4-in. cell size stabilized the twist much better than on the larger 3/8-in. cell cores. The twist in all panels was elminated by the bonding of face sheets onto the core under pressure.

Splicing of the core to form wider panels was accomplished by bonding rows of nodes together with the same adhesive used to bond webs together at the nodes. Figure 13 shows the 25-in. by 26-in. core sheets used in the fabrication of two sandwich panels. These

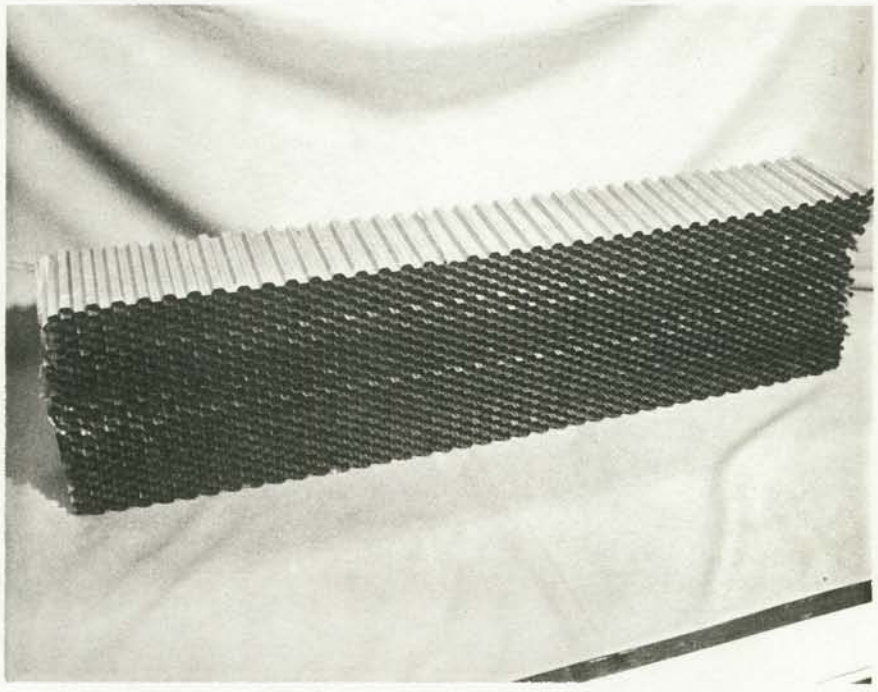

Figure 11. Graphite Composite Honeycomb, 3/8 in. Cell

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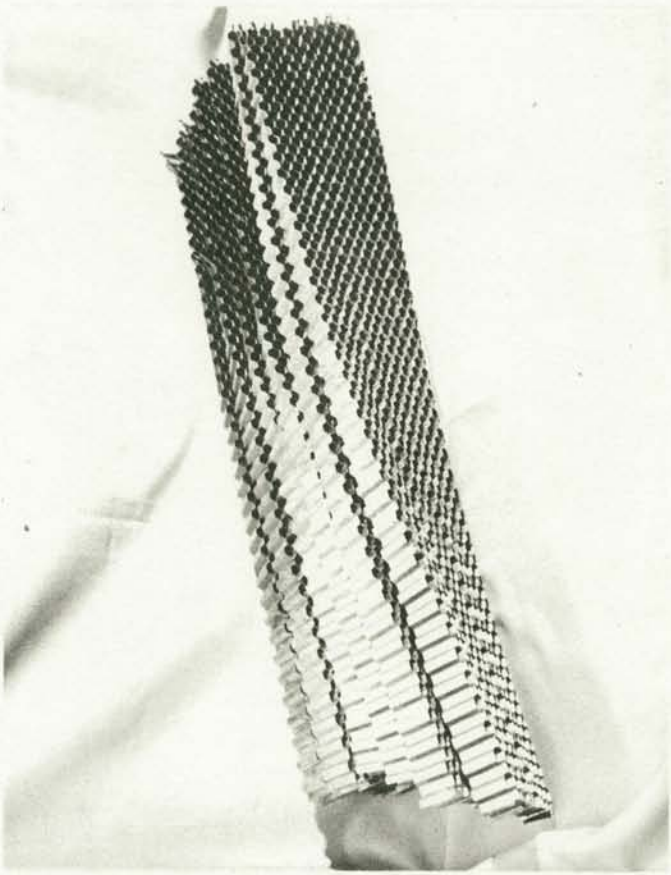

Figure 12. Effect of Unbalanced Web on Graphite Honeycomb

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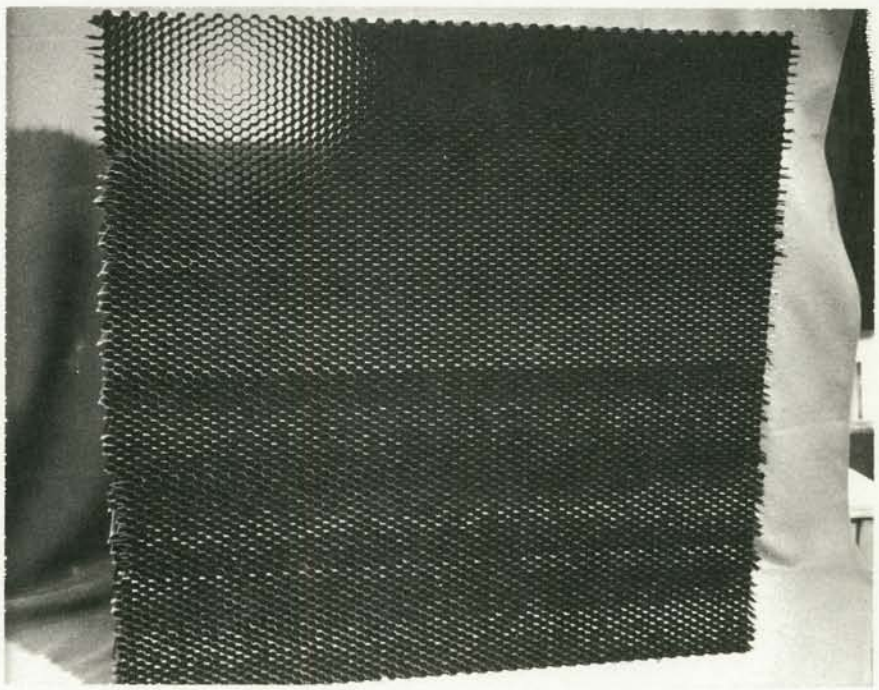

Figure 13. 26" x 25" Panel Formed by Splicing Narrower Widths

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were formed by splicing six pieces slightly wider than 4 in. together and then slicing to the proper thickness.

Table V gives process controls used by Hexcel during core fabrication. The careful controls used were evident in the detailed records maintained on each web used in a core block.

2. Core Cutting

The core was sliced into test specimens and panels using a production honeycomb cutting table. Non-porous tape is attached to the completed core on one open cell side. A vacuum from one side holds the core steady against a flat plate while a band saw containing fine tungsten carbide chips running at a speed of 3000 fpm at a feed of 4 in. per minute sliced the core. Only minor damage to the core, caused by vibration during the cutting, was observed.

3. Web Shear Testing

Prior to the fabrication of honeycomb, prepreg material was cured in flat, two-ply $\pm 45^{\circ}$ sheets and tested in shear to establish basic material properties and to optimize curing conditions. Testing was accomplished following a specialized shear procedure developed by Jackson[10] for thin web material.

Typical results from this test are shown on Tables VI and VII. Data from all four web materials was similar. Table VIII gives web properties of materials other than graphite/polyimide measured by the same procedure for comparison.

4. Post Cure Evaluation

In order to check the effect of post curing laminates in an air-circulating oven, several five-ply unidirectional panels were cured, machined into tensile test specimens and evenly divided into three groups. One group was post cured in an oven by the conventional method, a second group was post cured in a heated chamber with a preheated Argon environment, and the third group received no post cure at all. All samples were exposed to the same temperature-time history. The results shown below reveal that room temperature properties are reduced by post cure; however, post cure in a non-air atmosphere failed to improve the properties. Further tests on Core II revealed that the use of a post cure ending at $616^{\circ}K$ ($650^{\circ}F$) was critical to $588^{\circ}K$ ($600^{\circ}F$) properties and could not be eliminated. Thus, oven post cure in air was continued.

TABLE V

CORE FABRICATION QUALITY ASSURANCE SUMMARY

Code	Reference	Title	Scope	Methods	Sampling
PPC	MIL-Q-9858A	Preproduction checks	Raw Material Inspected for: A. Fabric Defects - Tears, splits holes, missed fill yarns, mixed yarns, resin out of specification B. Adhesive - To specification	Visual inspection and physical measurements - "In-plane shear" As required	Statistical 100%
IP-1C -1E	MIL-Q-9858A	In-process matl inspection	Web Prepreg (Flat/Corrugated) Inspected for: Dimensional control Fiber alignment Fiber damage Resin content and distribution	Visual inspection Standard technique	Statistical
IP-2C -2E	MIL-Q-9858A	In-process matl cure	Cured Webs Inspected for: Thickness control; fiber damage, resin content and distribution, void content, fiber alignment	Calibrated tooling Calibrated optical Visual inspection Standard technique for resin properties	Statistical
IP-3C -3E	MIL-Q-9858A p. 5, para 4	In-process adhesive nodes printed web	Printed Flat or Corrugate Web W/Adhesive on Nodes Inspected for: Adhesive tack, width of glue lines, distance between glue lines, adhesive pattern on node	Visual, calibrated optical, calibrated standards	Statistical
IP-4C -4E	MIL-Q-9858A	In-process adhesive node bond	H/C Block Inspected for: Node bond breaks, double laps and other indexing defects, width of node, brittle node, node strength	Visual and standard tests	Statistical
IP-5C -5E	MIL-Q-9858A	In-process prime-cured matl	Dimensional control, length and width H/C block inspected after each dip coat/cure cycle to ensure quality for next dip or final quality. H/C density, resin content wall thickness control	Physical measurements Standard techniques	100% each production block
IP-6C -6E	MIL-Q-9858A para 6 p 15	In-process H/C test slices	Product H/C Test Slice Inspected for: Node bond breaks, damage, sizing width, length, thickness; crinkled cells, cell size, cell pitch Physical tests - density; physical appearance	Visual Standard tests	100% each production block

TABLE VI

SHEAR STRENGTH AND MODULUS OF CORE I MATERIAL

Specimen No.	Type-Descriptors	Guage (in.)	Weight (gm)	Density (pcf)	Load at In-Plane Shear		
					Failure (lb)	Strength (psi)	Modulus (psi x 10^6)
1	HT-6234-31	0.0063	0.2700	54.8	558.9	14,880	1.3044
2	HT-6234-31	0.0060	0.2681	56.8	558.9	15,525	1.3262
3	HT-6234-31	0.0059	0.2587	55.7	570.9	16,127	1.3556
						15,511	1.3287
1	HT-6234-3m	0.0048	0.2114	56.4	552.9	19,359	1.6183
2	HT-6234-3m	0.0049	0.2034	52.7	483.9	16,459	1.5913
3	HT-6234-3m	0.0045	0.1869	52.5	461.9	17,031	1.5798
						17,616	1.5964
1	HT-6234-3n	0.0050	0.2384	60.1	485.9	14,997	1.7859
2	HT-6234-3n	0.0048	0.2351	62.2	525.9	18,260	1.5458
3	HT-6234-3n	0.0045	0.2227	62.3	546.9	20,077	1.8465
						17,778	1.7261
1	HT-6234-3o	0.0047	0.2350	63.5	429.9	15,244	1.7932
2	HT-6234-3o	0.0052	0.2444	59.9	503.9	16,213	1.5846
						15,415	1.6753

TABLE VII

IN-PLANE SHEAR STRENGTH AND MODULUS OF CORE II MATERIAL

Specimen No.	Type-Descriptors	Gauge (in.)	Weight (gm)	Density (pcf)	Load at In-Plane Shear		
					Failure (lb)	Strength (psi)	Modulus (psi x 10^6)
1	HT-6234-4-(44)-1a	0.0058	0.2789	61.28	695.9	20,066	1.4488
2	HT-6234-4-(44)-1a	0.0058	0.2670	58.87	488.9	14,146	1.6799
3	HT-6234-4-(44)-1a	0.0057	0.2629	58.58	531.9	15,552	1.6430
						16,688	1.5906
1	HT-6234-4-(44)-2a	0.0047	0.2506	67.43	521.9	18,428	1.7915
2	HT-6234-4-(44)-2a	0.0047	0.2542	68.11	663.9	23,344	1.6547
3	HT-6234-4-(44)-2a	0.0048	0.2528	67.45	571.9	20,024	2.0328
						20,599	1.8263
1	HT-6234-4-(44)-2b	0.0040	0.2511	79.72	406.9	16,954	2.1348
2	HT-6234-4-(44)-2b	0.0038	0.2477	82.35	445.4	19,432	2.2802
3	HT-6234-4-(44)-2b	0.0042	0.2553	76.47	480.4	18,883	1.8667
						18,423	2.0939

TABLE VIII

EXPERIMENTAL SHEAR STRENGTH AND MODULUS OF OTHER WEB MATERIALS

Item No.	Material	Web Thick. (mils)	No. of Samples	Shear Yield Strength (psi)	Std Dev (%)	Shear Modulus (psi x 10^6)	Std Dev (%)
1	Al 5052 H-39	2.5	10	24,825	2.3	3.457	4.2
2	Al 5052 H-39	1.4	6	26,778	1.6	3.176	3.6
3	Al 5052 H-39	0.9	5	24,778	0.7	3.326	0.8
4	Al 1100 Dead Soft	2.0	3	8.319	0.2	2.620	9.5
5	Al 1100-Boron Comp.	2.1	3	12,566	0.7	4.416	7.0
6	Polyimide (Pl) Film	0.6	5	12,681	2.5	0.148	9.5
7	Pl-boron Composite	0.7	4	17,887	3.6	4.973	8.0
8	Glass-fabric-composite Bias Weave	3.1	6	15,231	3.9	0.688	3.5
9	Glass-fabric composite Transverse Weave	3.0	3	8.565	3.9	0.309	3.2
10	2-ply Bias-glass-yarn Resin Composite	2.8	3	23,335	1.8	1.057	3.8

Evaluation of Post Cure Cycles HT-S/6234, 298°K (77°F)

	Strength (psi)	Modulus $_6$ (psi x 10^6)
No Post Cure	86,700	7.94
Oven Post Cure	63,900	7.67
Autoclave Post Cure (Argon)	49,020	7.38

5. Core Test Results

The second part of the core development was a program for measuring the honeycomb core properties. Testing was conducted by Hexcel. Shear and compression properties were measured at temperatures from 172°K (-150°F) to 588°K (600°F) generally per the methods of MIL-STD-401B.

Figure 14 illustrates the notation used for reporting the test data. The L direction is in the continuous ribbon direction, W direction is across the nodes and T is the height.

Figure 15 illustrates the procedure for determining core shear properties. The core specimen 2 in. W x 7 in. L x .5 in. T was bonded between thick steel plates which were displaced relative to each other during test, thus placing the bonded specimen in shear. Load deflection values were obtained from which shear strength and modulus were calculated. Modulus values were not obtained above 505°K (450°F) because of limits on the deflection measuring equipment. A film adhesive, Bloomingdale HT-424, was used to bond the core to the metal tabs. Although this adhesive has a short life at 588°K (600°F), it was sufficiently strong at 30 minutes to permit conditioning and test. Sheets of FM-34 polyimide film were tried and failed in the adhesive bond. Shear properties were determined in both the L and W directions.

Compressive properties of the various cores were determined in a direction normal to the plane of the facings as shown in Figure 16. Test specimens were 3 in. L x 3 in. W x .5 in. T with .020 thick aluminum face sheets. Compressive strength and core modulus values were obtained.

Tables IX through XII list the individual test results for each core, I through IV, respectively.

In general, the performance of all of the cores was proportional to their weights. Table XIV summarizes the results for Core IV and compares these values with those obtained from commercially available honeycomb of other materials. Results from the other cores are similar. As can be seen, at temperatures over 422°K (300°F), the structural efficiency of the graphite core is superior to the othermaterials in all properties except for the compressive modulus of 5056 aluminum. At room temperature

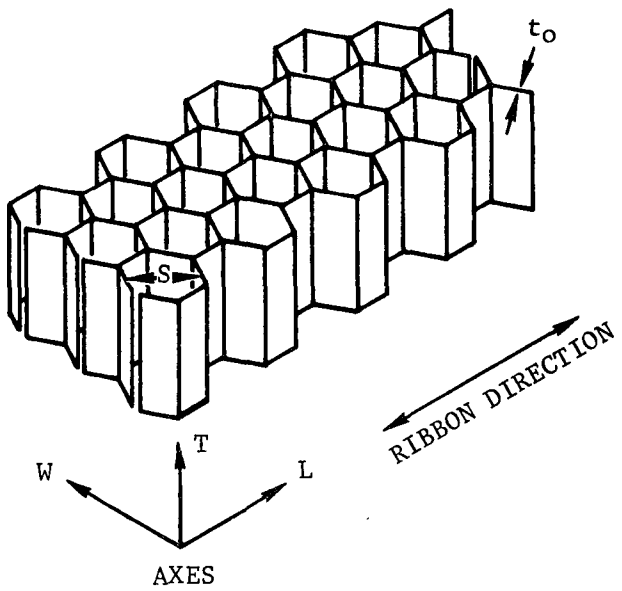


Figure 14. Axes Notation for Hexagonal Honeycomb

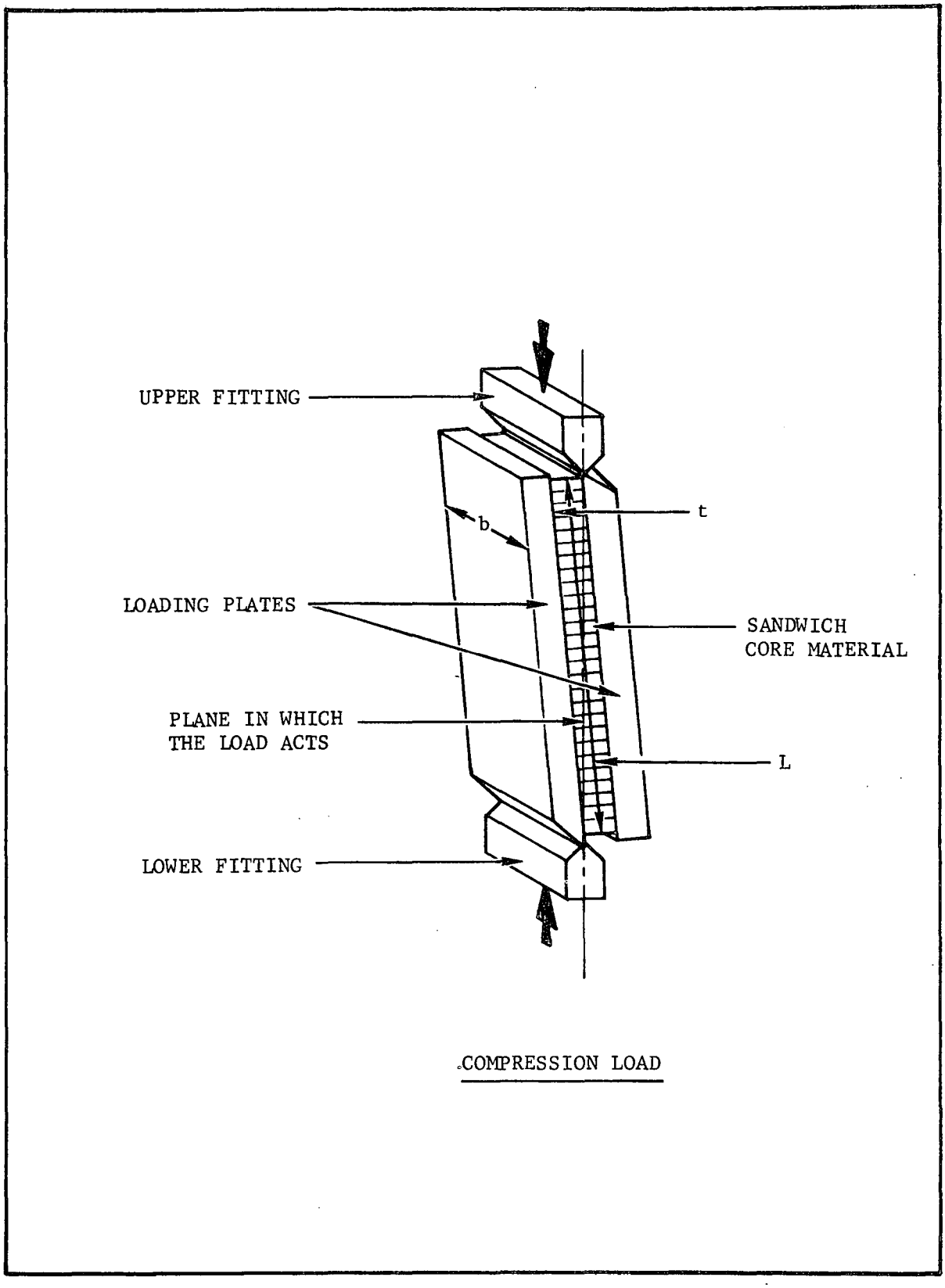


Figure 15. Test Apparatus for Shear Testing of Honeycomb

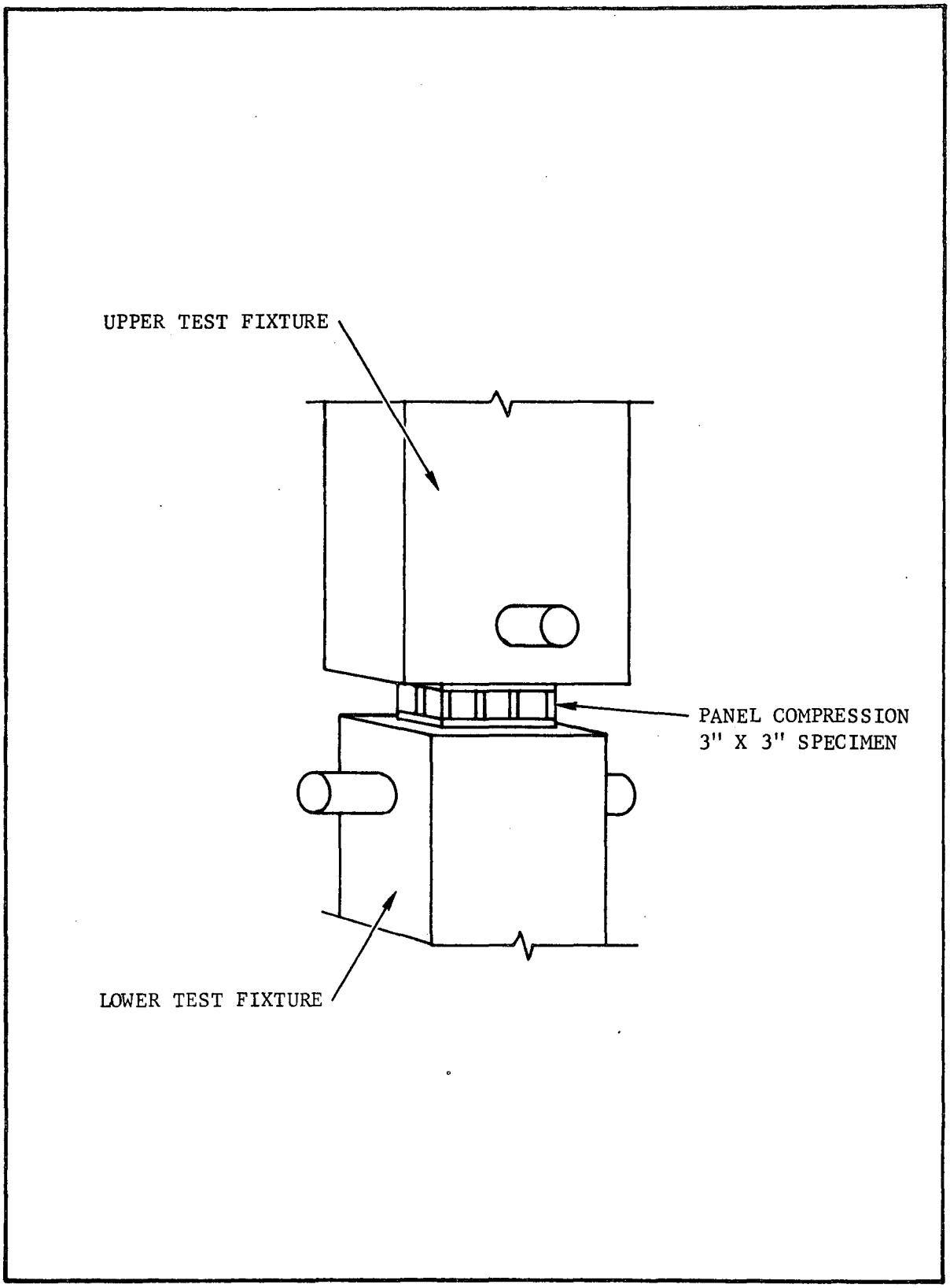


Figure 16. Test Apparatus for Compression Testing of Honeycomb

TABLE IX

SUMMARY OF HONEYCOMB CORE TEST RESULTS
CORE I - 1/4 IN. CELL SIZE

Test Temp.	Spec. No.	L Shear			W Shear			Flatwise Compression		
		Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)
298°K(77°F)	1	3.72	230	48.0	3.67	121	18.9	3.68	473	46.0
	2	3.74	245	53.9	3.66	128	21.6	3.60	451	45.3
	3	3.76	239	56.1	3.70	124	20.1	3.67	480	47.8
	4	3.77	233	46.5	3.62	116	20.1	3.65	490	44.1
	5	3.79	246	47.9	3.65	118	20.8			
	Avg	3.76	239	50.5	3.66	121	20.3	3.65	474	45.8
505°K(450°F)	1	3.69	255	80.1	3.74	134	22.9			
588°K(600°F)	1	3.76	170		3.47	61		3.73	263	28.6
	2	3.67	146		3.66	80		3.72	222	23.9
	3	3.84	167							
	Avg	3.76	161		3.57	71		3.72	243	26.3

TABLE X

SUMMARY OF HONEYCOMB CORE TEST RESULTS
CORE II - 3/8 IN. CELL

Condition	Test Temp.	Spec. No.	L Shear			W Shear			Flatwise Compression		
			Density (pcf)	Strength (psi)	Modulus (ksi)	Density (pcf)	Strength (psi)	Modulus (ksi)	Density (pcf)	Strength (psi)	Modulus (ksi)
453°K (350°F) Cure	298°K (77°F)	1	2.84	200	37.9	2.77	82	11.7	2.80	352	28.24
		2	2.82	188	30.5	2.76	96	13.0	2.80	367	26.68
		3	2.83	196	32.4	2.76	93	12.9	2.84	371	27.86
		4	2.85	182	36.1	2.74	87	11.5	2.81	361	27.10
		5	2.88	199	37.0	2.76	94	12.4	2.80	373	29.34
		Avg	2.84	193	34.8	2.76	90	12.3	2.81	365	27.85
588°K (600°F)	298°K (77°F)	1	2.69	192	38.97				2.70	343	41.6
		2	2.70	195	39.64						
		3	2.71	188	35.36						
		4	2.67	199	48.44						
		5	2.72	202	38.22						
		Avg	2.70	195	40.13				2.70	343	41.6
	505°K (450°F)	1	2.64	180	36.2	2.64	80	10.1			
		2	2.65	189	53.8						
		Avg	2.65	185	44	2.64	80	10.1			
	588°K (600°F)	1	2.65	55		2.65	30		2.71	80	10.0
		2	2.65	67		2.59	29		2.71	92	11.5
		3	2.73	72							
		Avg	2.68	65		2.69	30		2.71	86	10.7

TABLE XI

SUMMARY OF HONEYCOMB CORE TEST RESULTS
CORE III - 3/8 IN. CELL SIZE

Test Temp.	Spec. No.	L Shear			W Shear			Flatwise Compression		
		Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)
200°K(-100°F)	1	2.26	159	25.1	2.29	65	10.6	2.28	198	30.4
	2	2.39	177	28.1	2.25	62	10.4	2.30	195	26.1
	3	2.38	158	21.4	2.28	73	10.3	2.32	204	24.7
	Avg	2.34	164	24.9	2.27	67	10.4	2.30	199	27.1
298°K(77°F)	1	2.26	146	21.3	2.27	64	8.8	2.32	222	27.8
	2	2.26	162	35.7	2.36	69	8.7	2.32	203	26.0
	3	2.27	151	41.2	2.29	72	9.2	2.31	185	23.6
	Avg	2.26	153	32.7	2.30	69	8.9	2.32	208	25.8
505°K(450°F)	1	2.34	149	29.1	2.34	69	9.4			
	2				2.30	60	8.7			
	Avg				2.32	65	9.1			
533°K(500°F)	1	2.28	137		2.24	57		2.41	174	20.9
	2	2.33	139		2.26	59		2.40	172	21.4
	3				2.37	60				
	Avg	2.30	138		2.27	59		2.40	173	21.2
588°K(600°F)	1	2.28	78					2.3	116	11.6
	2	2.27	73							
	Avg	2.27	75							

TABLE XII

SUMMARY OF HONEYCOMB CORE TEST RESULTS
CORE IV - 3/8 IN. CELL SIZE

Test Temp.	Spec. No.	L Shear			W Shear			Flatwise Compression		
		Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)	Density (lb/ft^3)	Strength (psi)	Modulus (ksi)
172°K(-150°F)	1	1.89	130	30.9	1.94	70	14.9	1.91	169	17.3
	2	1.99	120	25.4	1.96	62	13.5	1.93	173	20.6
	3	2.01	122	23.7	1.97	67	14.1	1.92	191	21.9
	Avg	1.96	124	26.7	1.95	67	14.2	1.92	178	19.9
298°K(77°F)	1	1.95	144	35.4	1.83	78	13.7	1.90	183	13.6
	2	1.89	141	32.5	1.94	72	11.2	1.89	182	20.6
	3	1.97	125	29.2	1.96	78	12.5	2.02	218	19.7
	Avg	1.94	136	32.4	1.95	76	12.5	1.93	194	19.6
505°F(450°F)	1	1.99	118	27.8	1.93	64	12.8	1.96	153	19.6
	2	2.05	134	26.3	1.92	66	13.2	1.91	150	19.7
	3	1.92	117	29.3	1.88	75	14.7			
	Avg	1.99	123	27.8	1.94	69	13.5	1.94	152	19.65
533°K(500°F)	1	1.87	116		1.96	63		1.96	146	18.4
	2	2.04	103		1.92	65		1.95	153	19.8
	3	1.97	114		1.90	66		2.01	159	20.8
	Avg	1.96	111		1.93	65		1.97	153	19.7
588°K(600°F)	1	1.86	83		1.95	56		1.94	122	15.0
	2	2.08	113		1.94	59		1.91	112	11.0
	3	2.00	104		2.0	52		1.94	113	11.9
	Avg	1.98	100		1.96	56		1.93	116	12.6

TABLE XIII

COMPARISON OF CORE IV PROPERTIES
WITH
OTHER CORE MATERIALS

Property (psi)	Temperature (^{o}K)	(^{o}F)	HT-S/6234 Graphite/PI	5056 Aluminum	HRH-327* Glass/PI	HRH-10 Nomex
"L" Shear	172	-150	124			
	298	77	136	140	150	110
	505	450	123	88	123	53
	533	500	111	78	112	
	588	600	100			
"L" Shear Modulus	172	-150	26,700			
	298	77	32,400	27,000	14,000	4,200
	505	450	27,830	17,010	11,500	2,020
"W" Shear	172	-150	66.6			
	298	77	75.9	85	50	55
	505	450	69.4	53	41	26
	533	500	64.8	48	37	
	588	600	55.6			
"W" Shear Modulus	172	-150	14,200			
	298	77	12,500	13,000	6,000	2,200
	505	450	13,470	8,190	4,900	1,056
Compression	200	-100	178			
	298	77	194	160	200	150
	505	450	152	101	164	72
	533	500	153	90	150	
	588	600	116			
Compression Modulus	200	-100	19,900			
	298	77	19,600	45,000	20,000	11,000
	505	450	19,650	28,350	16,400	5,280
	533	500	19,700	25,200	15,000	
	588	600	12,600			
Density (lb/ft^{3})			1.94	2.0	2.5	2.0

* Lightest available core in glass/PI

it is superior to glass and Nomex but about equal to 5056 aluminum. Figure 17 gives core shear strength versus temperature for several core materials. The data on non-graphite cores comes from published property data[11] while the data on graphite was generated in this program. Considering that the graphite material thickness is less than 0.005 in., apparently degraded compared to standard gage material, and that the fiber volume is less than 40 percent, the results are extremely good. The top line on Figure 17 indicates the specific core shear strength attainable at high fiber volumes with standard gage material.

Typical failure modes of shear and compression specimens are shown on Figures 18 and 19, respectively. The high temperature failures are stability critical while the room temperature failures are strength critical. There did not appear to be any significant degradation at the corners of the hexagonal cells. The effect on properties of two-ply $\pm 45^{\circ}$ webs which are not balanced and symmetrical was not evaluated; however, the only apparent result was a slight twist in thin, narrow slabs of core. This twist was easily flattened and did not cause any difficulty in further processing.

6. Empirical Relations

Using the $\pm 45^{\circ}$ web test data and the measured core properties, the relations given below for predicting core properties were derived.

$$E_c' = .06 \frac{\rho_c'}{\rho_c} E_c$$

$$G_c' = .08 \frac{\rho_c'}{\rho_c} G_c$$

$$F_s' = .3 \frac{\rho_c'}{\rho_c} F_s$$

Where: E_c' = Core compressive modulus

G_c' = Core shear modulus

F_s' = Core shear strength

ρ_c' = Core density

ρ_c = Composite web density

E_c = Composite web elastic modulus

G_c = Composite web shear modulus

F_s = Composite web shear strength

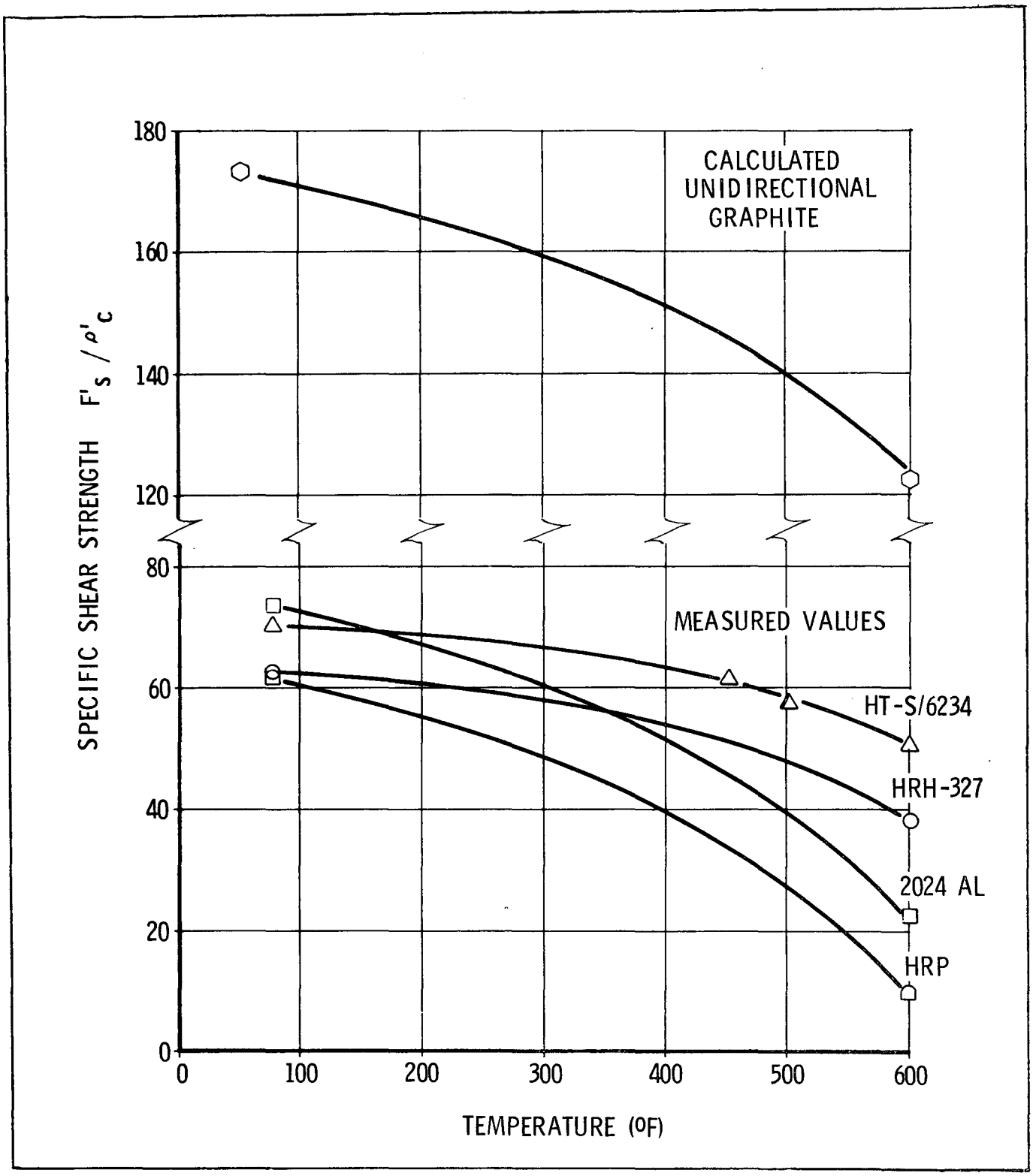
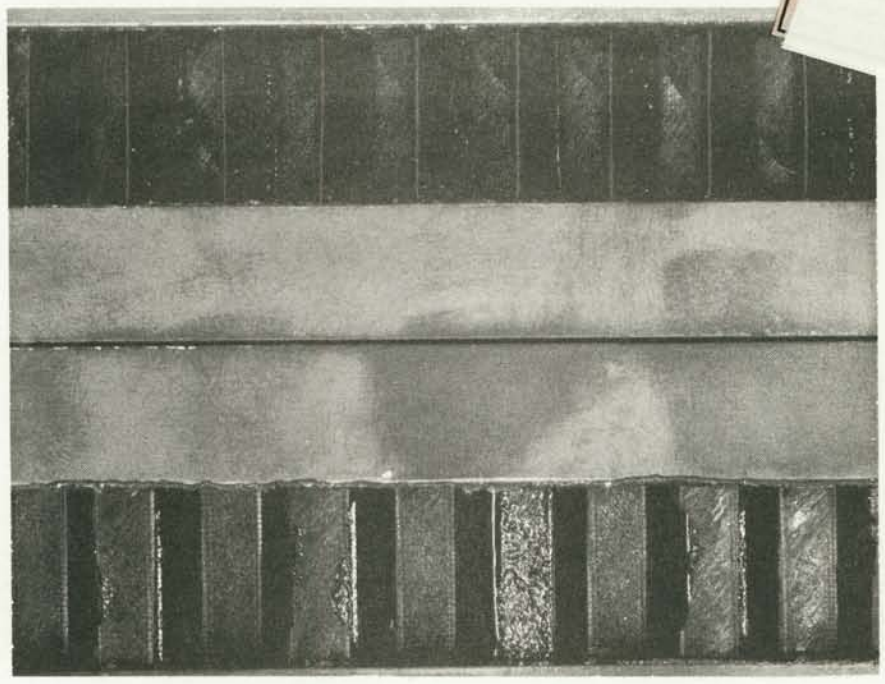
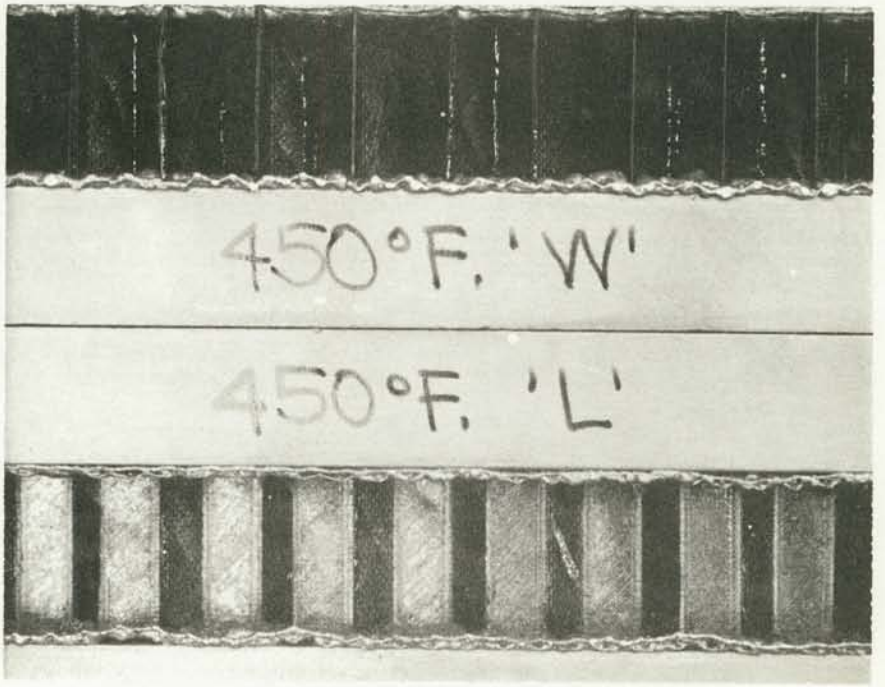


Figure 17. Effect of Temperature on Honeycomb Specific Shear Strength



A

3/8" Cell Failed Plate Specimens 77° F



B

3/8" Cell Plate Shear Failed Specimens - 450° F

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Figure 18.

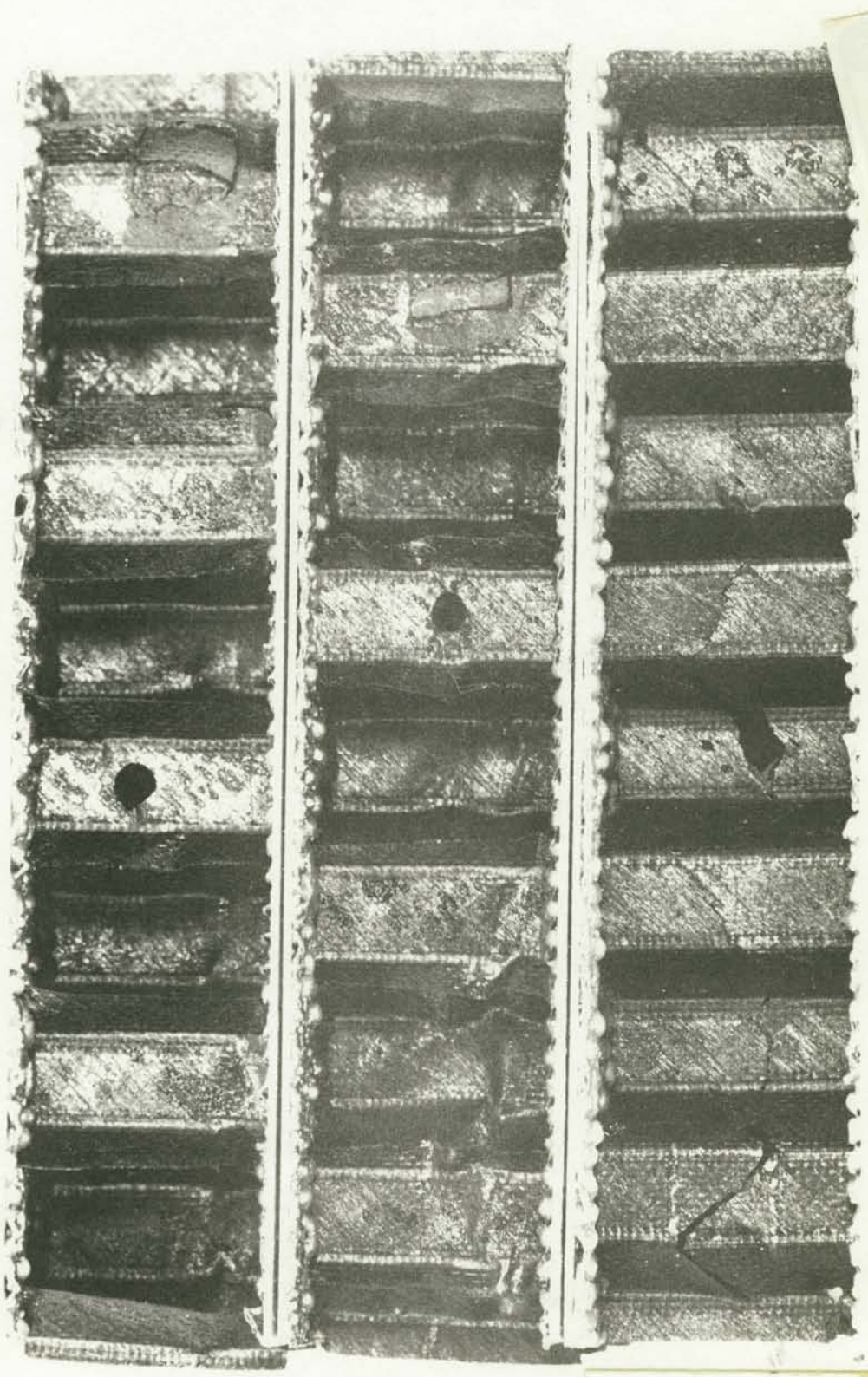

Figure 19. 3/8-in. Cell Stabilized Compression, Failed Specimens

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Table XIV gives a comparison of predicted properties using these relations with measured values from all four cores. Use of these relations for other core geometries and weights has not been verified but should give reasonably accurate estimates.

7. Honeycomb Costs

It is difficult to say anything meaningful about graphite honeycomb costs because of the question of volume. Approximately 2-1/2 cu ft of honeycomb were manufactured and tested on this program on a research and development basis, whereas thousands of cubic feet of aluminum honeycomb are manufactured. In an effort to give the reader some basis for evaluation and possible planning, a comparison based upon 3.5 lb/cu ft 1/4-in. cell size honeycomb is given below.

Material	Price/in-ft* ($)
2024 Aluminum	7
HRP Glass/Phenolic	5
HRH-372 Glass/Polyimide	30
Titanium 3AL/4V	80
HT-S/6234 Graphite/Polyimide	100

* 1 sq ft, 1 in. thick

The above costs are based upon a prototype production volume of approximately 5000 in-ft. Thus, it can be seen that graphite honeycomb, although higher than the other materials, is not several orders of magnitude more expensive presently; and volume production could make the material very cost competitive with the higher temperature core materials.

TABLE XIV

COMPARISON OF PREDICTED AND MEASURED PROPERTIES
OF
GRAPHITE COMPOSITE HEXAGON-SHAPED HONEYCOMB

Property	Core Density (lb/ft^3)			
	3.6	2.7	2.3	1.9
L Shear Modulus (psi)				
Predicted	54,430	40,900	34,850	29,520
Measured	50,500	40,130	32.700	32,406
L Shear Strength (psi)				
Predicted	233	175	149	127
Measured	239	195	153	132
Compressive Modulus (psi)				
Predicted	45,900	34,480	29,380	24,890
Measured	45,800	38,040	25,800	19,600

E. FACE SHEET TO CORE BONDING

In the adhesive selection, several liquid adhesives which appeared promising were procured, examined and tested and a selection made based on (1) 588°K (600°F) service life, (2) ease of fabrication, (3) availability and (4) bond weight.

The conventional core-to-face sheet bonding is accomplished by the use of sheet resin either with or without reinforcing scrim which generally weighs over .1 lb/sq ft in thicknesses sufficient to achieve a good face sheet-to-core bond. An optimized design is best accomplished when the adhesive forms a fillet at the contact point between the core webs and the face sheet.

In order to permit reasonable handling, film adhesives have high viscosity. They may soften when heat is applied, thus permitting some submergence of the core into the adhesive layer (restricted when scrim is used within the adhesive); but, generally, there is not enough flow to obtain good wetting on the sides of the core webs. Thus, the resin within the cell on the face sheet serves no useful purpose. This extra weight can be tolerated on panels with weighty components but not on ultra-light structures. The evaluation of cell edge adhesives was, therefore, introduced into the program. Four adhesives shown on Table XV were selected for evaluation.

Bloomingdale FM-34 filmed adhesive was not selected as a candidate adhesive for this program but was selected as an alternate pending inadequate adhesive strengths with the liquid adhesives studied since it is known that this particular adhesive works well with graphite composites to over 588°K (600°F).

In preliminary examination, the candidate adhesives were heated, vacuumed, diluted and cured to establish behavioral patterns for the materials to obtain the best fillets. Hot bench studies were conducted to tailor the supplier recommended bonding procedures making them more amenable to face sheet-to-core bonding.

Since it was felt that lap shear tests would not provide sufficient correlation between adhesive bond strengths in a core-to-face sheet situation, this portion of testing was eliminated; and, in its place, a series of tensile tests were run on actual core-to-face sheet bonds. A typical test specimen is shown in Figure 20.

Five 7-in. x 7-in. panels (0°, 0°, 90°, 0°, 0°) were cured with HM/RS6234 prepreg for the bond studies. These were subsequently cut into 2-in. x 2-in. squares, bonded to the tabs, and then bonded to the cores with one tab on each core face. Core samples 1-1/2 in. x 1-1/2 in. s 1/2 in. were cut from Core I. These were bonded using the following cure cycles:

TABLE XV

CANDIDATE ADHESIVES, FACE SHEET-TO-CORE BONDING

Adhesive	Manufacturer	Lot No.	Form	Thinner	Ratios Used For Dipping
1) BR-34	American Cynamide Bloomingdale Division Havre de Grace, Maryland (301) 939-1910	B-108 Mfg. 5-20-71	Paste 81% Solids (olive drab)	BR-2 (3/4 - NMP) (1/4 - Xylene)	20 parts BR-34 7 parts BR-2
2) Thermadite 17	Whittaker Corporation Narmco Material Div. 600 Victoria Street Costa Mesa, California (714) 548-1144	Batch #6 Mfg. 3-3-71 N.S. 6010	Liquid (amber)	(MEK)	* 1 part T-17 1 part MEK
3) Hexcelite HX-971	Hexcel Corporation 11711 Dublin Boulevard Dublin, California (415) 828-4200	Batch # 305020-1	Paste (olive drab) 80% Solids	(NMP)	20 parts adhesive 7 parts NMP
4) Hexcelite LR-305019-1	Hexcel Corporation 11711 Dublin Boulevard Dublin, California (415) 828-4200	Batch # 7108051	Paste (yellow)	(NMP)	20 parts adhesive 7 parts NMP
FM-34 (for bonding facesheets to metal test tabs)	American Cynamide Bloomingdale Division Havre de Grace, Maryland (301) 939-1910	Roll #B-321 Batch B-143 Sample S-1991 Mfg. 8-26-71	Film .017" thick (w/glass mat) at .135 lb/ft^2	BR-34 Primer and BR-2 Thinner	Place onto Primer coated metal

* Later changed to all Thermadite 17 or with small additions of MEK.

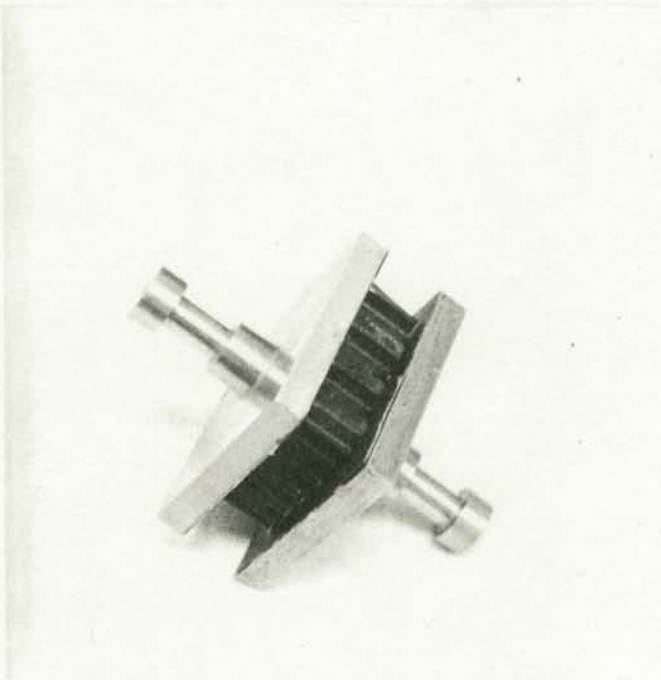

Figure 20. Face Sheet to Core Flatwise Tensile Test Specimen

TABLE XVI

ADHESIVE TEST RESULTS

Specimen Number Lab #68634-641	Type Adhesive	Test Temperature (1)	Adhesive Weight (gm)	Flatwise Tensile Strength (psi)
2/634	BR-34	588°K (600°F)		48.44
3/635	BR-34	588°K (600°F)	.257	181.78
4/636	BR-34	298°K (77°F)	.341	71.56
7	Hexcelite LR-305019-1	No Test (2)	.465	
8/637	Hexcelite LR-305019-1	298°K (77°F)	.545	1.5
9/638	Hexcelite LR-305019-1	588°K (600°F)	.526	30.22
12/639	Thermadite 17	588°K (600°F)	.383	166.67
13/640	Thermadite 17	298°K (77°F)	.284	217.78
14/641	Thermadite 17	588°K (600°F)	.303	205.33
22	Thermadite 17	172°K (-150°F)	(3)	151.56
23	Thermadite 17	298°K (77°F)	(3)	199.11
24	Thermadite 17	172°K (-150°F)	(3)	91.11
27	Thermadite 17	298°K (77°F)	(3)	266.67

(1) Cross head speed - .05 in./min
Chart speed - 5 in./min

(2) Specimen fell apart during removal from bonding fixture

(3) Adhesive weight accuracy in question

(4) 1/4-in. cell size

BR-34

30 min @ 377°K (220°F)
120 min @ 483°K (410°F)

Hexcelite Adhesive

30 min @ 377°K (220°F)
120 min @ 453°K (350°F)
Cool to 338°K (150°F) slowly

Thermadite 17

15 min @ 338°K (150°F)
20 min @ 405°K (270°F)
120 min @ 377°K (400°F)

Detailed sample preparation procedures are given in Appendix A.

Table XVI shows the specimen numbers, test temperatures, and test results. In all of the test specimens, failures occurred within the adhesive with the exception of the BR-34 adhesive specimens. In several failed parts, blisters were noted between the face sheets and the stainless steel tabs. This was attributed to solvents in the BR-34 adhesive passing through the face sheet and either expanding with the application of heat.

Since BR-34 bond strengths on several specimens wherein the blistering problem did not manifest itself were less than strengths obtained with another candidate, the selection was made without retesting the BR-34 adhesive. The resin remained as an alternate replacing FM-34 pending future problems with the current system.

The Hexcelite adhesives both faired poorly in the selection studies. Excellent filleting but poor bonds were obtained with both Hexcelite candidates (HX-971 and LR-305019-1). Shrinkage cracks were noticed within the cured fillets, and the adhesives had a granular appearance when examined under a microscope indicating some resin precipitation.

Whittaker Thermadite 17 high temperature adhesive was selected for the core-to-face sheet bonds on the basis of handling (wetting, appearance), honeycomb bond test results and adhesive weight.

Two problems were discovered with the adhesive, however. First, when diluted with MEK to a viscosity that worked well, the fresh solution tended to wick up the sides of the web at the node where the webs joined. This wicking was excessive and contributed nothing except reinforcement for the node bonds. After a short time exposure to the air (core "dipping" was carried out under a ventilating hood), the solution thickened (evaporation of MEK) and less wicking but more adhesive pick-up occurred. Until

these changes were understood, adhesive weight could not be controlled well. Eventually, a two-dip system was developed wherein the core was dipped in a deep but low viscosity layer of adhesive to give a good bond to the core. This coat is dried as noted in the procedure. A second dip into the adhesive, but at a thinner depth, gave the bulk of the fillet. Solvent in the solution helped to spread adhesive into a fillet on the face sheet which lay under the core. Consistent adhesive weights are obtained by this bonding method.

The second cause for concern with the Thermadite 17 was the excessive gassing that occurred during the core-to-face sheet bonding. Little gassing was noticed when inadequate adhesive was picked up by the core. However, when too much adhesive was picked up, the expansion of trapped gasses caused the entire surface of the cell to be covered with the foam-like material. As improvements were made, a more even quantity of adhesive was obtained. Gassing still occurred within the adhesive as the cure cycle tended to cause a skin to develop on the surface of the adhesive. An increase in temperature creates further expansion of gasses trapped underneath the tough surface skin of resin as shown in the failed tensile sample of Figure 21.

In evaluating the behavior of fillets, it was decided that these bubbles were not an undesirable event. The bubbles generally occur as one large opening right in the center of the fillet. The typical fillet has good surface adhesion to the composite both on the face sheet and the core with complete fitting in and around the junction or apex where the core web meets the face sheet. The skin on the outside of the bubble is in a position of optimum mechanical advantage. The bubbles, therefore, merely deduct undesirable adhesive bulk from an area where the adhesive would be less effective.

F. SANDWICH PANEL DESIGN

Minimum weight panel design was achieved by varying core height, cell size and face sheet thickness until a minimum weight configuration was obtained. The major failure modes in the subject panels were face sheet controlled. Either intercell buckling stress or face sheet bending stress limited further weight reduction. Core shear strength and face sheet-to-core bond strength were generally not the limiting parameters.

1. Core and Face Sheet Design

The major equations to be solved in achieving the design were as follows:

Intercell Buckling Stress

$$F_{CI} = \frac{2}{(1-\mu^2)} E_f \left(\frac{t_f}{S}\right)^2 \qquad (1)$$

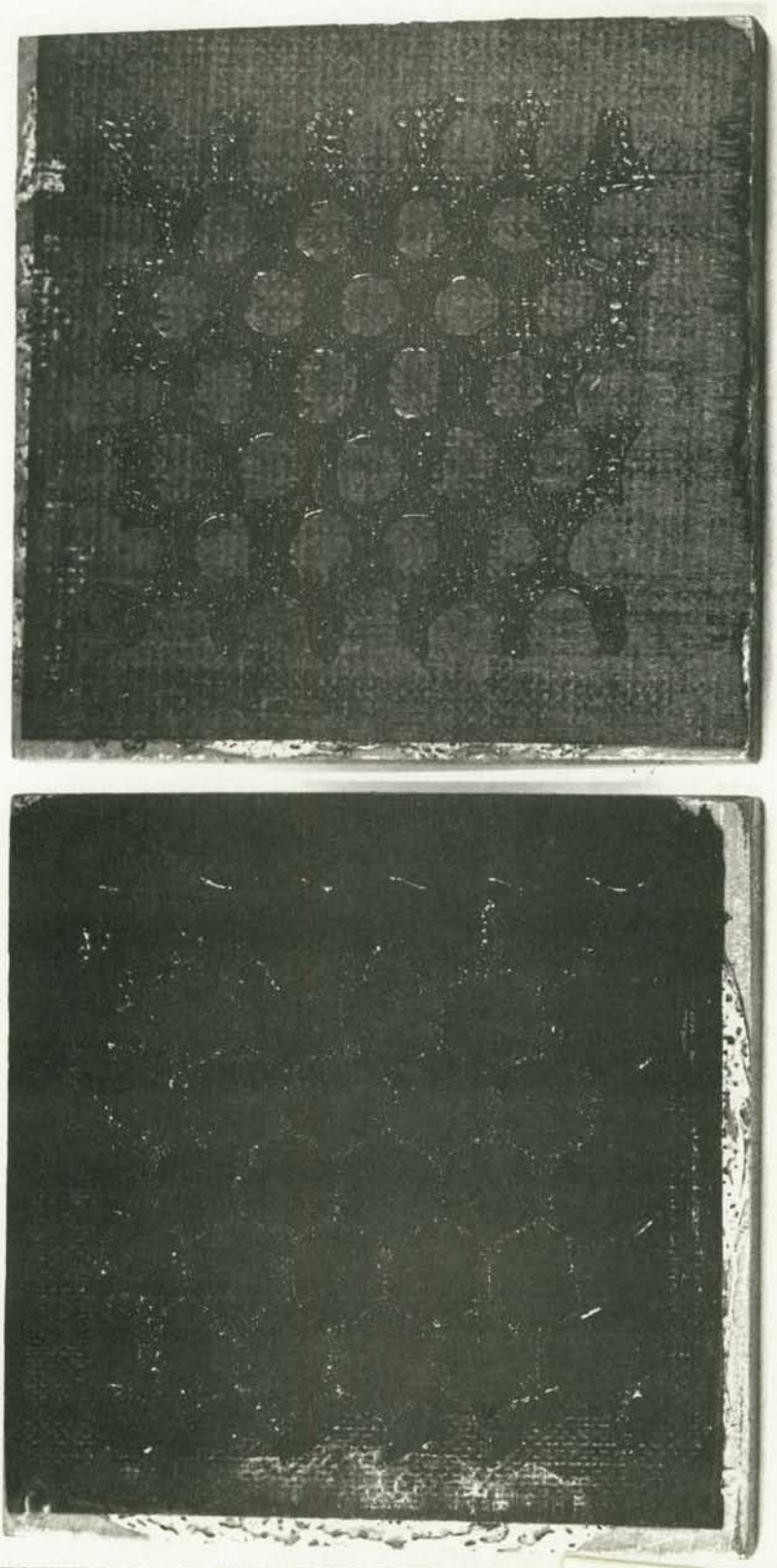

Figure 21. Thermadite 17 Face Sheet to Core Bond

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Face Sheet Bending Stress

$$F_B = \frac{PL^2}{8h\ t_f} \tag{2}$$

Core Shear Stress

$$F_{CS} = \frac{PL}{b\ (t+tc)} \tag{3}$$

Where: P = Distributed load (lb/sq in.)

L = Panel span (in.)

b = Panel width (in.)

t_f = Face sheet thickness (in.)

S = Cell size (in.)

h = Core height (in.)

t = Total panel height

μ = Face sheet Poisson's ratio

E_f = Face sheet modulus

Other types of failure modes such as shear crimping, face sheet wrinkling, and general buckling are not critical for a simply supported panel under distributed load.

The ultimate design loads were 6.0 psi during assent and 3.0 psi during entry. The design temperature during assent is 298°K (77°F) while the required design temperature during entry is 533°K (500°F) with a desired growth capability to 588°K (600°F) with an exposure duration of 200 hours.

Early in the program, after the initial tests on Core I and on thin gage face sheets, design studies were run to determine what the second cell size should be. In these studies, somewhat conservative face sheet allowables were used; however, the results showing lighter weight panels for 3/8 in. cell size are still valid. Figures 22 and 23 summarize the results of these studies. The figures show core shear stress, sandwich weight and face sheet thickness versus sandwich height for design loads of 4, 6 and 8 psi. Figure 22 applies to 1/4 in. cell size while Figure 23

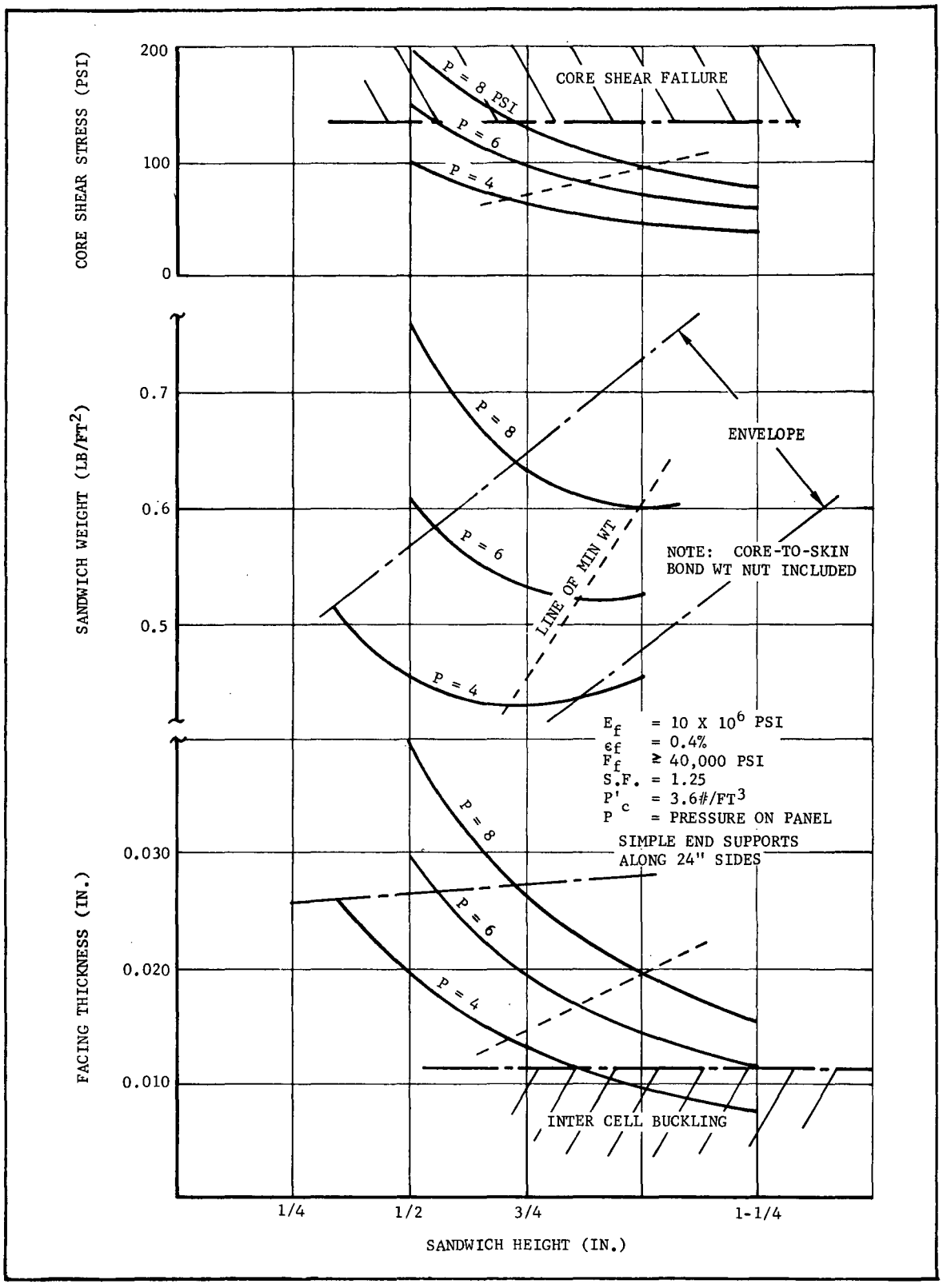

Figure 22. Sandwich Panel Design Study 1/4-In. Cell Size

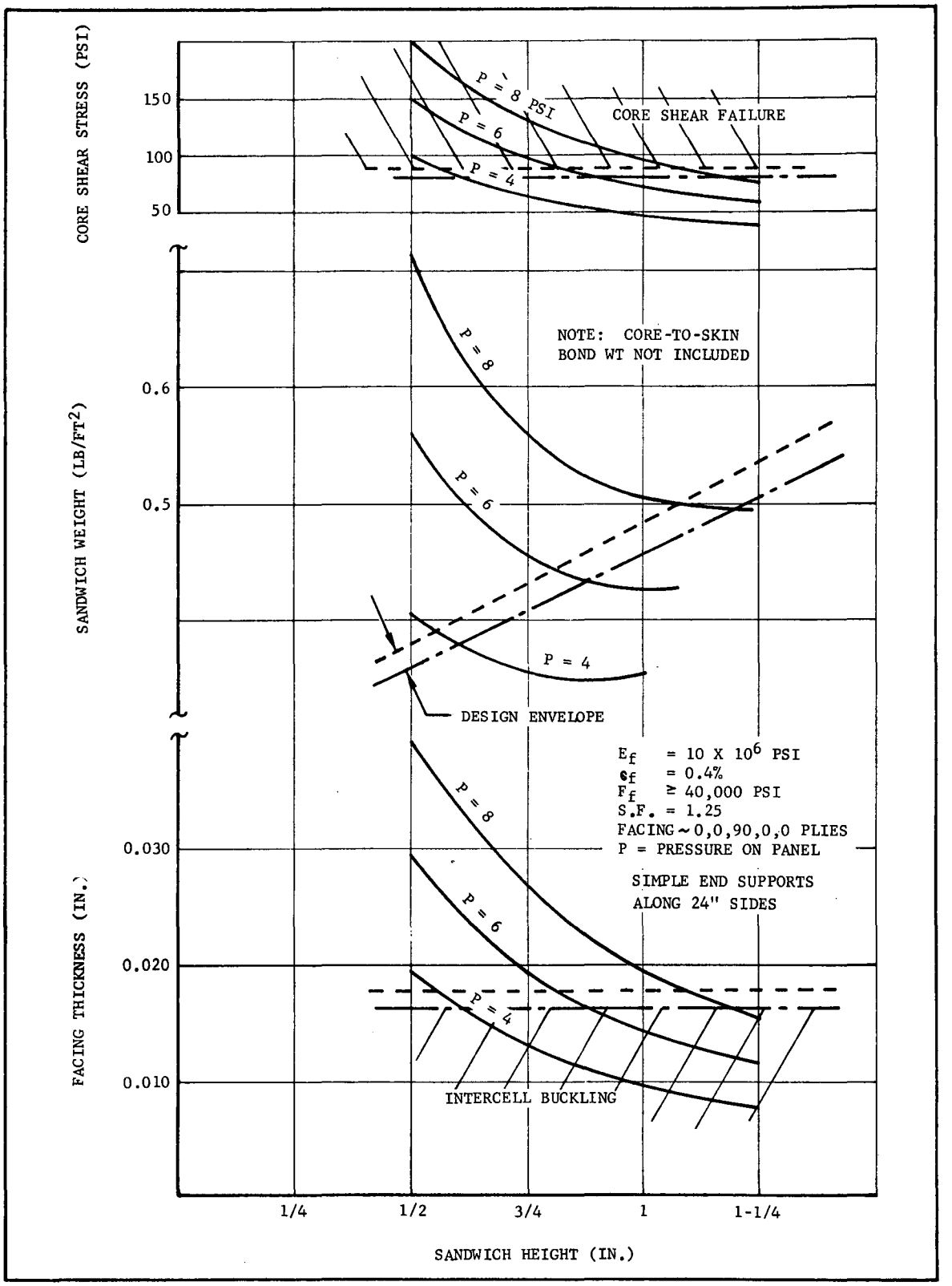

Figure 23. Sandwich Panel Design Study 3/8-In. Cell Size

gives the results for 3/8 in. cell size. By comparing the two figures, the lower weight of the 3/8 in. cell size is evident. The minimum weight panel for 3/8 in. cell size would have .016 in. thick face sheets on a 1.0 in. thick core.

The final design calculations followed the same approach using tested face sheet properties and Core IV honeycomb properties. The load at 533°K (500°F) is 50 percent of the 298°K (77°F) value, and material properties do not drop as rapidly; thus, 298°K (77°F) became the critical design temperature. With Core IV and using face sheets of 40,000 psi strength and a modulus of 15 x 10^6 psi, the minimum weight design contained .012 in. thick face sheets and a .9 in. core thickness. Total weight without adhesive was .32 lb/sq ft.

2. Edge Closure Design

Two types of edge closures, shown on Figure 24, were considered for the final panel, full depth foam and channel edge. Samples of Monsanto polyimide foam RI-7271-18 were obtained and tested as a core reinforcement. Compressive strength of the core was improved by a factor of eight over unfoamed core. In addition, the use of foam completely protected the thin face sheet and honeycomb edges from handling damage which had become a significant problem. Foam also appeared excellent for holding fasteners in place in the core without applying bearing or crimping loads to the face sheet. Further consideration of a channel edge closure was dropped.

3. Core Venting

A means of achieving core venting was not required as the thin gage core and face sheets contained micro-porosity. Sufficient porosity was available to allow escape of the volatiles by-products given off by the face sheet-to-core bonding adhesive during cure. Should venting be required at a later time, mechanical perforation of the cell wall should be acceptable.

G. SANDWICH BEAM TEST SPECIMENS

Sandwich beams 1-1/2 in. W x 8 in. L x 1 in. T were assembled using both Core I and Core II honeycomb, several face sheet orientations and Thermadite 17 adhesive. The primary purpose of these test elements was to combine the separate development programs and to determine the minimum quantity of adhesive required to produce sufficient shear strength in the face sheet-to-core bond. The discussion is separated into two parts, fabrication and testing.

1. Beam Fabrication

Fifteen beam test specimens were fabricated, and a target adhesive weight of .05 lb/sq ft/side was established. Table XVII summarizes the configuration and weights of the components. The first seven

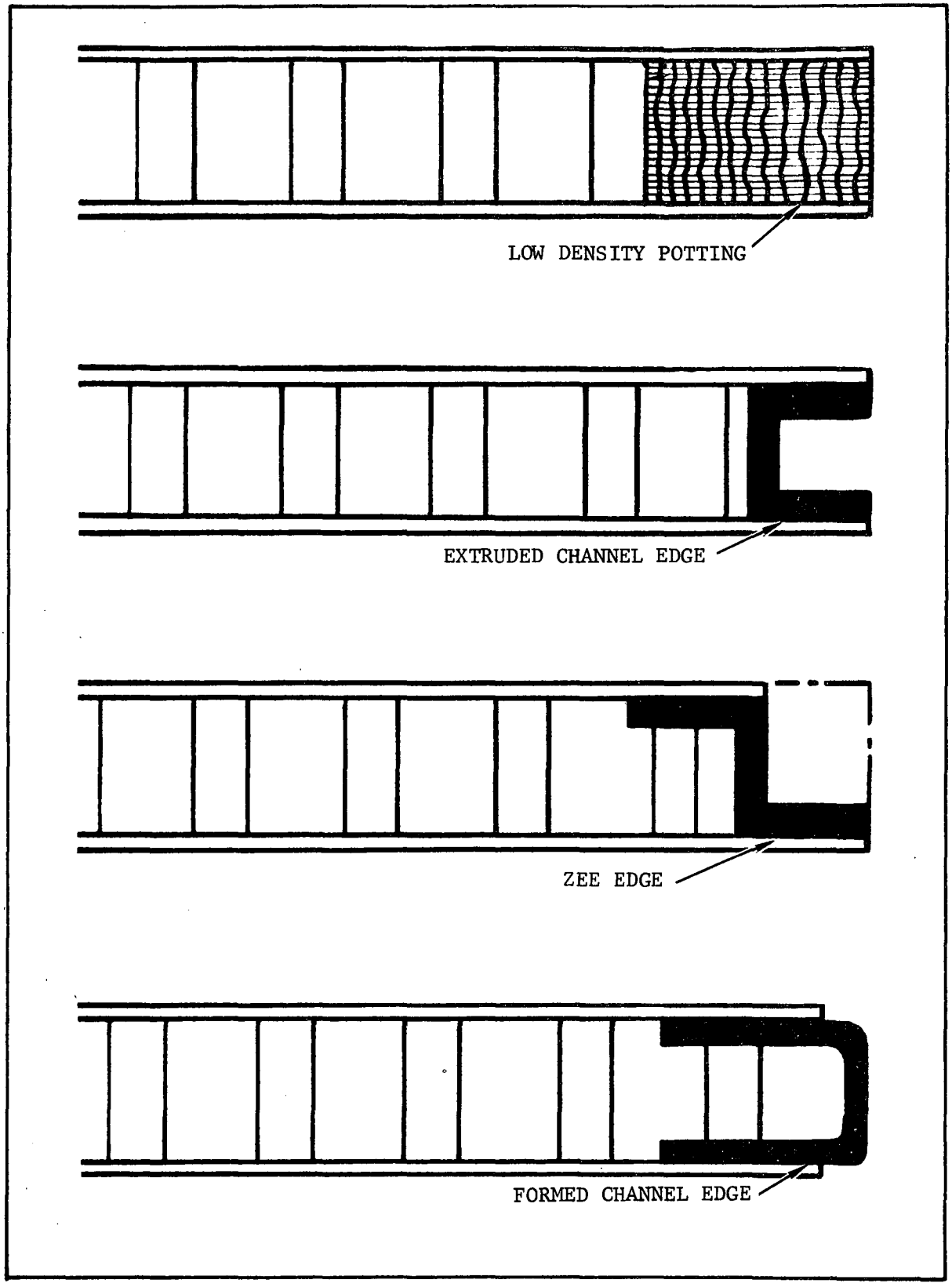

Figure 24. Edge Closure Concepts

TABLE XVII

SANDWICH BEAM SPECIMEN FABRICATION SUMMARY

Beam No.	Face Sheet Orientation	Core SN	Core Weight (lb/ft^2)	Face Sheet* Weights (lb/ft^2)	Adhesive Weight (lb/ft^2)
28	$[0]_3$	I	0.328	0.084	0.042
29	$[0]_5$	I	0.312	0.152	0.035
30	$[0]_5$	I	0.310	0.144	0.044
31	0, 0, 90, 0, 0	I	0.328	0.141	0.030
32	0, 0, 90, 0, 0	I	0.327	0.143	0.034
33	0, 0, 90, 0, 0	I	0.321	0.143	0.040
34	$[0]_3$	I	0.318	0.078	0.054
35	0, 0, 90, 0, 0	I	0.315	0.126	0.314
36	0, 0, 90, 0, 0	I	0.328	0.123	0.331
37	0, 0, 90, 0, 0	I	0.312	0.083	0.148
38	0, 0, 90, 0, 0	I	0.324	0.084	0.173
41	0, 0, 90, 0, 0, 0, 90, 0, 0	II	0.197	0.151	0.140
42	0, 0, 90, 0, 0, 0, 90, 0, 0	II	0.207	0.154	0.142
43	0, 0, 90, 0, 0, 0, 90, 0, 0	II	0.209	0.149	0.120
44	0, 0, 90, 0, 0, 0, 90, 0, 0	II	0.203	0.150	0.114

*Face sheet surface area may exceed areas of core

beams, Nos. 28-34, were fabricated with an average adhesive weight of .019 lb/sq ft/side. Adhesive pick-up was erratic and insufficient in many places to permit fillet formation.

Most of the problems were traced to the adhesive. Layering, whereby solvent separated from the resin and formed on the spread resin surface, was one problem, while a change in adhesive viscosity with time caused by solvent evaporation was a second.

On the next set of panels (Nos. 35 and 36), an excessive amount of adhesive, .155 lb/sq ft/side was obtained.

As an understanding of the adhesive developed and the pick-up controlled, a satisfactory procedure was obtained (Appendix B), and the final six panels achieved adhesive weights between .071 and .079 lb/sq ft.

2. Beam Testing

Beam testing was designed to check the performance of the composite honeycomb panels subject to bending type loads. Testing could be done by either three point or four point load application in order to produce the desired failure mode. For example, a three point test would produce higher face sheet stresses at a given load than the four point test, while the four point test would produce higher shear stresses. General test configuration is shown in Figure 25.

The steps required to prepare the specimens for testing were (1) a final post cure cycle and (2) the bonding of strain gages to the composite face sheets to measure strains. A cam controlled oven post cure cycle was used to condition the specimens. Strain gages were attached to the face sheet using M-Bond 610 high-temperature adhesive (Micromeasurements, Inc.) as the bonding adhesive.

Fabrication problems and secondary stresses not included in panel property predictions affected the test results of the first panels. Problems in obtaining an even distribution of liquid adhesive on the core-to-face sheet bonds resulted in improper filleting. These suspect areas were detected prior to beam testing using X-ray techniques. These unbonded areas greatly reduced the loading capability of the first panels.

In addition to the poor bonding, dimpling was observed on the face sheets of the composite panels. Since the face sheets were cured before they were bonded to the core, dimpling had not been expected. Dimpling manifested itself as an inward warpage of the face sheet into the open core cells. The dimpling was first noticed after completion of the adhesive cure. The phenomena was initially thought to result from insufficient face sheet cure or from softening of the face sheet by the adhesive. It persisted, however, despite post curing the composite parts prior to bonding. It was then observed that dimpling was associated with the fillet size of the adhesive and reduced fillet size reduced the

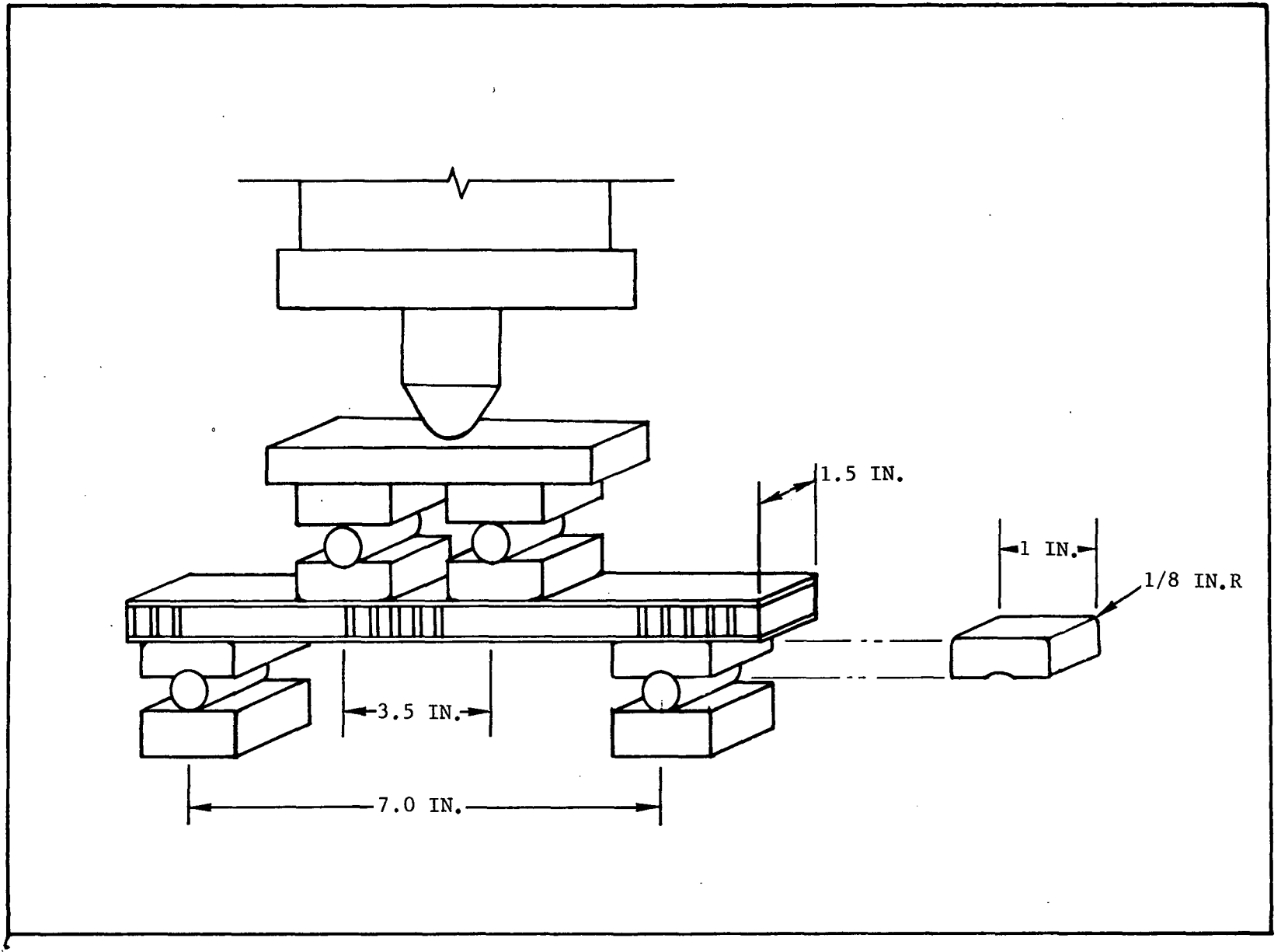

Figure 25. Sandwich Beam Flexure Test

severity of the problem. Thus, thermal shrinkage of the adhesive fillet combined with the thin face sheets results in warping the face sheet into the core cell. Changing to adhesive that has less cure shrinkage would eliminate this problem.

Loading the test panels was another problem encountered. The first panels (Nos. 28 through 32) were tested with a soft rubber pad under the load bars to distribute the load evenly in the flexture type tests. However, the pad caused a punch shear failure of the thin gage face sheet at the core nodes.

The rubber pad was eliminated on the tests of panels 35 and 36; and a 1/2 in. diameter round metal bar was used; however, core bearing failures under the bars resulted. The final change was to fabricate and insert metal pads between the load bars and face sheet. The pads effectively distributed the loads without causing undesired damage to the core or face sheets. A summary of the test results is given on Table XVIII. The inconsistent results of the first five beams reflect the adhesive and load application problems. The final six beams, however, demonstrated that sufficient bond shear strengths could be obtained at weights of .07 lb/sq ft/side with 3/8-in. core and that a face sheet modulus value of 17.0 x 10^6 could be used for design of the final face sheet thickness.

H. FINAL PANEL FABRICATION AND TEST

Based upon the properties obtained in the test program, two sandwich panels were designed and built to meet the load requirements of Section F. The resulting structure, shown in Figure 26, has 0.012 in. thick face sheets containing seven 0° plies and two 90° plies. The core is 0.9 in. thick of 3/8 in. cell size. Face sheet-to-core bonding was accomplished using Thermadite 17 as a cell edge adhesive. To prevent handling damage to the edges and to locally reinforce the panel at attachment points, the edges were reinforced with sintered polyimide powder (Monsanto Skybond RI-7271-18).

Three 3/16 diameter holes were drilled along two edges of the panel to provide attachment capability and to demonstrate machinability of the part.

The fabrication sequence begins with cure and post cure of the face sheets followed by the bonding operation. Fillets are formed on one side of the core by dipping the core into a 0.070 thick liquid adhesive sheet and then drying (Figures 27 and 28). Bonding of the first face sheet is completed with a second dip and placement of the core on the face sheet (Figure 29). The fillets are carefully inspected to ensure proper bonding. Foam reinforcement is then added and cured (Figure 30). To prevent the foam from absorbing a large quantity of Thermadite 17 during bonding of the second face sheet, the foam is sealed with BR-34 (Figure 31). The (BR-34) adhesive is cured and machined prior to the bonding of the second face sheet. The second face sheet is then bonded in the same manner as the first. A completed panel is shown in Figure 32. Details of the fabrication procedure are given in Appendix C.

TABLE XVIII

SANDWICH BEAM SPECIMEN TEST SUMMARY

Beam No.	Test Temp (^{o}K)	Test Temp (^{o}F)	Face Sheet Thickness (in.)	Failure Mode	Core Shear Stress (psi)	Face Sheet Stress (psi)	Face Sheet Modulus (psi x 10^{6})
28				No test			
29				No test			
30				No test			
31	298	77	0.012	Bond shear[1]	23	7,670	9.7
32	298	77	0.012	Compression[1]	34	10,050	9.5
33				No test			
34	298	77	0.0072	Punch shear[2]	57	13,940	11.9
35	588	600	0.012	Core bearing[3]	116	16,460	6.7
36	298	77	0.011	Tensile	77	12,346	7.14
37	298	77	0.006	Tensile	142	41,500	17.5
38	588	600	0.006	Tensile	110	32,200	16.1
41	298	77	0.013	Core shear	159	23,580	19.6
42	588	600	0.013	Core shear	92	9,720	15.0
43	298	77	0.010	Tensile	120	41,176	16.5
44	533	500	0.011	Core shear	105	16,748	20.9

[1] Area of poor bond

[2] Rubber loading pad pushed in face sheet

[3] Bearing at contact of loading rod

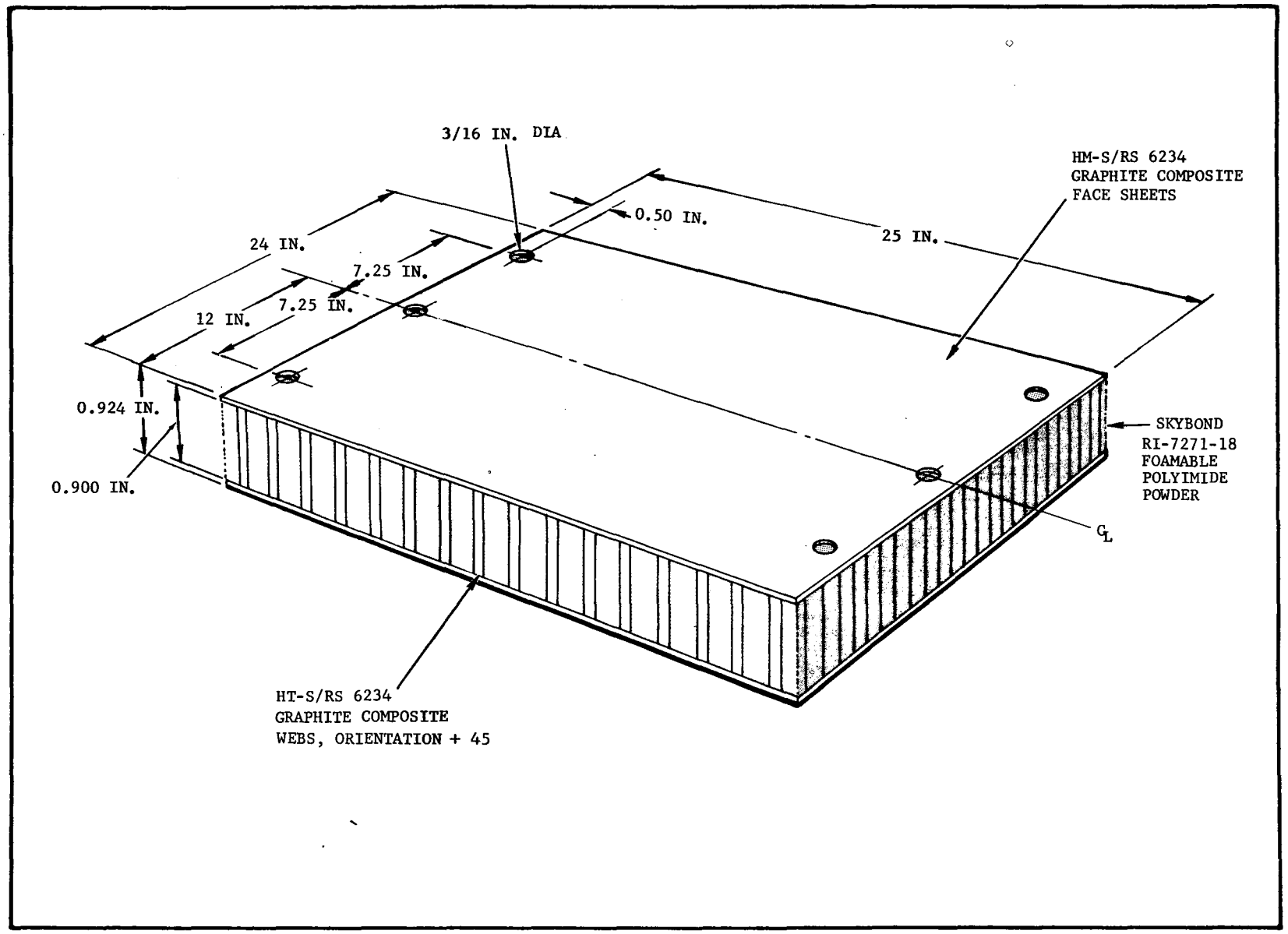

Figure 26. All Graphite Thermal Protection Support Panel

Figure 27. Adhesive Film Prior to Dipping Core

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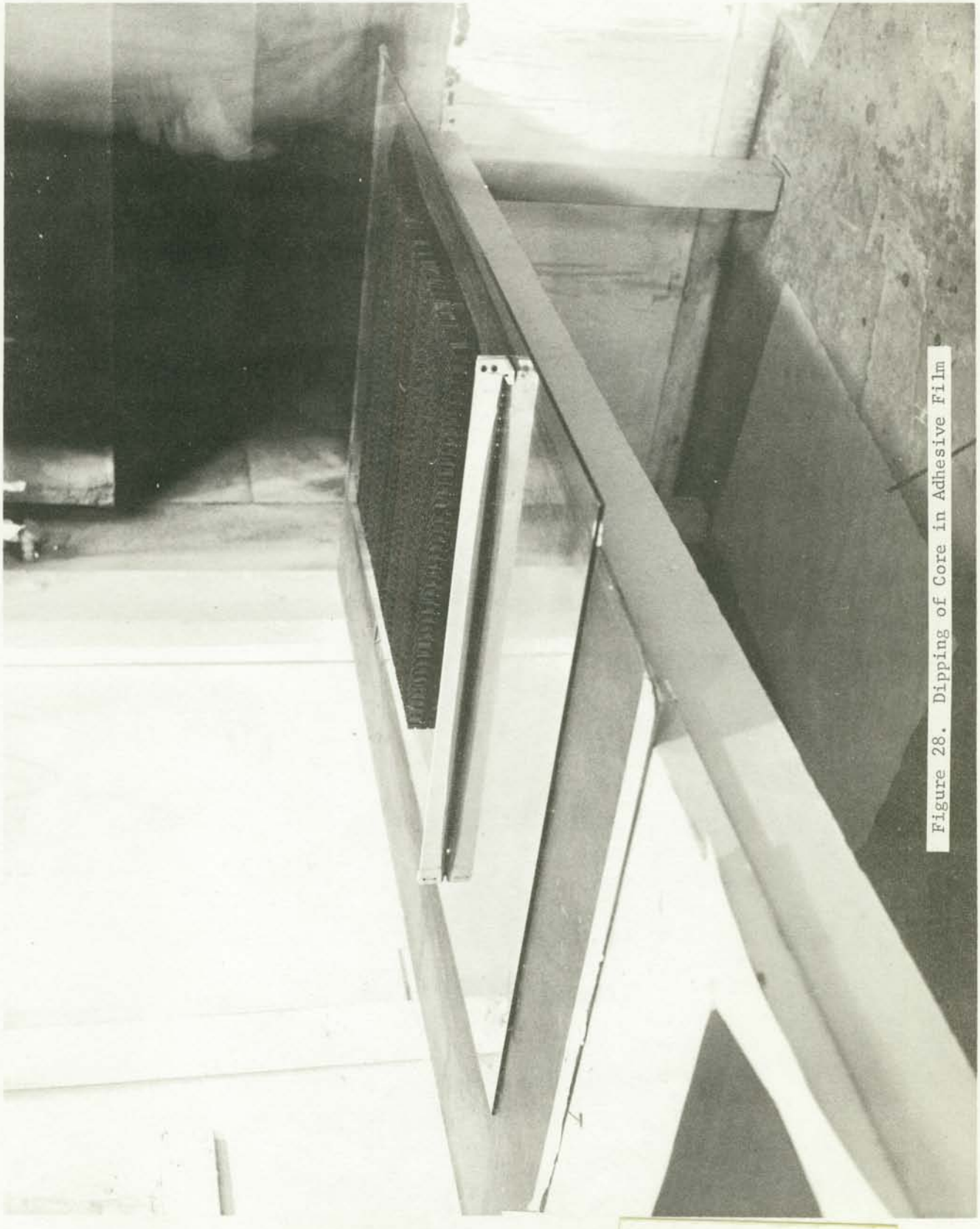

Figure 28. Dipping of Core in Adhesive Film

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Figure 29. Bonding of First Face Sheet

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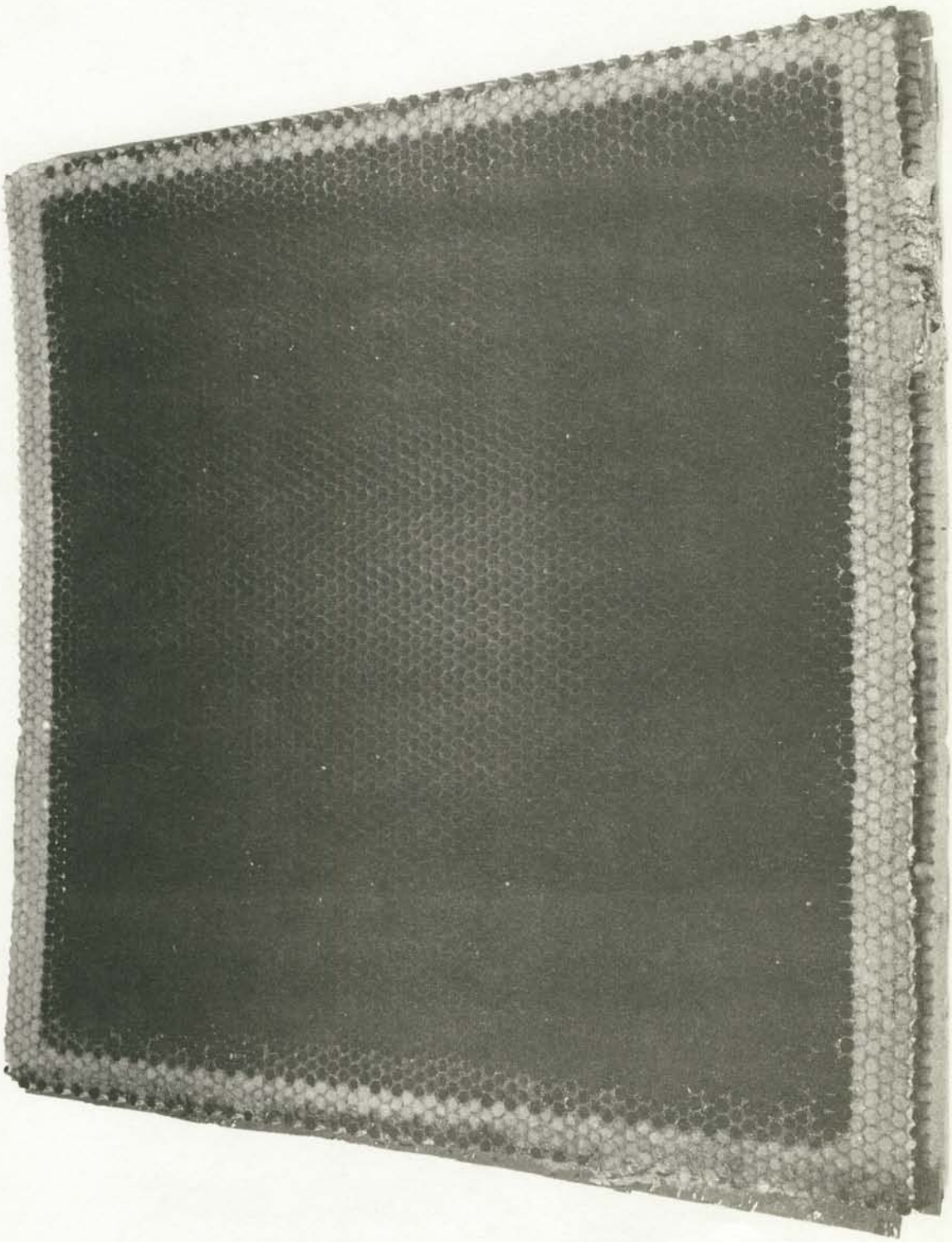

Figure 30. Foamed Cells at Edges of Panel

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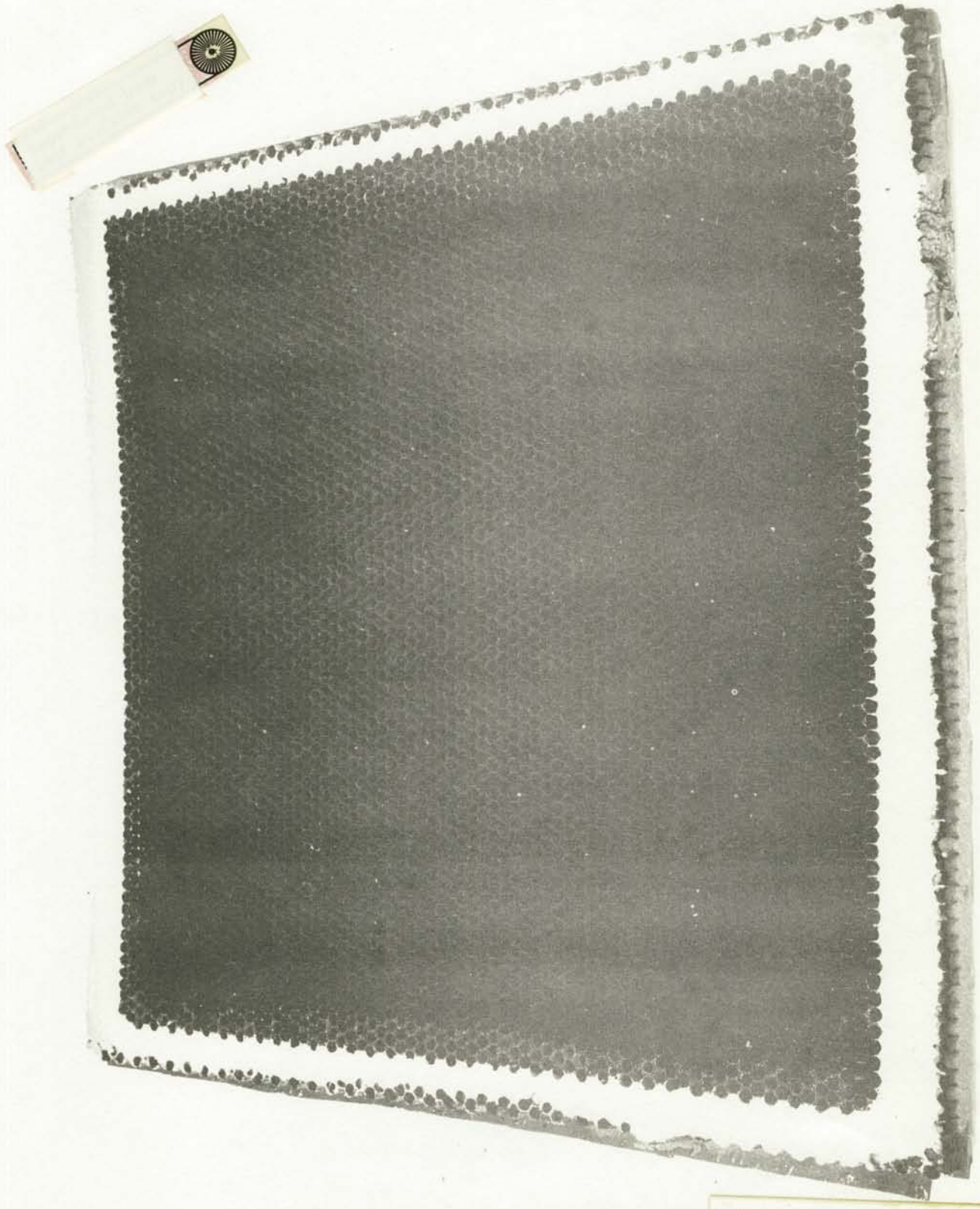

Figure 31. BR-34 Sealant Applied to Foam

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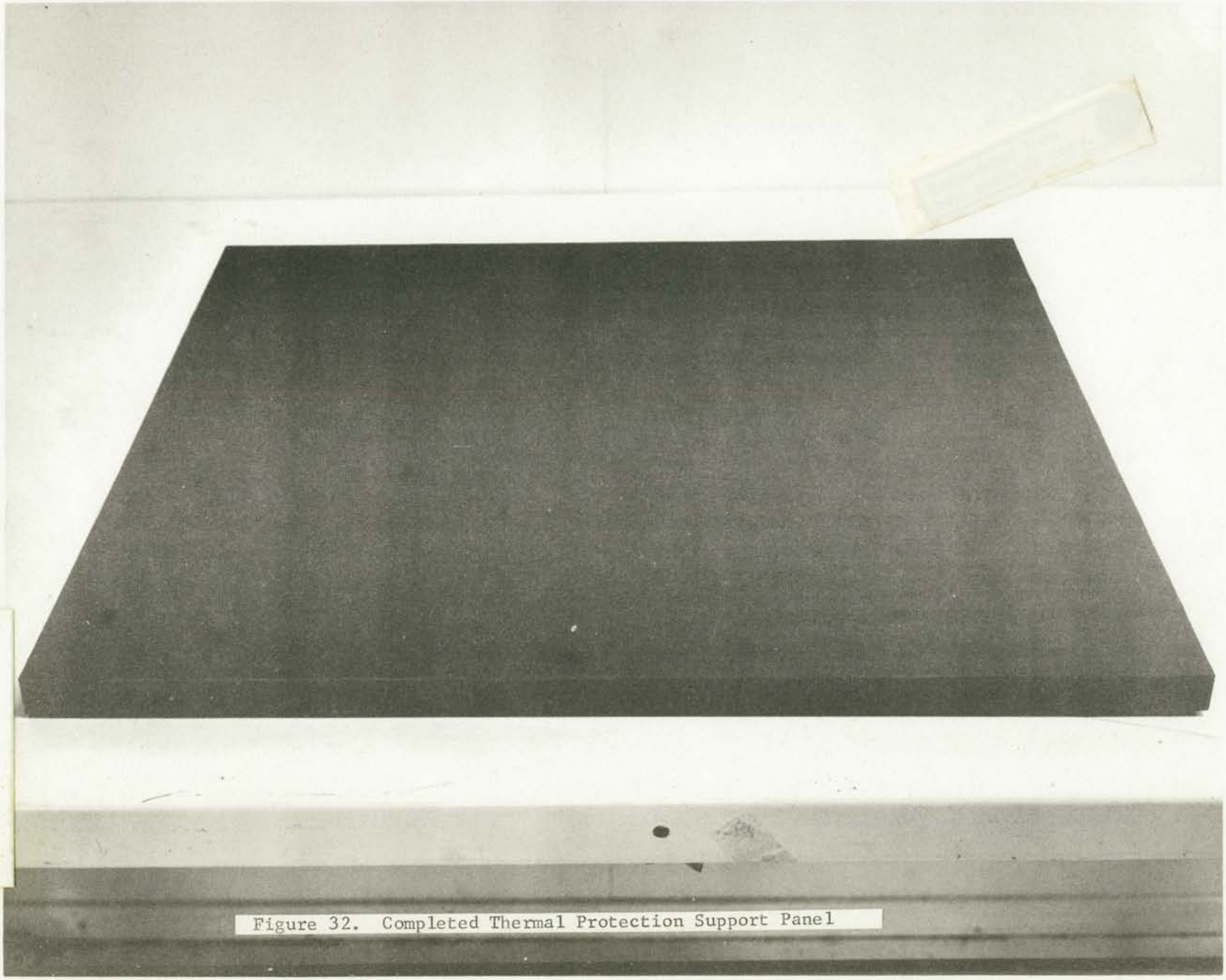

Figure 32. Completed Thermal Protection Support Panel

The initial panel fabricated was 24-in. long by 10-in. wide and included foamed cells across one end. Fabrication of this panel went very smoothly, and a weight of 0.42 lb/sq ft was obtained. The panel was cut into 14 beam test specimens 1.3-in. W by 8.5-in. L x .925-in. T shown on Figure 33. Testing was conducted to establish face sheet strengths in two directions, core shear in the L direction, flatwise compression and flatwise tension strength. Tests were conducted at 298°K (77°F) and 533°K (500°F).

Individual test values are shown on Tables XIX and XX while average values are summarized on Table XXI. Typical face sheet failures are shown on Figures 34 and 35 for tension and compression, respectively.

Several problems arose in the fabrication of the final two panels. In foaming cells completely around the edge of the panel, shrinkage of the foam tended to warp the panel which made bonding of the second face sheet difficult.

Techniques which had been established using flat panels had to be modified and heavier adhesive weights results as shown in the weight summary of Table XXII. It is recommended that the channel edge closure be re-examined as a possible replacement for foam as a result. An alternative would be to foam areas of the panel only where loads are introduced and to write a handling specification which would recognize the possible fragileness of the unprotected edges. The basic panel can be built to carry the loads at a weight of .42 lb/sq ft of panel.

The warpage problem resulted in some unbonded areas on the second face sheet bond of the first panel. These areas were subsequently repaired by inserting a .030 diameter hypodermic needle through the face sheet and forcing in Thermadite 17 resin. Cure was accomplished by placing the face sheet with the unbonds down on a metal plate in the oven and applying a 100 lb load on the panel. X-ray examination of the panel indicated the repair gave good bonds; however, the actual bond strength obtained was not obtained, and the strength of panel S/N-1 is suspect for that reason.

The process for bonding the second panel was modified by reducing the post cure temperature on the foam to reduce warping prior to bonding the second face sheet. This reduction does not result in the foam being undercured since the bonding of the second face sheet gives the foam further cure. A second modification was the addition of more load ($\sim$400 lbs) to the panel during final cure to assure better contact between the core and the face sheet.

1. Final Panel Design and Margins of Safety

The final panel design was checked for design adequacy. As discussed in Paragraph F.1., the critical design conditions were intercell buckling, face sheet bending stress and core shear stress. Using

TABLE XIX

HONEYCOMB PANEL TEST DATA
FACE SHEET STRENGTH

Sample No.	Temperature (°K)	Temperature (°F)	Strength (psi)	Strain (%)	Modulus (psi x 10^6)
12	172	-150	35,020	.24	14.9
14	172	-150	36,480	.19	18.7
			(35,750)	(.22)	(16.8)
6	298	77	42,880	.21	19.5
7	298	77	38,500	.20	18.3
10	298	77	40,200	.21	18.8
			(40,500)	(.21)	(18.9)
4	533	500	26,670	.18	14.8
5	533	500	29,780	.18	16.5
8	533	500	23,940	.13	18.4
9	533	500	31,520	.17	18.2
11	533	500	35,310	.20	17.2
			(29,440)	(.17)	(17.0)
A*	298	77	16,750	.22	7.4
B*	533	500	17,390	.29	5.9

* Indicates transverse face sheet properties. All other values longitudinal.

TABLE XX

HONEYCOMB PANEL
TEST DATA CORE PROPERTIES

Property	Sample No.	Temperature (°K)	Temperature (°F)	Value (psi)
Core Shear Strength, "L" Direction	1	298	77	145.5
	2	298	77	137.1
	3	298	77	136.3
				(139.5)
	4	533	500	115.2
	11	533	500	105.3
				(110.3)
Core Compressive Strength	9	298	77	232
	5	298	77	242
	B	298	77	254
	A	298	77	255
				(246)
	9	533	500	175
	8	533	500	164
	5	533	500	154
	4	533	500	153
				(161)
Flatwise Tensile Strength	9		-150	177.6
	A	298	77	139.7
	8	298	77	108.3
	B	298	77	112.5
				(120.1)
	A	533	500	113.1
	9	533	500	138.5
	5	533	500	132.0
	B	533	500	133.2
				(129.2)

NOTE: Core was 1.9 lb/cu ft, 3/8-in. cell size.

TABLE XXI

HONEYCOMB PANEL STRUCTURAL PERFORMANCE SUMMARY

Design Property	Value	
	298°K (77°F)	533°K (500°F)
Facing Strength (psi)		
Parallel to ribbon	40,500	29,440
Perpendicular to ribbon	16,750	17,390
Facing modulus (psi x 10^6)		
Parallel to ribbon	18.9	17.0
Perpendicular to ribbon	7.4	5.9
Flatwise Shear Strength (psi)		
Parallel to ribbon	140	110
Perpendicular to ribbon	80	66
Flatwise Compressive Strength (psi)		
With foam	1,000	600
Without foam	246	161
Flatwise Tensile (psi)	120.1	129.2
Face Sheet Weight (lb/ft^2)*	0.16	
Core Weight (lb/ft^2)*	0.16	
Adhesive Weight (lb/ft^2)*	0.10	
Foam Weight (lb/ft^2)*	0.00	
Total Panel Weight (lb/ft^2)*	0.42	

*Lb per ft^2 of panel

TABLE XXII

NASA SANDWICH PANEL WEIGHT SUMMARY

	Panel #1			Panel #2		
	Wt (gm)	Wt (lb)	lb/ft^2***	Wt (gm)	Wt (lb)	lb/ft^2***
Core	281	.619	.149	281*	.619	.149
Face Sheet #1	144	.318	.076	144*	.318	.076
T-17 (first coat)	124	.273	.066	91.5	.202	.048
Fillets (T-17)	45*	.099	.024	45	.099	.024
Foam (Monsanto)	231	.509	.122	267	.589	.141
BR-34 (first coat)	59	.130	.031	39.5	.087	.021
BR-34 (second coat)	--	--	--	7.5	.017	.004
Face Sheet #2	137	.302	.072	137*	.302	.072
T-17 (second coat)	110**	.243	.058	343.5	.757	.182
Totals	1131	2.493	.598	1356	2.990	.717

* Based on measured value for other panel.
** Includes repair of blisters on finished panel.
*** Assume final panel area = 24-in. x 25-in. = 600 $in.^2$ = 4.167 ft^2.

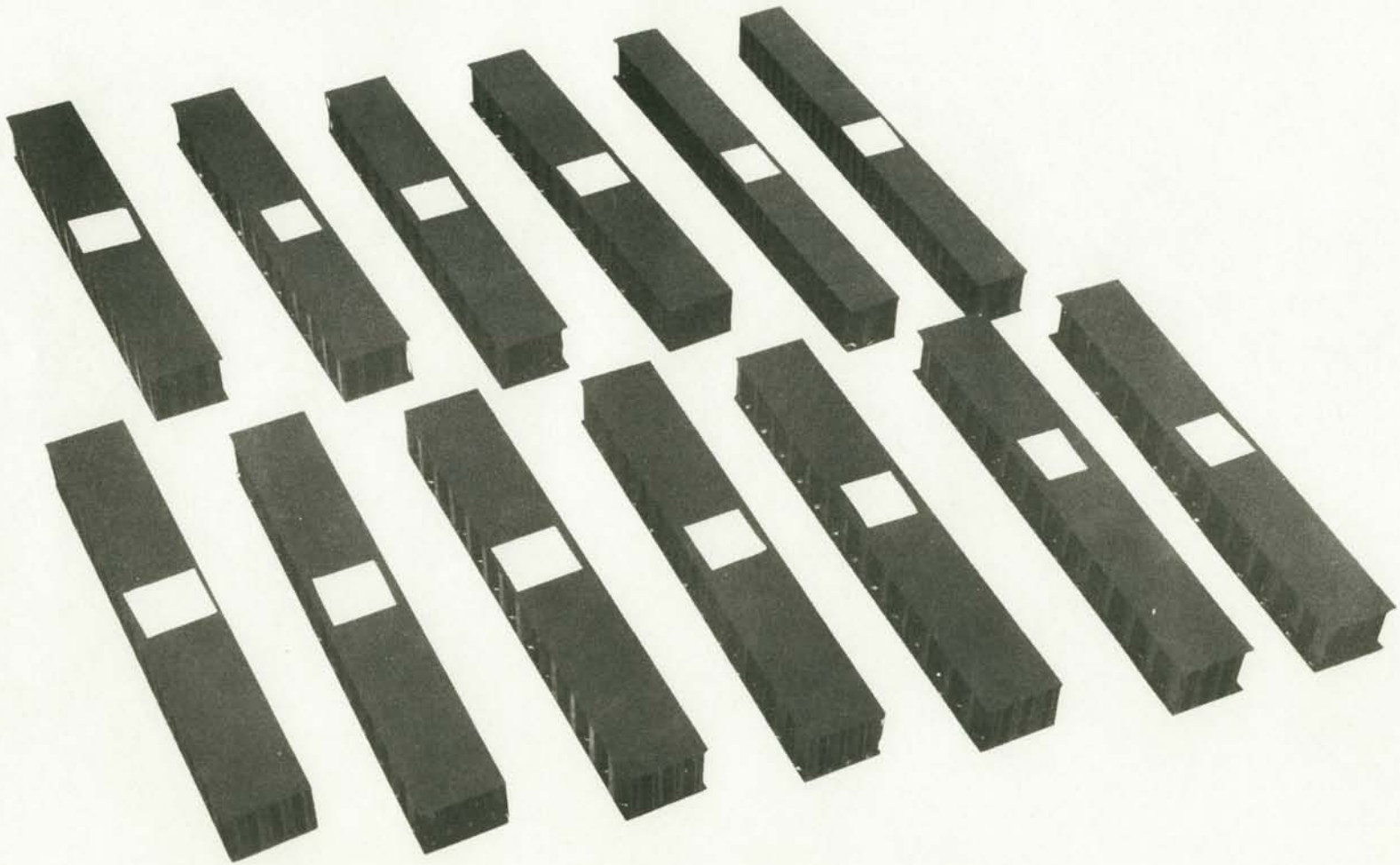

Figure 33. Final Panel Test Specimens

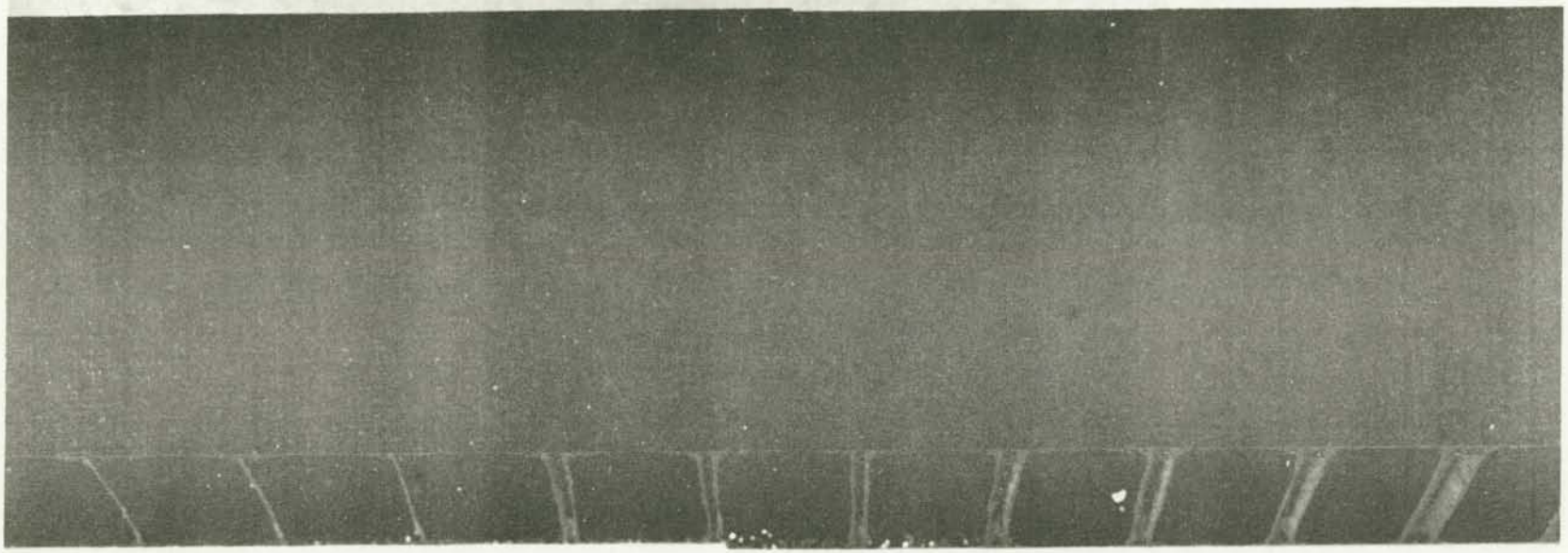

Figure 34. Typical Sandwich Beam Tension Failure

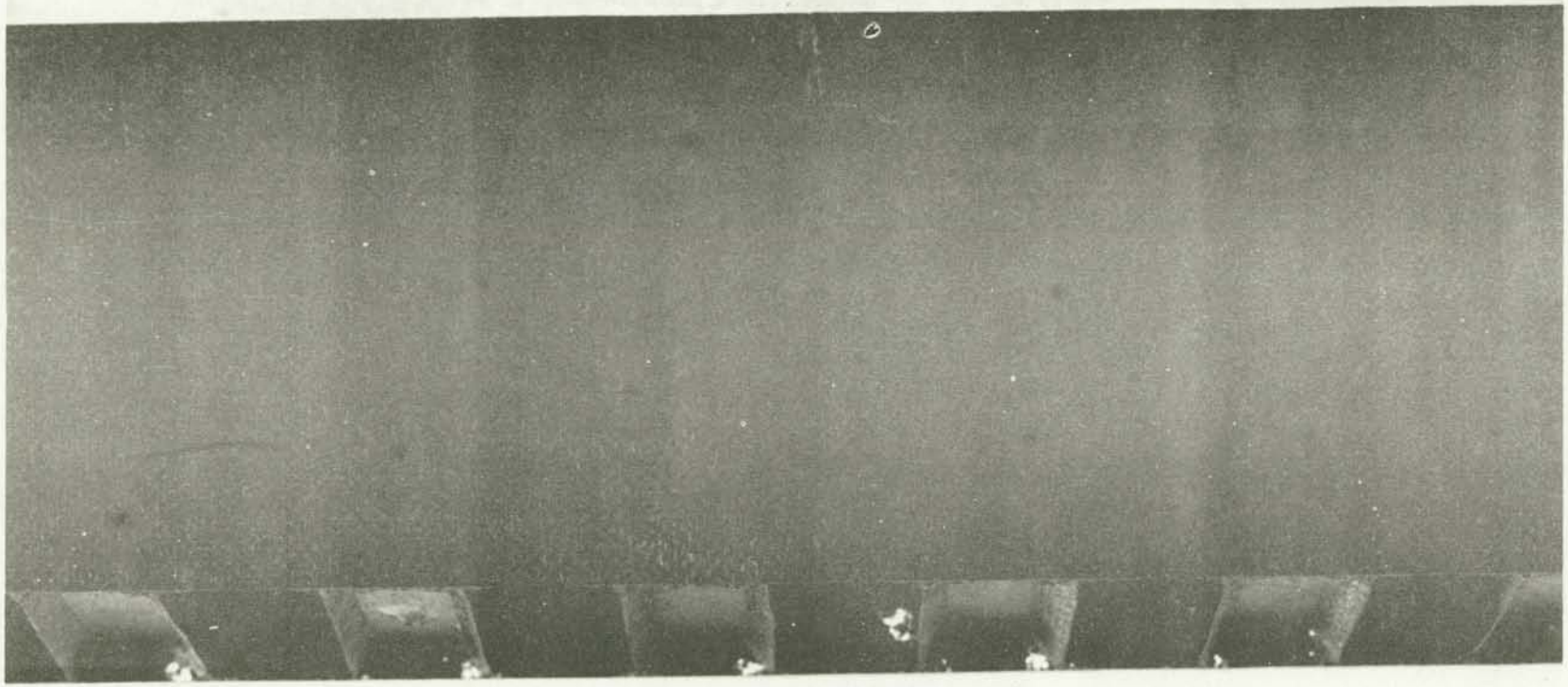

Figure 35. Typical Sandwich Beam Compression Failure

the measured properties and the measured dimensions of the fabricated panels, the stresses and margins of safety for each of these conditions are given below. Values are given for 298°K (77°F) during assent under 6.0 psi ultimate load. Margins of safety are greater at 533°K (500°F).

Face Sheet Bending Stress

$$F_b = \frac{PL^2}{8ht_f} = \frac{6(24)^2}{8(.91)(.012)} = 40{,}000 \text{ psi}$$

Ultimate Allowable = 40,500 psi

$$M.S. = \frac{40{,}500}{40{,}000} - 1 = 0.01$$

Core Shear Strength

$$F_{cs} = \frac{PL}{t+tc} = \frac{6(24)}{1.844} = 78 \text{ psi}$$

Ultimate Allowable = 140 psi

$$M.S. = \frac{140}{78} - 1 = .8$$

Inner Cell Buckling

$$F_{CL} = \frac{2}{1-\mu^2} E_f \left(\frac{t_f}{S}\right)^2 = \frac{2}{.96} (18.9 \times 10^6)\left(\frac{.012}{3/8}\right)^2 = 40{,}025 \text{ psi}$$

Applied Bending Stress = 40,000 psi

$$M.S. = \frac{40{,}025}{40{,}000} - 1 = 0.0$$

Face sheet bending stresses and inner cell buckling are seen to be the more critical design conditions. A large margin of safety is shown for core shear and face sheet-to-core bond.

A comparison of the predicted panel deflection at mid-span was made between the panels fabricated during this program, a minimum weight panel designed by McDonnell-Douglas and the minimum weight panel of Reference 1. All three used graphite face sheets but with heat-resistant glass honeycomb. The panel deflection (Δ) is obtained from the equation

$$\Delta = \frac{5P(L)^4}{384D} + \frac{PL^2}{8hG_c}$$

Where

$$D = \frac{E_c t_c^3}{12\lambda_f} + \frac{E_f}{12\lambda_f}(t^3 - h^3)$$

P = 6 psi

L = 24 in.

Properties for the three cases are given below:

	E_c (psi)	G_c (psi)	h (in.)	Cell Size (in.)	Core Density (lb/ft^3)	Face Sheet Modulus (psi x 10^6)	Thick (in.)
HRH-327	25,000	17,000	.75	3/16	3.0	18.9	.012
HT-S/6234	19,600	32,400	.91	3/8	1.9	18.9	.013
HRP	10,000	9,000	.64	3/8	2.2	14.5	.013

The deflection values for bending, shear and total deflection were as follows:

Face Sheet	Honeycomb	Bending Deflection (in.)	Shear Deflection (in.)	Total Deflection (in.)
Graphite	HRH-327	.035	.034	.069
Graphite	HT-S/6234	.027	.014	.041
Graphite	HRP	.061	.075	.136

The higher shear modulus of the graphite core is very evident in reducing shear deflection which results in a significantly lower total panel deflection.

I. SUMMARY AND CONCLUSIONS

Thin gage graphite composite was manufactured in ply thicknesses of 0.0018 in. for two-ply $\pm 45^\circ$ HT-S core web material and 0.0012 in. for five- to nine-ply HM-S face sheet material. Property degradation in unidirectional thin gage material was similar to that reported with fiberglass. Cross plied material appeared to have reduced degradation.

The manufacture of lightweight carbon fiber honeycomb was accomplished using standard fiberglass technology without difficulty. Honeycomb properties obtained exceeded those of fiberglass and Nomex core material at

the same weights at all temperatures tested. Properties exceeded those of aluminum at temperatures over 422°K (300°F). Core weights less than 2.0 lb/cu ft were obtained.

Sandwich panels using graphite honeycomb and graphite face sheets produced weight savings of 16 percent over other types of construction for back-up structure for the shuttle orbiter thermal protection system with a 50 percent reduction in panel deflection.

In view of the honeycomb properties obtained with thin gage graphite at rather low fiber volumes, development of heavier gage honeycomb should produce weight savings of up to 40 percent over present honeycomb materials and should be vigorously pursued.

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11. Mechanical Properties of Hexcel Honeycomb Materials, TSB-120 Hexcel Corporation, Dublin, California.

APPENDIX A

ADHESIVE BOND STUDY SPECIMEN PREPARATION PROCEDURE

Materials

Solvents: Available in plastic squirt bottles properly marked

(1) MEK (Methyl Ethyl Ketone)
(2) Triclene (Tri-chlorethylene)
(3) N-Methyl Pyrrolidinone (NMP)

Pasa Jell No. 101 (Semco, Los Angeles, California)
Scotchbrite abrasive cloth (fine)
Alconox Detergent (Alconox, Inc., New York, N.Y.)
FM-34 Polyimide adhesive sheet film (.017 in.) Bloomingdale Division of American Cyanamide, Havre de Grace, Maryland

Adhesives under study

(1) BR-34 (Bloomingdale Adhesives Division of American Cyanamide)
(2) Hexcelite LR-305019-1 (Hexcel)
(3) Hexcelite HX-971 (Hexcel)
(4) Thermadite 17 (Whittaker)

Tabs

Stainless steel "case bond" table (borrowed from Chemical Laboratory, Hercules)

Face Sheets

6234/HT five plies, 0, 0, 90, 0, 0 (.009 in. panel thickness), manufactured and cut to 2 in. x 2 in. size by Hercules

Core

Honeycomb manufactured and cut to 1-1/2 in. x 1-1/2 in. by Hexcel Corporation (1/4 in. cell)

Facilities and Tooling

Vacuum pump (portable)
Dessicator (vacuum)
Hand pump hydraulic press (heated)
Standard - typical laboratory with aluminum bars
Hot Plate - Thermolyne type 1900 model HP-A1915B
Thermometer - 433°K (500°F) maximum
Pitcher - stainless steel - 1 gallon wide mouth
Gardner Knife
Honeycomb Bonding Fixture - #NAS 9-11368-1A and 1B Assembly
Large Hotpack Oven - 588°K (600°F) capability
Large glass plate (18 in. x 18 in. minimum)
Preliminary bonding fixture
Miscellaneous: tape, cloths, spatulas, beakers, etc.

Step A. Face Sheet-to-Tab Bonding

I. Resin Preparation

(1) Remove FM-34 adhesive film from 255°K (0°F) storage and wait 3 hours until adhesive has reached ambient conditions.

(2) Cut film adhesive to desired size (2 in. x 2 in.) with solvent cleaned scissors.

NOTE: Use clean white gloves to handle adhesive.

(3) Place adhesive in vacuum dessicator for 24 hours (minimum) prior to bonding.

II. Metal Tab Preparation

(1) Use scotchbrite to remove large contaminates on bonding surface of tabs.

(2) Solvent clean surface with MEK and stiff bristled brush.

(3) Grit blast bonding surface with fine (100 grit) Al_2O_3.

(4) Solvent clean with MEK and stiff brush.

(5) Rinse in hot tap water.

(6) Rinse in cold tap water and dry in 333°K (140°F) oven (10 minutes).

(7) Apply a substantial thickness of Pasa Jell 101. Use an acid brush or spatula. Leave on for 10 minutes.

(8) Rinse off with cold tap water - remove all acid (acid brush).

(9) Rinse all surfaces clean with tap water.

(10) Pour distilled water over tab (water break test).

(11) Dry for 15 minutes at 333°K (140°F).

(12) Apply primer within 16 hours.

III. Primer Application

(1) Thin BR-34 primer with BR-2 thinner after the primer has warmed to room temperature. (The BR-2 thinner is 3 parts NMP and 1 part xylene solvents.) The ratio of primer to thinner is 20:7.

(2) Apply primer to dry metal tab using sable hair brush. A quickly applied very thin coat is essential to prevent blistering.

(3) Allow part to air dry for 1 hour at room temperature (minimum).

(4) Place parts in oven at 377°K (220°F) for 30 minutes (minimum).

(5) Raise oven temperature to 483°K (410°F) and hold for 45 minutes.

(6) Cool to room temperature and bond immediately.

IV. Composite Face Sheet Preparation

(1) Remove all grease and release agents on composite by first abrading with scotchbrite or similar abrasive.

(2) Wash off dust with triclene solvent.

(3) Dry for 5 minutes at 333°K (140°F).

(4) Cool to room temperature and bond immediately.

V. Bond Face Sheets to Tabs

(1) Remove one 2 in. x 2 in. piece of adhesive film from dessicator and place on cleaned surface of composite.

(2) Position the composite on a thin metal plate 7 in. x 7 in. or so. (Frekote the aluminum plate prior to bonding.)

(3) Position the primed surface of the tab onto the adhesive film and close the press. (Several tabs may be bonded simultaneously by shimming the shorter tabs.) Watch for slippage!

(4) Heat tabs to 366°K (200°F) with contact pressure. (See Figure 1.)

(5) Raise temperature to 588°K (600°F).

(6) As temperature reaches 450°K (350°F), slowly increase pressure to 100 psi.

(7) Maintain temperature and pressure at 588°K (600°F) for 2 hours.

(8) Cool to 422°K (300°F) at 422°K (300°F)/hour.

(9) Remove from press and trim excess resin from edges of composite.

Step B. Core to Face Sheet Bonding

I. Face Sheet Preparation

(1) Remove grease, Frekote, or whatever from the exposed composite surface of the tabs with scotchbrite or emery cloth.

(2) Remove the abraded dust with triclene solvent and a clean acid brush.

(3) Dry at 333°K (140°F) for 10 minutes.

(4) Go immediately to next step or store parts in a sealed aluminized bag for no more than 16 hours.

II. Core Preparation

(1) Measure linear bond length of core (total length of foils).

(2) Examine edges for damage, etc., and record.

(3) Dip the core in Alconox detergent/water solution which is preheated to 333°K (140°F) for 5 minutes. (Use a large beaker and hot plate.)

(4) Remove part, rinse in distilled water, and hang for 15 minutes to dry in 333°K (140°F) oven.

(5) Position just above solvent bath of triclene, heated to boiling in a stainless steel pitcher. (Core is lowered to about 1-2 in. above surface of solvent.) Caution: This must be done under a hood with the exhaust fan on full!!

(6) Dry at 333°K (140°F) in oven for 15 minutes.

(7) Obtain weights on all parts to be bonded.

(8) Bond immediately or seal in moisture proof bag for 16 hours maximum.

III. Adhesive Preparation

(1) Remove the liquid adhesive from the storage freezer.

(2) Each of the four adhesives must be diluted just prior to use. Dilute each as shown below:

(a) BR-34

Add 7 parts of BR-2 thinner to 20 parts of BR-34 liquid adhesive. Mix in thoroughly using a small spatula. Stir for 5 minutes minimum.

NOTE: The components of this solution separate readily and so the solution must be mixed right up to the spreading, and the core must be dipped immediately.

(b) Hexcelite
&
(c) Add 7 parts of NMP solvent to 20 parts of either of the two Hexcelite liquid adhesives. Mix in well.

(d) Thermadite 17*

Add 1 part of MEK to 1 part of Thermadite 17 liquid adhesive.

(3) Pour the adhesive onto a clean glass plate (Figure 2). Spread the resin to a .020 in. thickness with a gardner knife immediately.

(4) Dip the core so that all the cells receive adhesive (Figure 3). Rap the core lightly flat onto clean dry glass to remove excess adhesive.

(5) Place onto a holding fixture so that dipped core hangs freely in a vertical position.

(6) Allow to air dry for 5 minutes at room temperature.

(7) Follow with the respective heat drying cycle:

FM-34	Hexcelites	Thermadite 17
10 min. @ 378°K (220°F)	10 min. @ 378°K (220°F)	15 min. @ 338°K (150°F)
20 min. @ 483°K (410°F)	20 min. @ 450°K (350°F)	

(8) Allow to cool to room temperature. Bond immediately or store briefly in vacuum.

IV. Core-to-Face Sheet Bond

(1) Frekote the interior of the preliminary bonding fixture and accessory tooling (Figure 4).

(2) Place a prepared tab into the hold and locate the centering fixture in the cavity over the tab as shown in Figure 5.

---

* Later changed to 15 parts of MEK to 100 parts Thermadite 17 to reduce capillary translation of adhesive into cell.

(3) Spread adhesive on the glass plate to .020 in. depth.

(4) Immerse the core into this adhesive until a fresh second coat is applied to each cell foil.

(5) Immediately transfer this into the bonding fixture so the adhesive side of the core contacts the tab face sheet and note filleting (Figure 6).

(6) Immediately position a square of silicone rubber over the top of the composite core in the fixture.

(7) Place a metal weight over the assembly to assure core-to-face sheet contact.

(8) Cure cycles: place in circulating air oven for final cure cycle.

(a) BR-34

30 min. @ 377°K (220°F)
120 min. @ 483°K (410°F)

(b) Hexcelite Adhesives
&
(c) 30 min. @ 377°K (220°F)
120 min. @ 450°K (350°F)
Cool to 338°K (150°F) slowly

(d) Thermadite 17

15 min. @ 338°K (150°F)
20 min. @ 405°K (270°F)
120 min. @ 477°K (400°F)

V. Second Bond to Complete Honeycomb

(1) Remove the top and core positioner after first core-to-face sheet bond.

(2) Carefully turn fixture over to remove bonded tab assembly, weigh and record.

(3) Position remaining tab, face sheet up, into final bonding fixture cavity. (Figure 7 shows vacuum bonding chamber.)

(4) Dip core/face sheet assembly following procedure and steps outlined in Section III and Section IV. (Use only those steps required to apply the adhesive to the core.)

c.2

(5) Locate the assembly in the fixture cavity to complete the assembly. (See Figure 8.) (NOTE: The cavity was designed so that vacuum could be applied if required for an adhesive.)

(6) Complete the closure of the assembly (Figure 9).

(7) Follow the appropriate cure cycles as used in the first bonds.

(8) After cure, remove the complete assembly and place in oven for post cure (Figure 10).

(9) Post Cure (all resins) - 28°K (50°F) steps with 2-hour holds from 477°K (400°F) to 588°K (600°F). Then, 4-hour holds at 588°K (600°F) and 602°K (625°F). Parts are slowly cooled to 394°K (250°F) before removal from post cure oven.

(10) Cool slowly to room temperature, remove from oven and place in special container for delivery to testing.

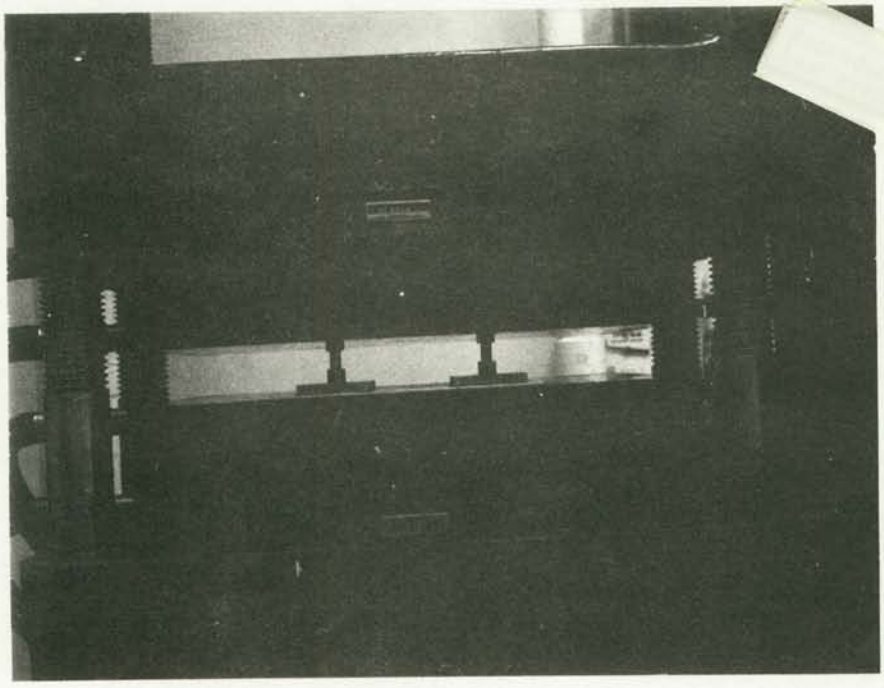

Figure A-1. Bonding Composite Face Sheets onto Metal Tabs

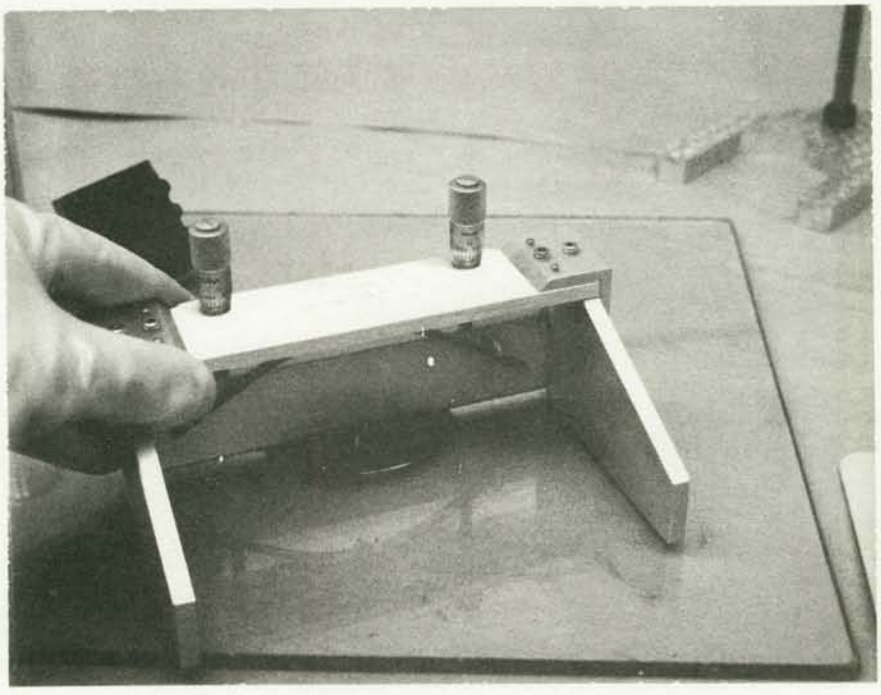

Figure A-2. Speading Adhesive to Measured Film Thickness

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Figure A-3. Placement of Core into Measured Depth of Adhesive (NOTE: This picture shows dipping of adhesive for final bond.)

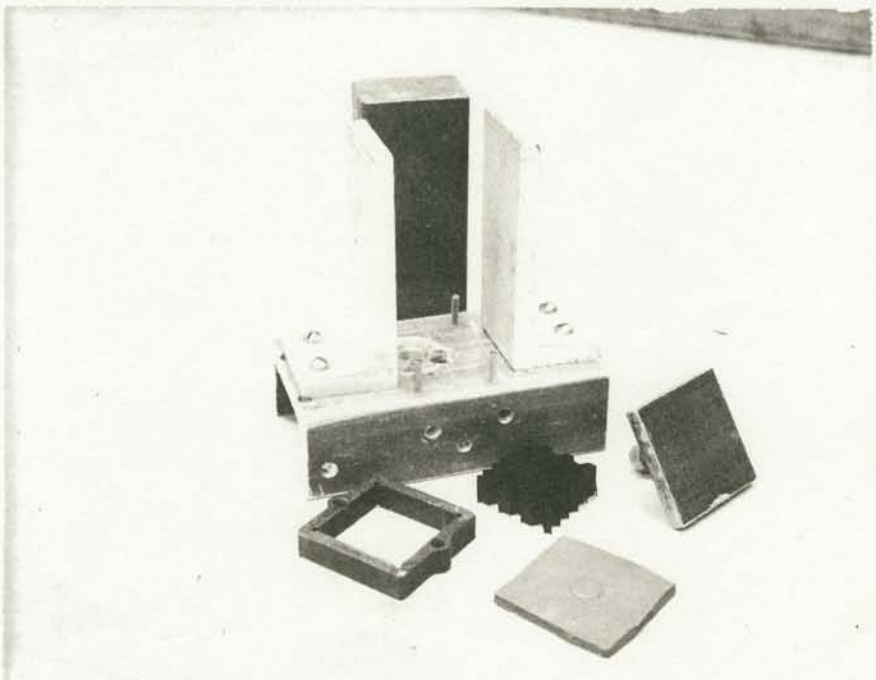

Figure A-4. Apparatus for First Tab to Core Bond

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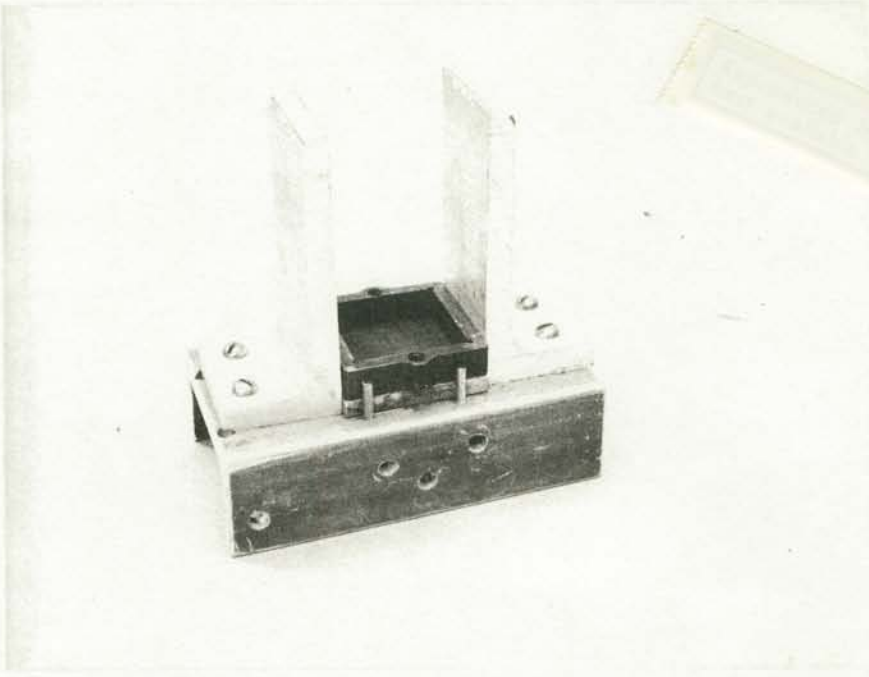

Figure A-5. Locating Fixture Placed Over Tab

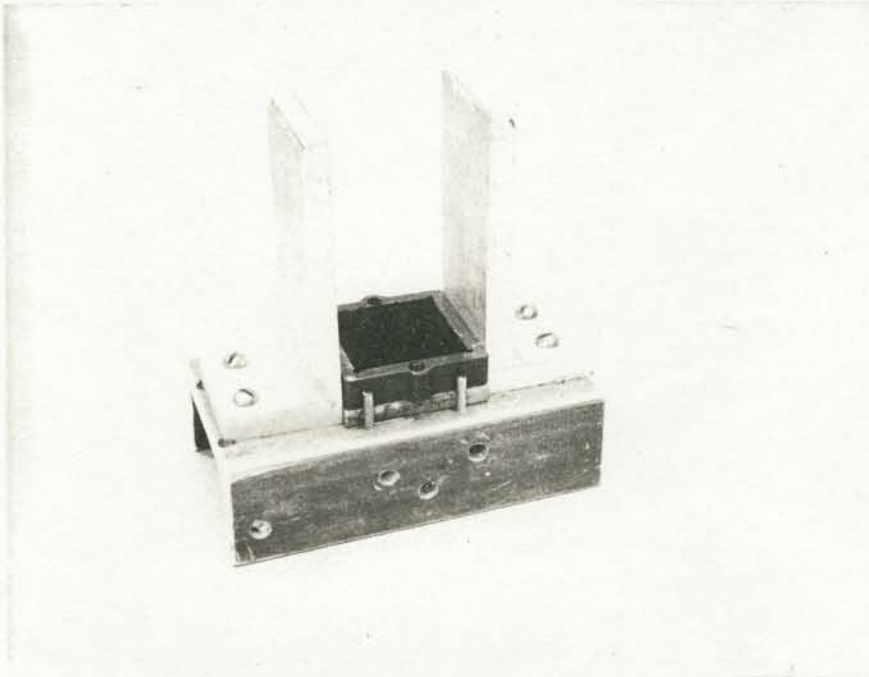

Figure A-6. Honeycomb Specimen Dipped In Resin and Placed in Fixture

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Figure A-7. Bonding Fixture (NOTE: Set up for Vacuum Cure)

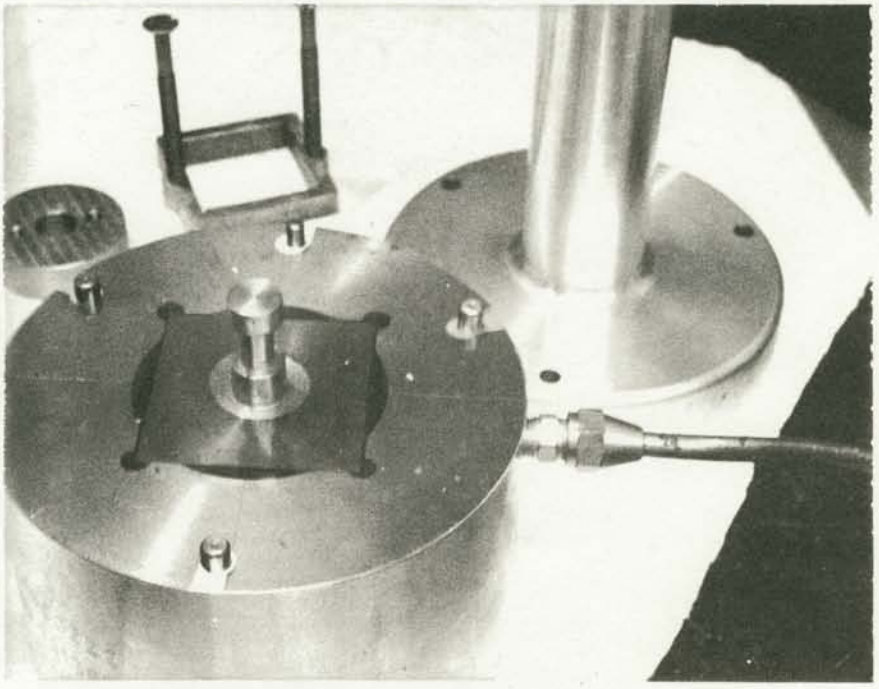

Figure A-8. Preparation for Final Cure

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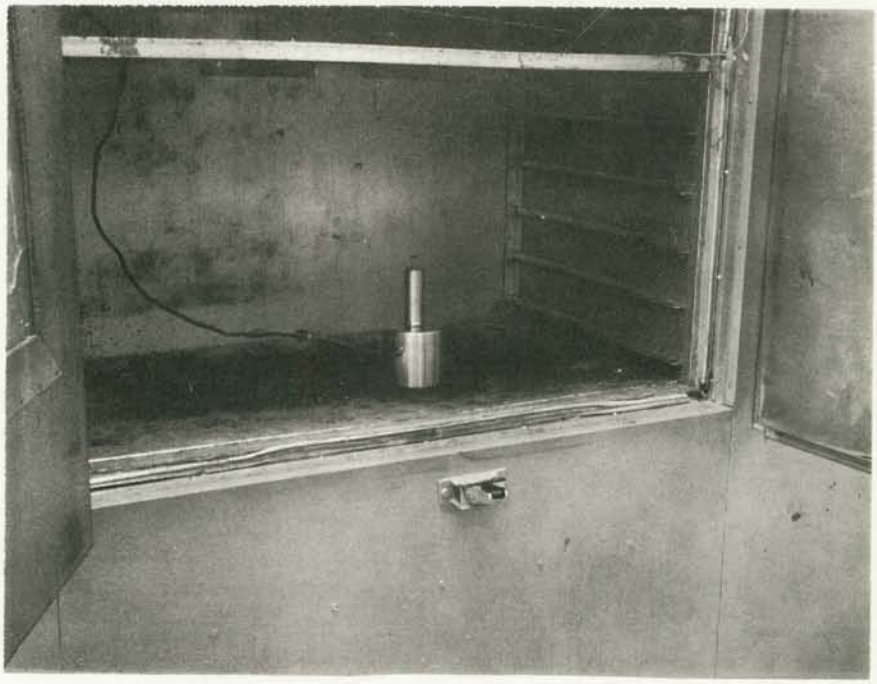

Figure A-9. Final Cure (Oven)

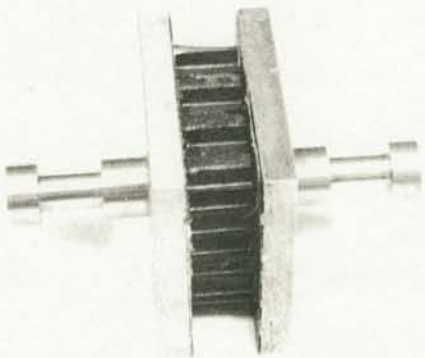

Figure A-10. Finished Test Specimen

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APPENDIX B

COMPOSITE PANEL BONDING PROCEDURE

1. SCOPE

1.1 The purpose of this procedure is to describe the proper method of bonding thin composite face sheets to composite core in honeycomb panel fabrication. The safety precautions outlined in this procedure are to be followed by all personnel performing the bonding steps.

2. REQUIREMENTS

2.1 All persons involved in the bonding program are responsible for knowing and following this procedure.

3. MATERIALS AND EQUIPMENT

3.1 Materials

Thermadite 17 polyimide liquid bonding adhesive (Whittaker)
Graphite/resin composite face sheet (2 req./panel)
Composite core (honeycomb cells)
Methyl Ethyl Ketone (MEK) solvent
Alconox detergent (powder) (Alconox, Inc.)
Scotchbrite abrasive pads (fine)
Trichlorethylene (Triclene) solvent

Equipment

Hot plate - Thermolyne type 1900, model HP-A1915B
Pitcher - stainless steel - 1 gallon, wide mouth
Gardner knife
Hotpack recirculating air oven - 477°K (400°F) capability
Large glass plate (18 in. x 18 in. minimum)
Miscellaneous: tape, weights, spatulas, beakers, etc.

4. SAFETY

4.1 Safe methods will be the responsibility of each operator.

4.1.1 All operations shall be carried out under a fully operational fume hood.

4.1.2 All operators must know the location of available fire extinguishers in the event of a fire during the vapor degreasing operation.

4.1.3 Pylox gloves shall be used wherever possible to prevent resin exposure hazards.

5. CORE-TO-FACE SHEET BONDING

5.1 Face Sheet Preparation

5.1.1 Remove grease, dust, etc., from exposed composite surfaces using an abrasive such as Scotchbrite.

5.1.2 Wash off the abraded dust with MEK solvent.

CAUTION: Use fume hood.

5.1.3 Dry at 333°K (140°F) for 10 minutes in recirculating air oven.

5.1.4 Proceed with the fabrication or store in sealed polyethylene bags (14 hours maximum).

5.2 Core Preparation and Composite Cleaning

5.2.1 Examine core and note defects, node bonds, etc.

5.2.2 Dip the core and face sheets in a preheated Alconox detergent/ water solution for 5 minutes at 338°K-366°K (150°F-200°F).

5.2.3 Remove parts and rinse in distilled water.

5.2.4 Dry parts in 394°K (250°F) oven for 15 minutes and remove from oven.

NOTE: Do not allow parts to contact oven surfaces.

5.2.5 Position composite parts above mildly boiling solvent bath (Triclene). Use large mouthed, stainless steel pitcher. (Core is lowered to about 1 in. above the surface of the solvent.)

CAUTION: This operation must be done under a hood with the exhaust fan on full!

5.2.6 Dry in 394°K (250°F) oven for 10 minutes.

5.2.7 Obtain weights on all parts being bonded.

5.2.8 Bond immediately or seal in moisture-proof bag for 16 hours maximum.

5.3 Adhesive Preparation

5.3.1 Remove the adhesive from refrigerated storage.

5.3.2 After warming to room temperature, dilute the adhesive with MEK solvent as described below.

Add 15 parts of MEK to 85 parts of Thermadite 17. Stir together until uniform viscosity is attained.

CAUTION: Avoid toxic fumes. Use fume hood.

5.3.3 Pour adhesive on a clean glass plate surface.

5.3.4 Spread the resin evenly with a Gardner knife immediately.

NOTE: Blade gap = .070 in. across blade for 3/8-in. core.

5.3.5 Dip the core in the adhesive and press flat on the glass plate.

5.3.6 Remove core and visually inspect cells. If an area is insufficiently or unevenly coated, reform adhesive film and redip.

5.3.7 Position core on holding fixture in 338°K (150°F) oven and dry for 15 minutes.

5.3.8 Pick up adhesive and save for second dip. Clean glass plate with MEK solvent.

CAUTION: Properly dispose of solvent waste.

5.3.9 Remove core from oven and allow to cool (1 minute).

5.4 Core-to-Face Sheet Bond

5.4.1 Pour and spread a second film of adhesive on glass plate.

NOTE: Blade gap = .070 in. across blade for 3/8-in. core.

5.4.2 Dip the core in the adhesive and press on the glass plate to prevent warped core problems.

5.4.3 Remove core and visually inspect cells. A thicker coating of adhesive than the first time should be observed. Redip core if insufficient adhesive was picked up on any or all of the core.

5.4.4 NOTE: Do not permit sideways motion of the core. This results in non-reproducible bonds.

5.4.5 Place face sheet on a flat metal plate.

5.4.6 Position the core over the face sheet and carefully lower as desired. Look into cells to confirm proper filleting.

NOTE: Filleting often requires several minutes to occur.

5.4.7 Place a 1/4-in. silicone rubber pad over the upper core surface and add weights on the sample so as to get 1/2-1 psi pressure evenly distributed over the core.

5.4.8 Place the assembly in a 338°K (150°F) oven for 15 minutes.

5.4.9 Raise temperature of oven to 394°K (250°F) and maintain for 15 minutes.

5.4.10 Increase the temperature to 405°K (270°F) for 15 minutes.

5.4.11 Raise temperature to 454°K (350°F) and cure for 60 minutes.

5.4.12 Allow to cool to room temperature slowly.

5.4.13 Remove from oven, clean sample and weigh to determine Dip #1 adhesive weight.

5.5 Bond Second Face Sheet to Core

5.5.1 Detergent wash and vapor degrease core and remaining face sheet. (5.2.1-8)

5.5.2 Weigh sample for adhesive weight determination.

5.5.3 Prepare and dip the remaining core surface in the adhesive. (5.3.1-9)

NOTE: Same adhesive drying cycle.

5.5.4 Dip core the final time and locate on second face sheet (5.4.1-7).

5.5.5 Give core final cure:

5.5.5.1 15 minutes at 338°K (150°F).

5.5.5.2 15 minutes at 394°K (250°F).

5.5.5.3 15 minutes at 405°K (270°F).

5.5.5.4 120 minutes at 477°K (400°F).

5.5.6 Allow to cool slowly to room temperature.

5.5.7 Remove from oven, clean and weigh for adhesive weight determination.

5.5.8 Examine part by NDT if required.

5.5.9 Post cure panel using stepped post cure cycle.

NOTE: Cam-controlled oven with very slow cooldown rate.

APPENDIX C

FINAL PANEL ASSEMBLY
(INCLUDING FOAM EDGE CLOSURE DETAILS)

1. SCOPE

1.1 The purpose of this procedure is to detail changes and additions made to the standard composite honeycomb panel fabrication procedure.

2. REQUIREMENTS

2.1 All persons involved with the final panel fabrication (two large panels for delivery to NASA/Houston) are responsible for knowing and following this procedure and the basic procedure on panel fabrication.

3. MATERIALS AND EQUIPMENT

In addition to the materials listed in the basic procedure, the following items will be required.

3.1 Materials

Non-porous Armalon cloth, DuPont
Polyimide foam (18 pcf), RI-7271-18 (Monsanto)
Rubber sheet (1/8 in. x 30 in. x 30 in.), high temperature

Equipment

Aluminum plate 3/8 in. x 30 in. x 30 in., with 1/16 in. holes on 1 in. centers
Steel plate (polished surfaces) 1/4 in. x 3 ft x 5 ft
Resin film knife (Gardner design blade 30 in. L x .070 in. gap)
Dip tank - open wood box with film liner
Miscellaneous: aluminum wire mesh, stainless cotter pins, 620°K (650°F) oven, autoclave

4. SAFETY

4.1 See safety methods in general procedure.

5. CORE-TO-FACE SHEET BONDING

5.1 Face Sheet Preparation

5.1.1 Face sheets are several inches oversize in L and W dimensions. Orientations and face sheet number are indicated by notches on two of the four edges of the panel.

5.1.2 Follow procedures listed in Section 5.1 of general procedure with the following changes noted:

5.1.5 Add that care must be taken to prevent cracking panel on edges. Overflexing must be avoided because of large surface area and thin face sheet thickness.

5.2 Core Preparation and Composite Cleaning

5.2.1 Follow procedures listed in Section 5.2 of general procedure with the following changes noted:

5.2.2 Alconox detergent/water solution is not preheated (hot tap water).

5.2.3 Rinse parts in cold tap water.

5.2.4 When drying parts, face sheets are placed with the bonding surface up on a prorous screen in the oven. The core is suspended from an aluminum screen by the use of stainless steel (2-in.) cotter pins to attach the core to the screen. All parts are horizontal during all stages of this procedure. Dry for 15 minutes at 422°K (300°F).

5.2.5 Triclene solvent at ambient temperature is poured into the large tray to a depth of 1/2 in. to 1 in. The core is placed in the solvent. Tilt the tray to cause areas of core to be totally immersed in solvent. Exercise caution when handling large pieces, particularly core, as liquid in cells causes excessive increase in weight and may cause core breakage if not handled properly. Pour the liquid from the tray before attempting to lift the core.

5.2.6 Dry for 30 minutes at 422°K (300°F).

5.2.8 Bond immediately or repeat cleaning procedure if not bonded within a four-hour period.

5.3 Adhesive Preparation

5.3.1 Follow procedure listed in Section 5.3 of general procedure with the following exceptions:

5.3.4 Use 30-in. wiper blade (similar to Gardner knife) with gap set at .070 in.

5.3.9 Allow five minutes for core to cool.

5.4 Core-to-Face Sheet Bond

5.4.1 Follow procedure listed in Section 5.4 of general procedure with the following exceptions:

5.4.5 Non-porous Armalon is placed between face sheet and aluminum base plate.

5.4.7 A steel plate is placed on top of assembly. This is sufficient to prevent core from moving until assembly is placed in oven.

Additional weights, 100-200 lbs, are then added, evenly dispersed, on top of steel plate.

6. EDGE REINFORCEMENT

6.1 The following steps are added to the procedure to describe the process for foam filling the panel edges for added resistance to damage caused by handling of the display panel and possible premature cell buckling of the test panel.

6.2 Cell Filleting (Second Bonding Surface)

6.2.1 Repeat steps 5.2.5 through 5.4.4 of general procedure including modifications and the following changes:

5.3.5 and 5.4.2 Core cells are coated for a distance of 3 in. in from the edges only.

6.2.2 Place open cells of the panel on a sheet of non-porous Armalon which covers the aluminum plate.

6.2.3 Place a steel plate on the top face sheet.

6.2.4 Repeat steps 5.4.8 through 5.4.12 of general procedure.

6.2.5 Remove from oven and peel Armalon from filleted cells on edges.

6.2.6 Mount in milling machine on a flat plate.

6.2.7 Machine core surface flat (on filleted edges).

6.3 Foam Filling and Cure

6.3.1 Select a metal rod 6-in. length by a diameter which will just pass freely through a properly filleted cell opening without binding.

6.3.2 Using a hand grinder with a spherical tool bit having a diameter slightly larger than the diameter of the metal rod, open all cells which may have been closed or sealed by the filleting adhesive.

6.3.3 Blow out any dust with an air gun.

6.3.4 Mark off areas to be foam-filled with masking tape and cover central area of core with heavy kraft paper (to prevent spillage of foam into unwanted areas).

6.3.5 Pour foam into all cells that are left exposed. Hand vibration

will aid in "settling" of the foam. Additional compaction is required to obtain 12-18 lb/cu ft density.

6.3.6 Compaction is obtained by inserting the previously mentioned metal rod into a plastic (or metal) funnel with a small diameter just slightly larger than the rod. The funnel is positioned over the open cells, close to the surface, and filled with additional foam. By pressing the rod through the orifice in the fillet, compaction of the foam in the cell is accomplished. A slight withdrawal of the rod permits foam from the funnel to enter the open cell. This new material is compacted and the cell completely filled and compacted quickly by repeating this process several times.

6.3.7 When all cells are filled, remove the paper and tape.

6.3.8 Add foam to a depth of 1/4 in. above the surface of the core.

6.3.9 Place a layer of non-porous Armalon over the top of the core.

6.3.10 Place the panel on a layer of non-porous Armalon which covers a bottom metal support plate.

6.3.11 Place the steel plate on the top.

6.3.12 Position on large I-beams in heated chamber.

6.3.13 Cure (heat slowly to 588°K (600°F) (two hours) and maintain for two hours). Cool slowly (over two-hour period) to $< 366^{\circ}K$ ($200^{\circ}F$).

6.3.14 Remove from cure and peel Armalon from foamed surface.

6.3.15 Mount panel in milling machine by clamping on a flat metal plate.

6.3.16 Machine foam to a depth of .010 in. below the surface of the core (to be filled by adhesive before bonding).

6.3.17 Weigh part to determine weight of foam.

6.3.18 Mark corners of final panel in the first face sheet by using a hand grinder with a thin circular wheel.

6.4 Foam Sealing

6.4.1 Remove dust from foamed area by brushing with triclene using an acid brush.

6.4.2 Heat to 422°K (300°F) and dry for one hour minimum.

6.4.3 Paint undiluted BR-34 primer on the foam with a clean acid brush. A thick coating is desired.

6.4.4 Place two layers of TX-1040 teflon-coated scrim on the adhesive followed by a layer of heavy Armalon. This assembly is placed on the aluminum plate.

6.4.5 Place the steel plate on top of the assembly and place in a large heating chamber.

6.4.6 Cure the BR-34

30 minute heat rise to 377°K (220°F).
Hold at 377°K (220°F) for 30 minutes.
30 minute heat rise to 483°K (410°F).
Hold at 483°K (410°F) for 60 minutes.
60 minute cooldown to room temperature.

6.4.7 Disassemble and machine flush with top of unfilled core. (Use milling machine.)

6.4.8 Repeat steps 6.4.1 through 6.4.2.

6.4.9 Paint a very thin coating of adhesive over pits exposed by the machining of the adhesive surface.

6.4.10 Repeat steps 6.4.4 through 6.4.6.

6.4.11 Disassemble and sand smooth with fine emory paper.

6.4.12 Using hand grinder, carefully remove adhesive and foam from inner cells that should not be filled.

6.4.13 Weigh and record approximate adhesive weight.

7. BOND SECOND FACE SHEET TO CORE

7.1 Follow procedures listed in Section 5.5 of general procedure with the following exceptions:

5.5.9 Prior to post cure, panel should be machined to final size and mounting holes drilled.

7.1.1 Clamp panel to a sheet of 1/4 in. plexiglas on milling machine.

7.1.2 Trim panel edges using alignment marks in first face sheets.

7.1.3 The three holes on each end of the panel are drilled with a 3/16 in. carbide twist drill.

7.1.3.1 Hole pattern is marked on panel.

7.1.3.3 The holes are centered and then drilled.

8. POST CURE

8.1 See Section 5.5.9 of general procedure.