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CONSOLIDATION OF GRAPHITE/THERMOPLASTIC TEXTILE PREFORMS FOR PRIMARY AIRCRAFT STRUCTURE

S11-24

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Abstract

The use of innovative cost effective material forms and processes is being considered for fabrication of future primary aircraft structures. Processes that have been identified as meeting these goals are textile preforms that use resin transfer molding (RTM) and consolidation forming. The Novel Composites for Wing and Fuselage Applications (NCWFA) program has as its objective the integration of innovative design concepts with cost effective fabrication processes to develop damage-tolerant structures that can perform at a design ultimate strain level of 6000 micro-inch/inch. In this on-going effort, design trade studies were conducted to arrive at advanced wing designs that integrate new material forms with innovative structural concepts and cost effective fabrication methods. The focus has been on minimizing part count (mechanical fasteners, clips, number of stiffeners, etc.), by using cost effective textile reinforcement concepts that provide improved damage tolerance and out-of-plane load capability, low-cost resin transfer molding processing, and thermoplastic forming concepts. The fabrication of representative Y spars by consolidation methods will be described. The Y spars were fabricated using AS4 (6K)/PEEK 150g commingled angle interlock 0/90-degree woven preforms with ±45-degree commingled plies stitched using high strength Toray carbon thread and processed by autoclave consolidation.

INTRODUCTION

The Novel Composites for Wing and Fuselage Applications (NCWFA) Program is performed by the Grumman Aircraft Systems Division of Grumman Corporation and its subcontractors, Textile [redacted]ek Corporation, under the sponsorship of NASA Langley Research Center, Hampton, Virginia 23665-5225. Mr. H. Benson Dexter is the NASA/LARC Contracting Officer Technical Representative.

Background

The full weight savings and life cycle cost savings potential of state-of-the-art composites have not been achieved because of design strain levels limited by the materials LOW

- Damage tolerance
- Fracture toughness
- Notch strength
- Out-of-plane strength

and HIGH

- Material cost
- Manufacturing cost

We need

- Novel material forms
- Design strain levels of 6,000 + micro in./in.
- Cost effective manufacturing concepts

PROGRAM OBJECTIVES

The overall objective of the NCWFA program is to integrate innovative design concepts with cost effective fabrication processes to develop damage-tolerant primary structures that can perform at a design ultimate strain level of 6000 micro-inch/inch.

1) Develop optimum wing design concepts with high performance fiber architecture to achieve
   - Improved damage tolerance and durability
   - High notch strength
   - Increased out-of-plane load capability

2) Develop integrally stiffened fuselage bulkhead concepts that
   - Eliminate skin/stiffener separation failure modes
   - Minimize fabrication cost

3) Explore textile processes to achieve affordable integral skin/stiffener structures by automated
   - Weaving
   - Knitting
   - Stitching

4) Explore RTM and consolidation/forming hybrid Gr/TP fiber forms for cost-effective fabrication of primary wing and fuselage components

5) Conduct tests to validate structural performance and correlate test results with analytical predictions.

PROGRAM TASKS

The program is divided into five major tasks: Task 1 – Wing Design Concepts; Task 2 – Fuselage Bulkhead Design Concepts; Task 3 – Wing Spar-Rib Intersection Design Concepts; Task 4 – Design and Fabricate a Generic High Strain Wing Torque Box Component; and Task 5 – Structural Test of the Wing Torque Box Component. The work reported here was accomplished in Task 1.

Task 1 - Wing Design Concepts

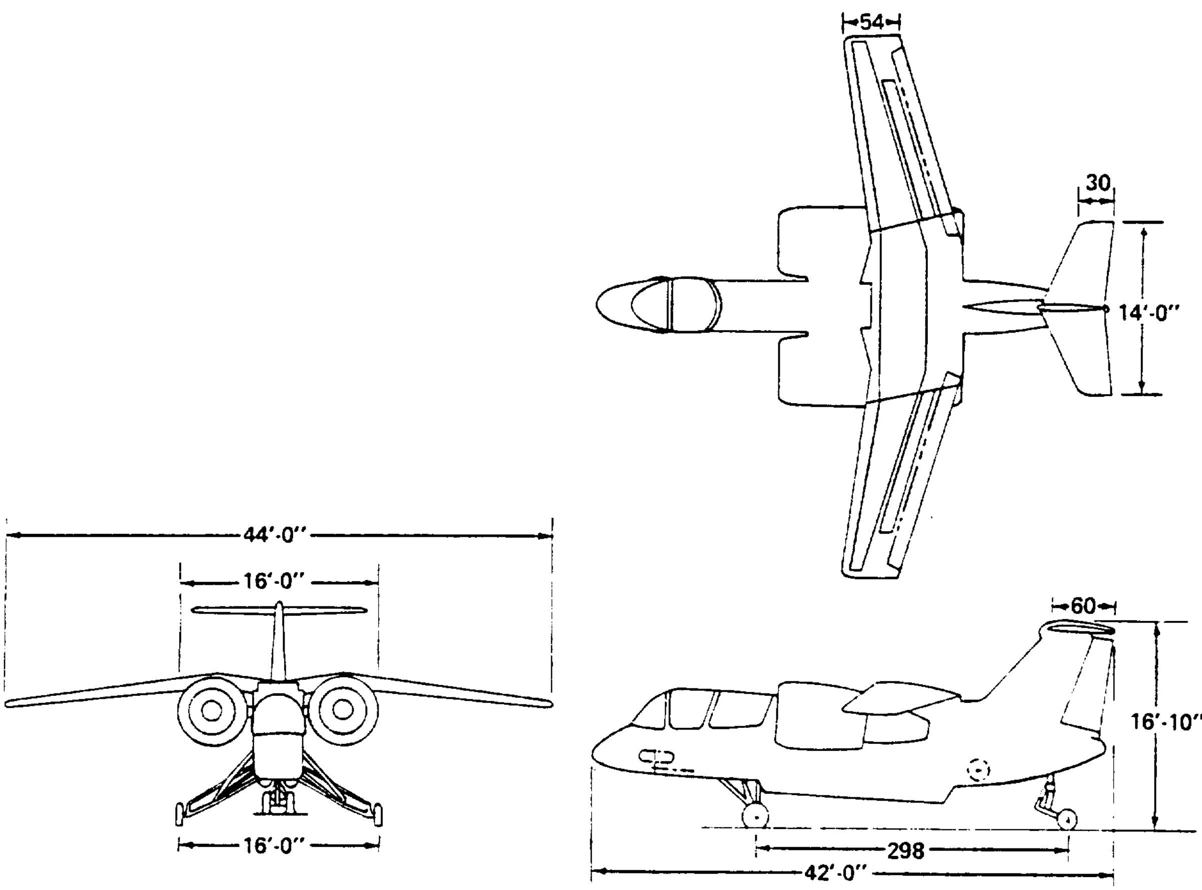
Design Trade Studies:

- Baseline, VSTOL 698-420
- Generate advanced wing designs using innovative structural concepts (target weight savings of 50%)
  - Multi-directional weavings (fiber form architecture)
  - Stitching
  - Softening strips
  - Compliant laminates
  - Integral cover to substructure
  - Crack arrestment strips
  - Y, blade and hat stiffeners
  - Spread 0° covers
  - Discrete cap covers
- Newer/emerging materials:
  - Fibers (E>40 msi, F>600 ksi)
  - Commingled yarns
  - Powder-based resin matrices
  - Toughened TS and TP resin matrices
- And cost effective processes (target cost savings of 25%):
  - RTM
  - Autocomp
  - Consolidation forming

BASELINE AIRCRAFT

The baseline aircraft selected for this program is a subsonic patrol VSTOL aircraft, Grumman design 598-420. This design is a high-wing, T-tail, turn-tilting nacelle configuration which combines both power-plant and control vanes immersed in the fan stream.

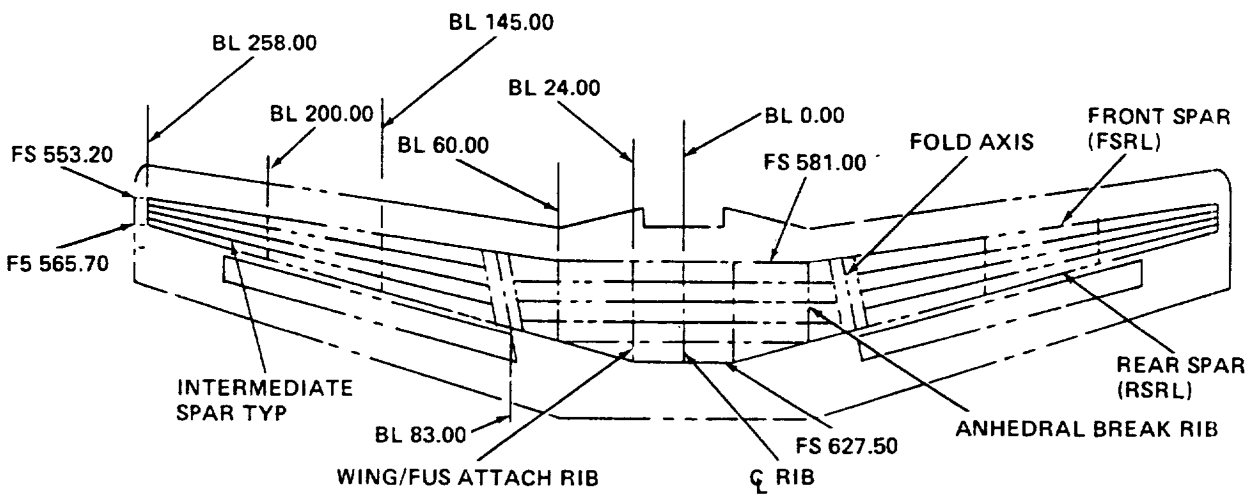
BASELINE SUBSONIC PATROL V/STOL SEA CONTROL CONFIGURATION



WING STRUCTURAL CONFIGURATION

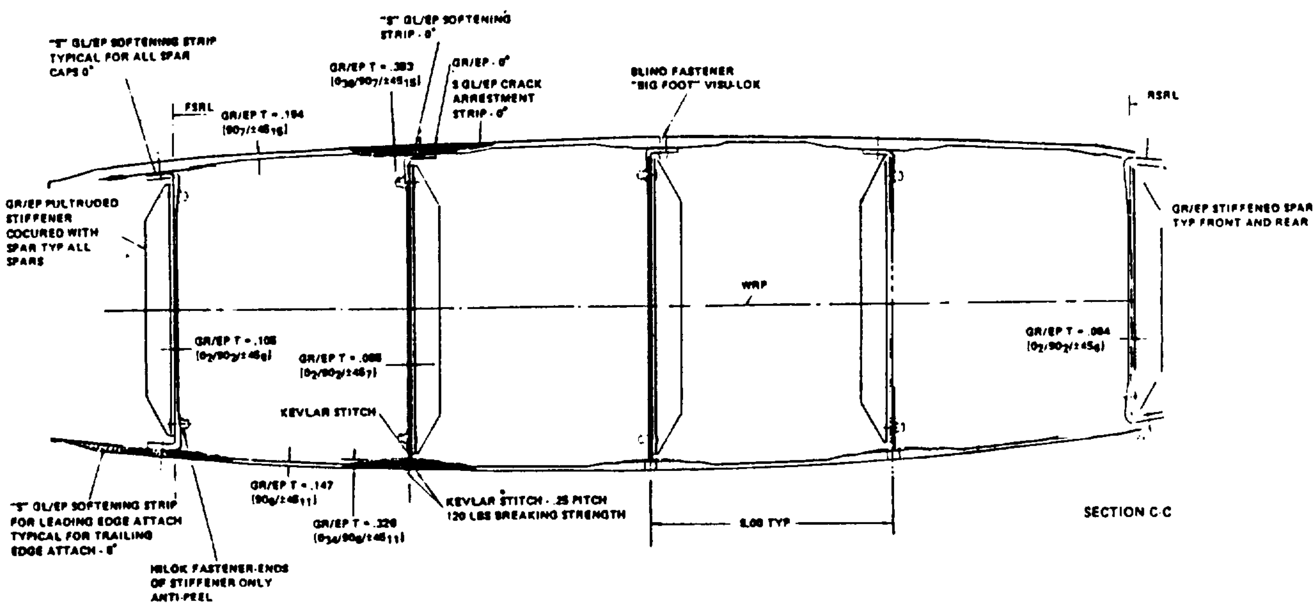
The structural configuration for the wing is shown below. The wing has a span of 44 ft and a fold span of 16 ft and is sized to allow installation of the conformal radar. The thickness ratio is 14% at the root and 12% at the tip with a maximum depth of 14.4 in. at the centerline. Fuel is carried in the wing box from fold-joint to fold-joint. Roll control in conventional flight is provided by spoilers mounted on the rear beam.

Five-Spar Wing Box Configuration



WING BASELINE CONFIGURATION

Consistent with the structural arrangement, design requirements, and advanced composite wing design technology, a baseline wing configuration was established from previous design efforts on the High Strain Wing Program. The upper and lower covers are Gr/Ep laminates, working to a design ultimate strain level of approximately 6000 micro-in./in., and include Gl/Ep for softening strips and crack arrestment strips (for damage tolerance). The substructure consists of a front, rear, and three intermediate spars. The spar webs are flat angle-stiffened Gr/Ep laminates, with the intermediate spars integrally co-cured and stitched (with kevlar) to the lower cover. Gr/Ep sinewave ribs were used, except at the wingfold and tip where titanium and Gr/Ep plain panels were used, respectively.



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In achieving the objectives of the NCWFA Program, composite design concepts incorporated into the baseline wing have been studied. These can be classified into two categories: multi-spar and multi-rib. The structural arrangement considered spar/stiffener orientation, spar/stiffener spacing, and rib pitch. The structural geometry was varied to achieve a least weight/cost cross section of detail structural elements.

Structural Concepts Trade Studies, Wing Torque Box Structures

- Torque box covers
  - Flat monolithic (unbuckled)
  - Discrete cap (unbuckled and buckled)
  - Lumped spar cap (buckled)
  - Isolated discrete cap (buckled)

  Multi-spar

  - Hat stiffened (unbuckled and buckled)
  - Tee stiffened (unbuckled and buckled)
  - Wye stiffened (unbuckled and buckled)
  - Blade stiffened (unbuckled and buckled)

  Multi-rib

- Spar webs
  - Shear resistant
  - Stiffened web (unbuckled and buckled)
  - Sinewave Shear Resistant
- Spar caps
  - Angle
  - Tee
  - Wye
- Rib webs and caps
  - Similar to spars

Structural Concepts
Structural Sizes/Weight Derivation

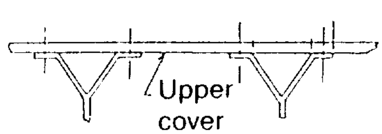
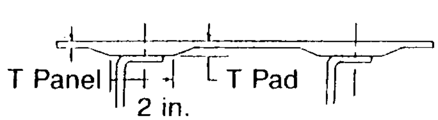
- Minimum weight design of each concept considered derived to compare concepts on a common basis
- Structural sizing/weight analysis performed using multi-station-wise basis
- Appropriate analytical methods used to determine least weight geometry & thickness to satisfy strength/stability and stiffness for each component/concept considered
- Analytical methods yield geometry/thickness that represent upper limit to efficient use of structural material from which theoretical weights are derived
- Non-optimum factors (NOFs) applied to theoretical weights to project realistic assembly weights
- NOFs derived from previous composite programs/studies account for weight penalties associated with
  - Load introduction
  - Build-ups around cut-outs
  - Fasteners
  - Ply transition and smoothing
  - Variation in laminate thickness and density

MULTI-SPAR CONCEPT

Our multi-spar concept was derived from previous studies, which indicated a five spar configuration to be the most efficient from both a weight and cost standpoint. A total of 15 ribs was used in our arrangement.

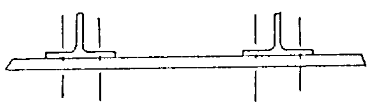
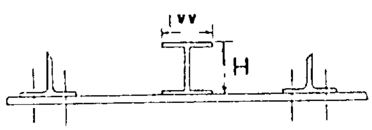
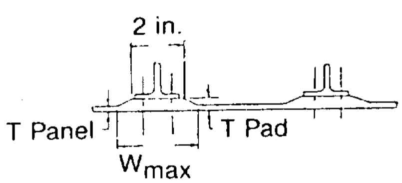
Two types of wing cover configurations were evaluated which have the potential of successfully increasing the working strain to levels at least 50% higher than those of the baseline. The two types evaluated were plain panel-spread and discrete cap. The first type, plain panel-spread, is essentially a monolithic skin of approximately constant thickness at any chordwise cut. In addition, the laminate consists of the same family of lamina orientations (0°, 90°, ±45°) at any point. The second type, discrete cap, utilizes a skin of two distinct laminate orientations. Between spars, the skin panel consists of a high strain to failure laminate of 90° and ±45° layers. The absence of 0° layers, in this panel has two additional advantages: first, for a given thickness it will possess a higher resistance to buckling loads; and second, the laminate's EA (extensional stiffness) is very low as compared to the total section, resulting in a lesser axial load applied to the unsupported segment of skin. At each spar 0° layers are added to the panel laminate resulting in a local pad. The 0° layers provide the axial filament control to the laminate and carry the preponderance of axial load. Located over the spar, the high loads are rigidly supported, minimizing any instability problems.

Structural Concepts
Upper Cover Configurations

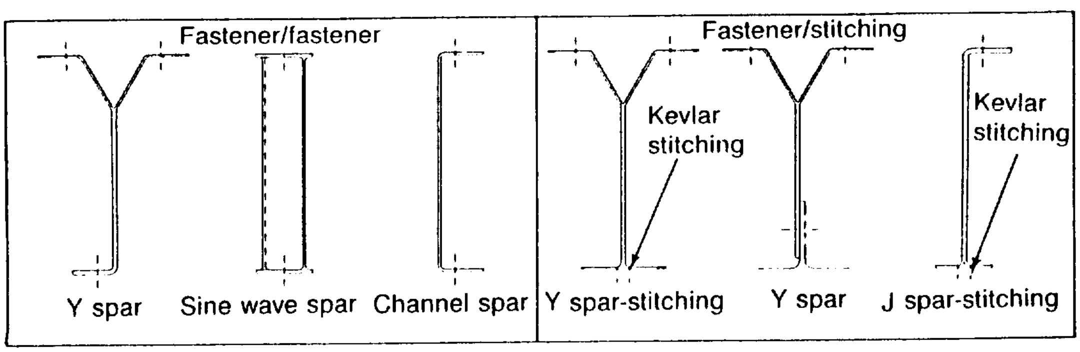
	Advantages	Disadvantages
Spread zero upper cover (with "Y" intermediate spars) 	• Least cover fab cost • Very efficient comp cover when combined with Y spar • Easily repaired • Good battle damage tolerance due to multiple load paths	• Max rows of fasteners – assy cost impact • High strain concentration – fasteners through laminate with high % of 0-deg plies • Damage tolerance totally material dependent • Excessive S/S shear carrying material
Spread zero upper cover with integral "I" stiffner 	• Minimizes number of spars • Reduced assembly costs • Good battle damage tolerance due to multiple load paths	• High strain concentrations – fasteners through laminate with high % of 0-deg plies • Damage tolerance totally material dependent • Difficult to repair
Discrete cap upper cover 	• Most efficient comp cover design for multi-spar configuration • Min number of substructure attachments • Excellent damage tolerance due to multiple load paths & compliant laminates	• Increased laminate tailoring • High strain concentration factor – fasteners through laminate with high % 0-deg plies • Difficult to repair

Structural Concepts

Lower Cover Configurations

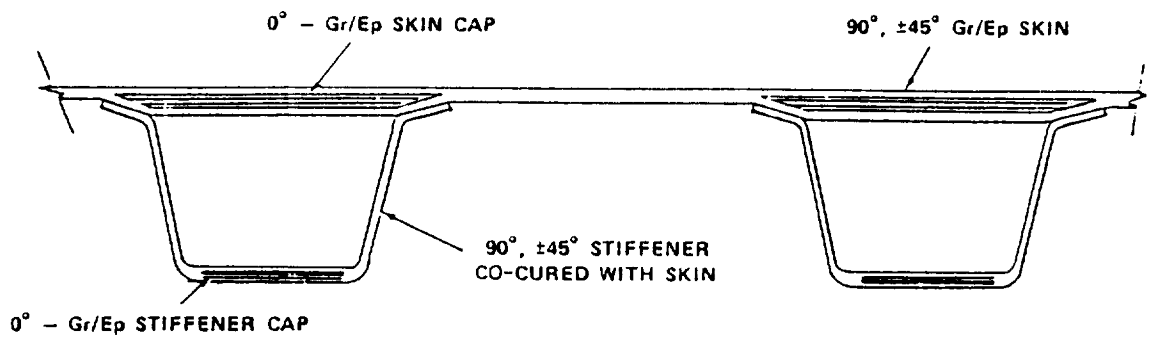
	Advantages	Disadvantages
Spread zero lower cover – Tee & angle spar support 	• Least cover fab cost • Very efficient comp cover when combined with Y spar • Easily repaired • Good battle damage tolerance to multiple load paths	• Max rows of fasteners – assy cost impact • High strain concentration – fasteners through laminate with high % of 0-deg plies • Damage tolerance totally material dependent • Excessive S/S shear carrying material
Lower cover with integral "I" stiffener 	• Minimizes number of spars • Reduced assembly costs • Good battle damage tolerance due to multiple load paths	• High strain concentrations – fasteners through laminate with high percent of 0-deg plies • Damage tolerance totally material dependent • Difficult to repair
Discrete cap lower cover 	• Most effficient comp cover design for multi-spar configuration • Min number of substructure attachments • Excellent damage tolerance due to multiple load paths & compliant laminates	• Increased laminate tailoring • High strain concentration factor-fasteners through laminate with high % 0-deg plies • Difficult to repair

Spar Design Concepts

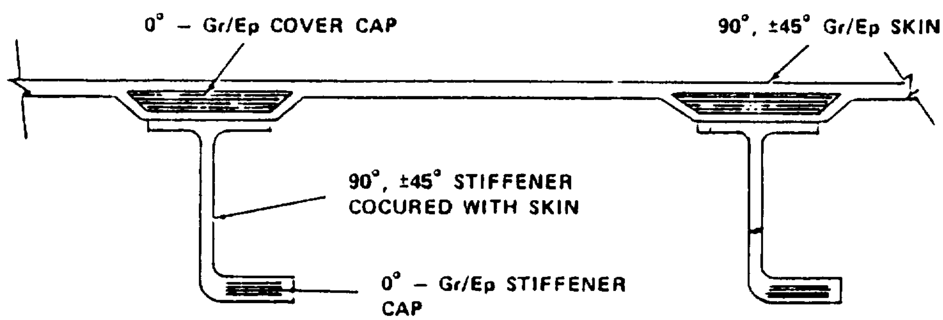


In general, subsonic patrol aircraft wings are relatively thick where strength/stability conditions govern. Consequently it is of interest to investigate cover configurations in which load-carrying material in the cross section is redistributed so as to achieve increased flexural stiffness over that of the relatively uniform thickness cross-section multi-spar cover designs. This concept leads to the consideration of longitudinal stiffening systems as an integral part of the cover itself. The integral hat and open J stiffener configurations were considered in the study and are illustrated below in combination with the skin. The designs were sized for all combinations of stiffener pitch equal to 4, 5, 6 and 7 in. and rib spacing equal to 15, 20, 25 and 30 in. Because of relatively high structural efficiency and potential ease of manufacture, stiffeners parallel to the front spar were selected as the preferred stiffener orientation.

Cover Concepts, Multi-Rib



INTEGRAL HAT-STIFFENED



INTEGRAL J- STIFFENER

MATERIAL-ORIENTED DESIGNS WEIGHT SUMMARY

For the baseline wing and the various material-oriented high strain wing concepts, theoretical cover and substructure weights were derived analytically on a multi-station basis utilizing t's generated for the various forms of construction. To account for such weight items as penalties associated with load introduction, attachments, cutouts, variations in laminate thickness and density, the theoretical weights are multiplied by an empirically determined "non-optimum factor", thereby yielding a realistic assembly weight.

A weight breakdown of the multi-spar design, for both material systems (IM7/8551-7A and G40-800/F584 Gr/Ep), and multi-rib design (IM7/Tactix 123 Gr/Ep) is shown below. The multi-rib design concept consists of four hat stiffeners outboard of the fold, seven inboard and twenty-five ribs at a 25-inch pitch.

The weight savings generated by these concepts show significant improvement over the baseline. The multi-spar design, using G40-800/F584, provided a savings of 543 lb, or 42% of the metal torque box weight of 1233 lb. The multi-rib design, using IM7/Tactix 123 Gr/Ep, yielded a 541 lb savings or 41% of the metal torque box weight.

Weight Breakdown for Selected Wing Designs (Material-Oriented)

COMPONENT	BASELINE WING TORQUE BOX (LBS)	MULTI-SPAR IM7/8551-7A (LBS)	MULTI-SPAR G40-800/F584 (LBS)	MULTI-SPAR (CONCEPT C) HAT-STIFFENED (LBS)
UPPER COVER	293.80	258.30	246.20	266.60
• BASIC INTERSPAR COVER	240.50	223.90	211.80	266.60
• SOFTENING STRIP PENALTY (0° GL/EP)	2.60	---	---	---
• DAMAGE TOLERANCE PENALTY (0° GL/EP)	10.60	---	---	---
• DAMAGE TOLERANCE PENALTY (+45° GL/EP)	0.00	---	---	---
• SPAR CAPS (INC WRINKLING PENALTY)	40.10	34.40	34.40	
LOWER COVER	224.10	192.40	182.70	185.70
• BASIC INTERSPAR COVER	187.20	175.30	165.60	185.70
• SOFTENING STRIP PENALTY (0° GL/EP)	2.20	---	---	---
• DAMAGE TOLERANCE PENALTY (0° GL/EP)	8.00	---	---	---
• DAMAGE TOLERANCE PENALTY (+45° GL/EP)	1.50	---	---	---
• SPAR CAPS (INC WRINKLING PENALTY)	24.90	17.10	17.10	---
FRONT SPAR (SYNCORE STIFF)	88.60	73.80	73.80	98.80
REAR SPAR (SYNCORE STIFF)	36.00	32.90	32.90	40.10
INTERMEDIATE SPARS (SYNCORE STIFF)	110.00	101.80	101.80	---
RIBS	52.20	52.20	52.20	96.60
TOTAL TORQUE BOX	806.20	711.40	689.60	687.80
WEIGHT SAVINGS OVER BASELINE	---	94.80	116.60	118.40
% SAVINGS	---	11.80	14.50	14.70

COMBINED MATERIAL/CONFIGURATION CONCEPTS

After completing the material-oriented design concepts, our efforts were directed toward developing combined material/configuration concepts. This involved the use of Y-spars and Y-stiffeners to support the covers. For the upper cover, the following concepts were studied:

1) Spread 0° supported by 5 or 6 Y-spars
2) Isolated discrete cap supported by 5 or 6 Y-spars
3) Isolated discrete cap supported by integrally cured Y-stiffeners

The basic philosophy in using intermediate Y-spars is that they reduce panel widths and required thickness on the upper cover. Although an increase in weight is expected for the intermediate spars, the weight savings produced by the upper cover will adequately compensate for it, and yield an overall weight savings.

The same loading conditions that sized our previous spar concepts were used to size the Y-spar configuration. For all Y-spar designs, the angle was set at 120° to provide equilibrium and balance. The distance between the legs of the Y-spar at the attachment to the upper cover depends on the spar spacing. To obtain the maximum benefit from the Y-spar configuration, the fastener spacing is half the spar spacing.

G40-800/F584 tape was used for the upper and lower covers and 3-D IM7/Tactix 123 and 3-D commingled AS4/PEEK 150G weave was utilized to size the Y-spars. For the multi-spar concepts, only the intermediate spars were designed with the Y configuration. The SynCore-stiffened design was used for the front/rear spars.

The corresponding lower cover design configurations were as follows:

1) Spread 0° supported by 5 or 6 Y-spars
2) Isolated discrete cap supported by 5 or 6 Y-spars
3) Spread 0° supported by blade stiffeners.

Weight Summary – Similar to previous design concepts, the theoretical weights, derived for the material/configuration concepts, were multiplied by an empirically determined non-optimum factor, to yield a realistic assembly weight. The table below shows a weight breakdown of the multi-spar designs (spread 0° and discrete cap) and multi-rib design. The weight savings generated by these concepts show significant improvement over the baseline. The multi-rib design, using G40-800/F584 with Y stiffeners, provided the greatest savings (573 lbs. or 46% of the metal torque box weight of 1233 lbs.)

Weight Breakdown for Selected Wing Designs (Material & Configuration Oriented)

COMPONENT	BASELINE WING TORQUE BOX (LBS)	MULTI-SPAR (SPREAD 0°) (LBS)	MULTI-SPAR (DISCRETE CAP) (LBS)	MULTI-SPAR (Y-STIFFENED) (LBS)
UPPER COVER	293.80	182.80	191.50	215.50
• BASIC INTERSPAR COVER	240.50	169.00	177.70	215.50
• SOFTENING STRIP PENALTY (0° GL/EP)	2.60	---	---	---
• DAMAGE TOLERANCE PENALTY (0° GL/EP)	10.60	---	---	---
• DAMAGE TOLERANCE PENALTY (±45° GL/EP)	0.00	---	---	---
• SPAR CAPS (INC WRINKLING PENALTY)	40.10	13.80	13.80	---
LOWER COVER	224.10	207.00	186.60	208.90
• BASIC INTERSPAR COVER	187.20	200.20	179.80	208.90
• SOFTENING STRIP PENALTY (0° GL/EP)	2.20	---	---	---
• DAMAGE TOLERANCE PENALTY (0° GL/EP)	8.00	---	---	---
• DAMAGE TOLERANCE PENALTY (±45° GL/EP)	1.50	---	---	---
• SPAR CAPS (INC WRINKLING PENALTY)	24.90	6.80	6.80	---
FRONT SPAR (SYNCORE STIFFENED)	88.60	73.80	73.80	98.80
REAR SPAR (SYNCORE STIFFENED)	36.00	32.90	32.90	40.10
INTERMEDIATE SPARS (Y-SPARS)	110.00	159.00	159.00	---
RIBS	52.20	52.20	52.20	96.60
TOTAL TORQUE BOX	806.20	707.70	696.00	659.90
WEIGHT SAVINGS OVER BASELINE	---	98.50	110.20	146.30
% SAVINGS	---	12.20	13.70	18.10

CONCEPT EVALUATION

Each design concept was rated in terms of the following parameters: weight, risk, manufacturing and production costs, durability/damage tolerance, repairability, inspectability and operation and support costs.

With the concept rating forms, along with layouts, engineers from different disciplines were able to rate the various novel composites wing concepts. These disciplines included Advanced Materials and Manufacturing, Tooling, Design/Structural Analysis, Quality Control and Reliability/Maintainability. The results are incorporated in the following table, for the multi-spar and multi-rib concepts. The Total Score column represents the total of each discipline's score for that parameter. The Average Score column represents the Total Score divided by the No. of R (rating disciplines), which is four in all cases. For example, for the first parameter, Weight, Concept I received scores of 100, 125, 125, 100, from the four disciplines, which resulted in a Total Score of 450 and an Average Score of 113 (450/4). The sum of the Average Scores then represents the rating for that particular concept.

Concept Evaluation, Multi-Spar Concepts

PARAMETERS	WEIGHTING FACTOR	CONCEPT I IM7/8551-7A SYNCORE-STIFFENED			CONCEPT II G40-800/F584 SYNCORE-STIFFENED			CONCEPT IV G40-800/F584 SPREAD 0°/Y-SPARS			CONCEPT V G40-800/F584 DISCRETE CAP/Y-SPARS		
		TOTAL SCORE	NO. OF R	AVG SCORE	TOTAL SCORE	NO. OF R	AVG SCORE	TOTAL SCORE	NO. OF R	AVG SCORE	TOTAL SCORE	NO. OF R	AVG SCORE
WEIGHT	25	450	4	113	700	4	175	575	4	144	675	4	169
RISK	10	300	4	75	300	4	75	240	4	60	240	4	60
MFG RDT & E AND PRODUCTION COSTS	18	552	4	138	528	4	132	552	4	138	552	4	138
DURABILITY AND SURVIVABILITY	14	378	4	95	364	4	91	378	4	95	406	4	102
REPAIRABILITY	15	435	4	109	435	4	109	405	4	101	420	4	105
INSPECTION/ACCESS	10	290	4	73	290	4	73	220	4	55	220	4	55
OPS & SUPT COSTS	8	224	4	56	224	4	56	236	4	59	236	4	59
SUM OF AVG. SCORES				659			711			652			688

R90-4125-007

CONCEPT SELECTION

The relative closeness of the ratings for Concepts II, V and VI, and subjective nature of the evaluation make them virtually equivalent. However, continued effort will be directed towards Concepts V (Multi-Spar: Y-Spar) and VI (Multi-Rib: Y-Stiffened), since they represent the latter stages of development and the most potential to attain the program's goals.

Concept Evaluation, Multi-Rib Concepts

PARAMETERS	WEIGHTING FACTOR	CONCEPT III IM7/TACTIX 123 HAT-STIFFENED			CONCEPT VI IM7/TACTIX 123 Y-STIFFENED		
		TOTAL SCORE	NO. OF R	AVG SCORE	TOTAL SCORE	NO. OF R	AVG SCORE
WEIGHT	25	700	4	175	925	4	231
RISK	10	250	4	63	250	4	63
MFG RDT & E AND PRODUCTION COSTS	18	456	4	114	480	4	120
DURABILITY AND SURVIVABILITY	14	406	4	102	364	4	91
REPAIRABILITY	15	405	4	101	390	4	98
INSPECTION/ACCESS	10	260	4	65	250	4	63
OPS & SUPT COSTS	8	245	4	61	212	4	53
SUM OF AVG. SCORES				681			719

- Y-spar representative of intermediate wing spar segment in size, complexity and load carrying capability (shear flow of 1,015 lb/in. in 5-spar wing configuration)
- Three 40-in. Y-spar preforms woven by Textile Technologies, Inc. on NASA Jacquard loom using angle interlock fiber architecture
  - Commingled AS4(6K)/PEEK 150g Tows
  - 0/90-degree weave and ±45-deg fabric stitched with Fiberglass/Toray H.S. thread
- Demonstrate structural integrity of Y-spars
  - Two Y-spars destructively sectioned
    - Mechanical & physical properties tests
    - Standard for ultrasonic NDI
  - One Y-spar tested in four-point beam bending

Commingled AS4/PEEK 150G
Y-Spar Configuration
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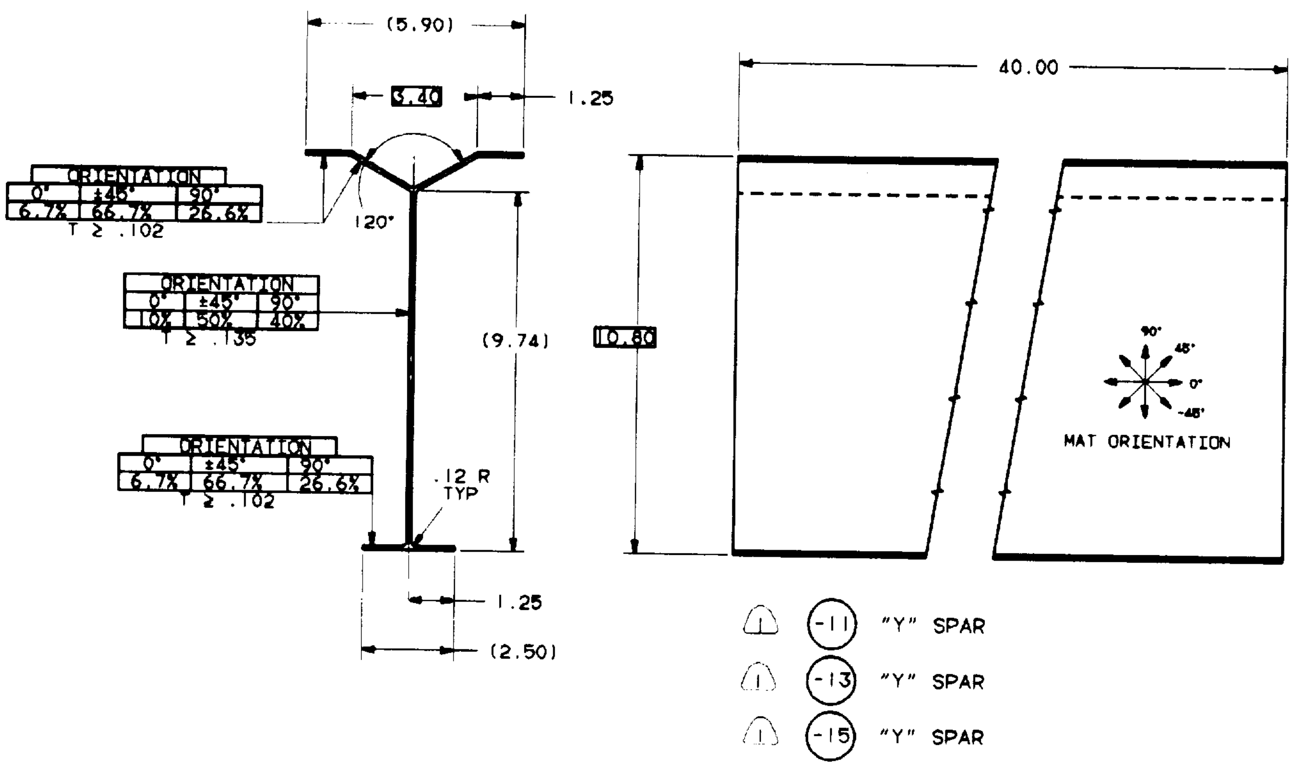


MANUFACTURING EFFORT OVERVIEW

- Commingled AS4/PPS 0°/90° I-Beams
  - Design and fabrication of woven commingled AS4/PPS 3-D I-Beam preforms
  - Consolidation/forming of I-Beam preforms
  - NDI and dimensional analysis of I-Beams

- Commingled AS4/PEEK 150g Y-spars
  - Design and fabrication of woven commingled AS4/PEEK 150g Y-spar preforms
  - Consolidation/forming of Y-spar preforms
  - NDI and dimensional analysis of Y-spars
  - Structural test of Y-spar

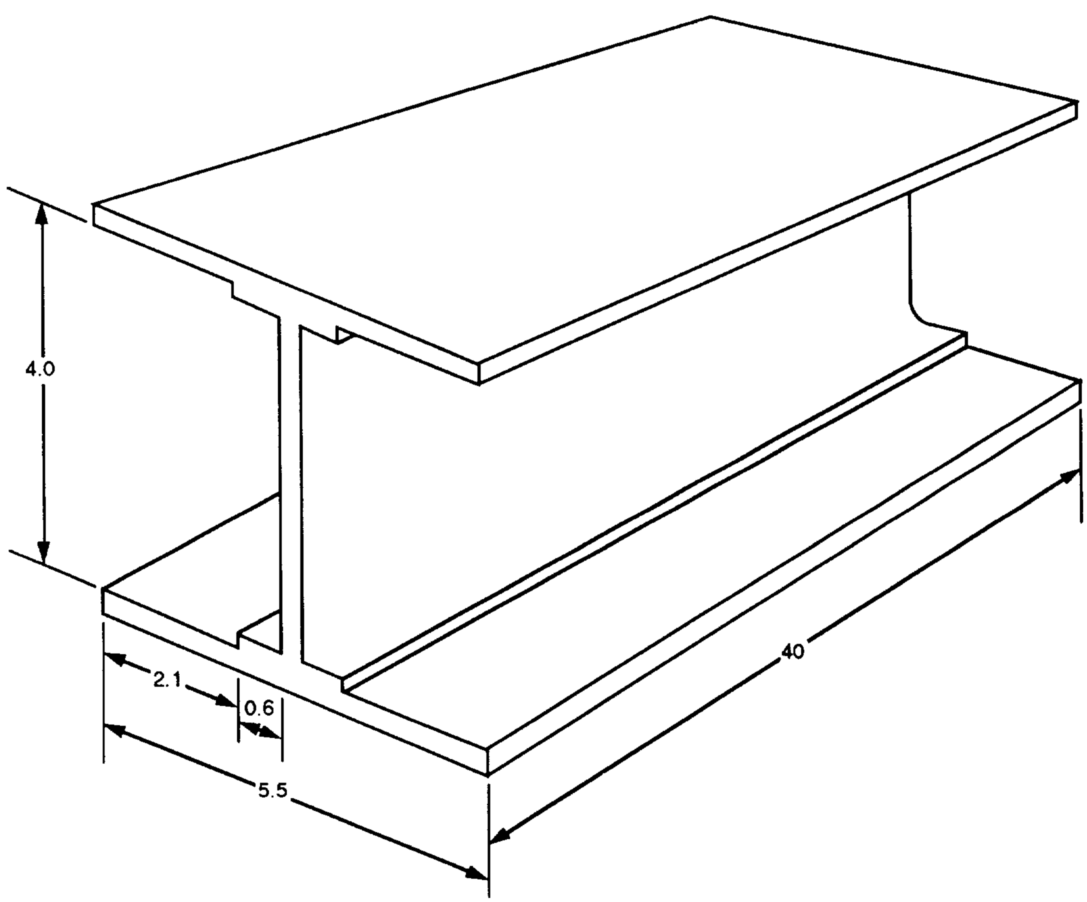
COMMINGLED AS4/PPS 0°/90° I-BEAMS

Textile manufacturers at present cannot weave 3-D preforms with 0°, 90° and ±45° fiber reinforcement orientations. Preforms with fibers oriented 0°/90° to each other are woven to provide 3-D carcasses. Plies of fabric are then stitched to these carcasses in 45°/135° orientations to provide preforms which when consolidated will provide structural parts.

A series of woven commingled AS4(3K)/PPS 0°/90° I-beam carcasses were consolidated to provide processing data for these intermediate preform configurations. Emphasis was placed on the consolidation characteristics of these material forms and resultant percent fiber volume values. It was realized that the structural properties of the consolidated 0°/90° I-beams were minimal (without 45°/135° reinforcement); therefore testing for physical properties was emphasized in these processing studies.

Textile Technologies, Inc. (TTI) was requested to weave three I-beam preforms using commingled AS4/PPS fiber. The 3-D preforms were to be fabricated using commingled tows with a 60/40 graphite fiber to PEEK 150g filament volume ratio. The 0°/90° preforms were to be configured to accommodate the following target dimensions after consolidation: length – 40 in., cap width – 5.5 in., and web height – 4.0 in. The thickness of the web was to be 0.072 ± 0.006 in. The web flanges were to be 0.60 in. wide and 0.036 ± 0.003 in. thick.

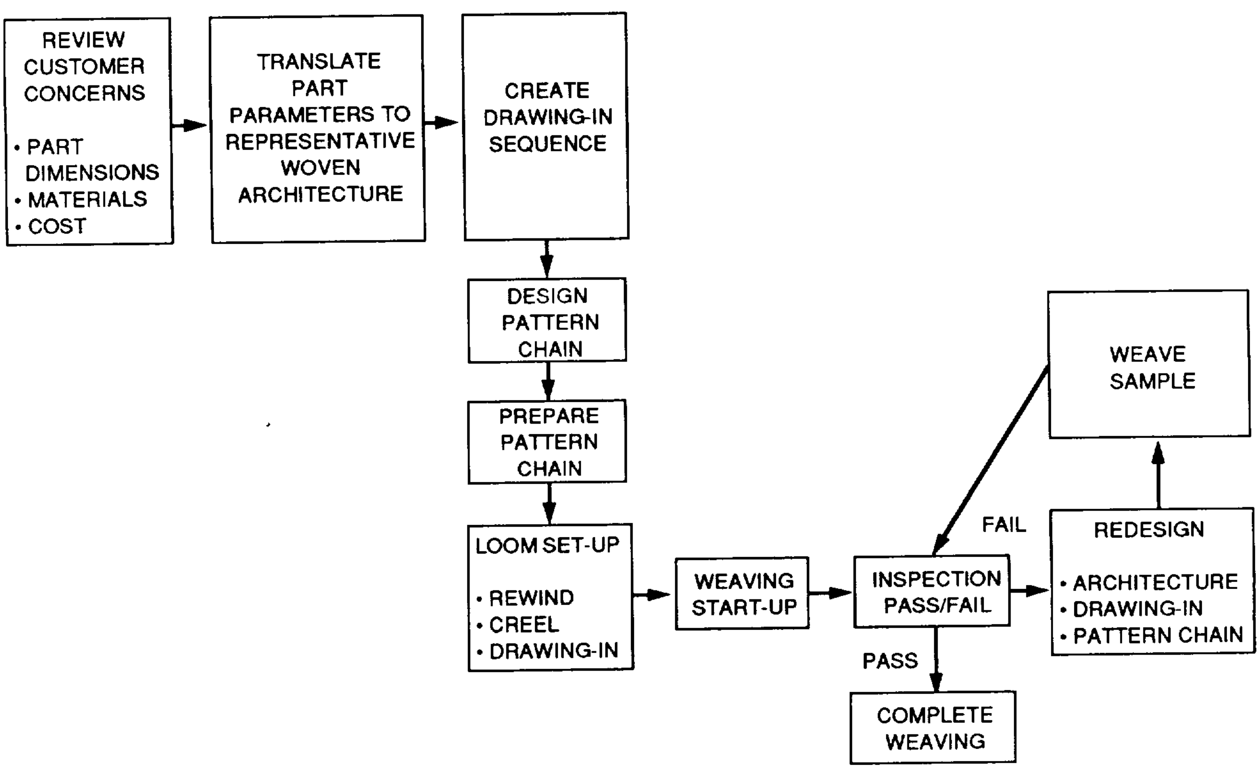
Woven Commingled AS4/PPS 0°/90° I-Beam



DESIGN METHODOLOGY

TTI reviewed configuration and material requirements plus cost concerns for the proposed commingled AS4/PPS I-beam. These customer requirements were then translated into an architecture for a woven 3-D preform which upon consolidation would yield a structure meeting design specifications. Preparation of a preform architecture is supported by the use of the interactive computer program Framework. This computer program permits the textile designer to rapidly determine the effect of fiber mix on the final thickness and fiber volume in given areas of the woven structure.

The loom is set up to accommodate the weaving requirements of the preform architecture. (A Jacquard loom was used to fabricate the commingled AS4/PPS preforms.) A series of trial weaving runs are then performed. Following each operation the appearance, dimensions and weight of the preform are evaluated. Based on these determinations the preform architecture is refined as necessary to produce an acceptable part. Since 3-D weaving is not an exact science this design/manufacturing iteration may have to be performed a number of times.

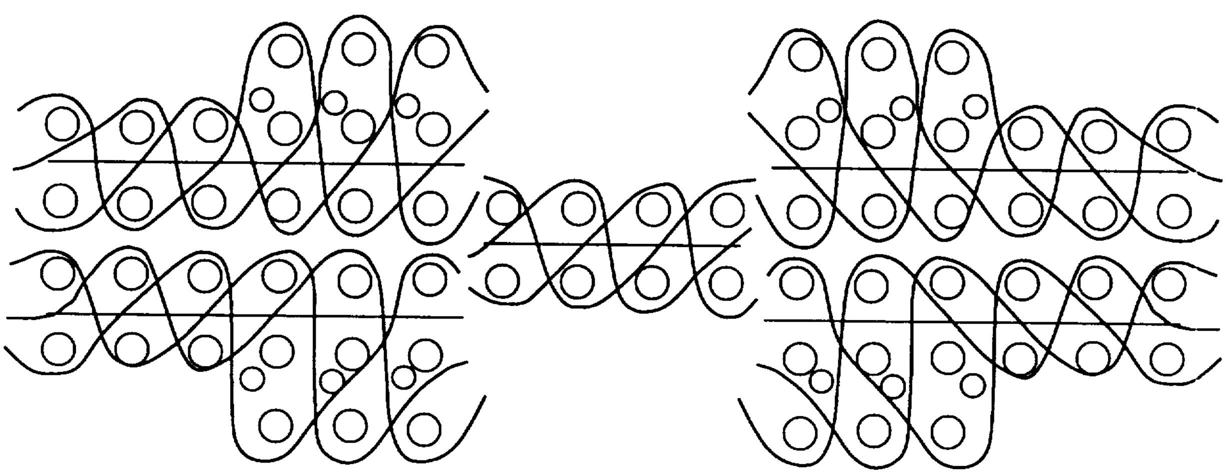


WOVEN PREFORM ARCHITECTURE

The architecture of a given preform shows the relative orientation of the fibers used to build that fabric part. In the case of the commingled AS4/PPS I-beam preforms, three fiber types (by function) were used: fill, stuffers and warp weavers. The stuffers are continuous, non-crimped fibers, installed in the same direction as the interlaced (with the fill fibers) warp weavers.

The architecture for the commingled AS4/PPS 0°/90° I-beam describes fiber configurations in the web and caps of the I-beam. The stepped area in the I-beam cap is also shown.

Architecture of Woven Commingled AS4/PPS 0°/90° I-Beam



	TOWS	THK
FILL	4	.040"
STUFFERS	8	.064" (EXCEPT IN WEB SECTION)
WARP WEAVERS	4	.040"

MATERIAL: AS4 (3K)/PPS COMMINGLED

FRAMEWORK
Consolidated Thickness Spread Sheet

The Framework is an interactive computer program that predicts the thickness of a consolidated preform based on the physical characteristics of the fibers used by the weaver in the fill and warp directions of the preform. These inputs are identified by an asterisk in the Framework shown for the web of the I-beam preform. They are end count (fiber ends per in.), denier (grams per 9000 meter) and fiber density. In the case of the I-beam web, a thickness of 0.060 in. and a percent fiber volume of 62.8 percent were predicted for the consolidated part.

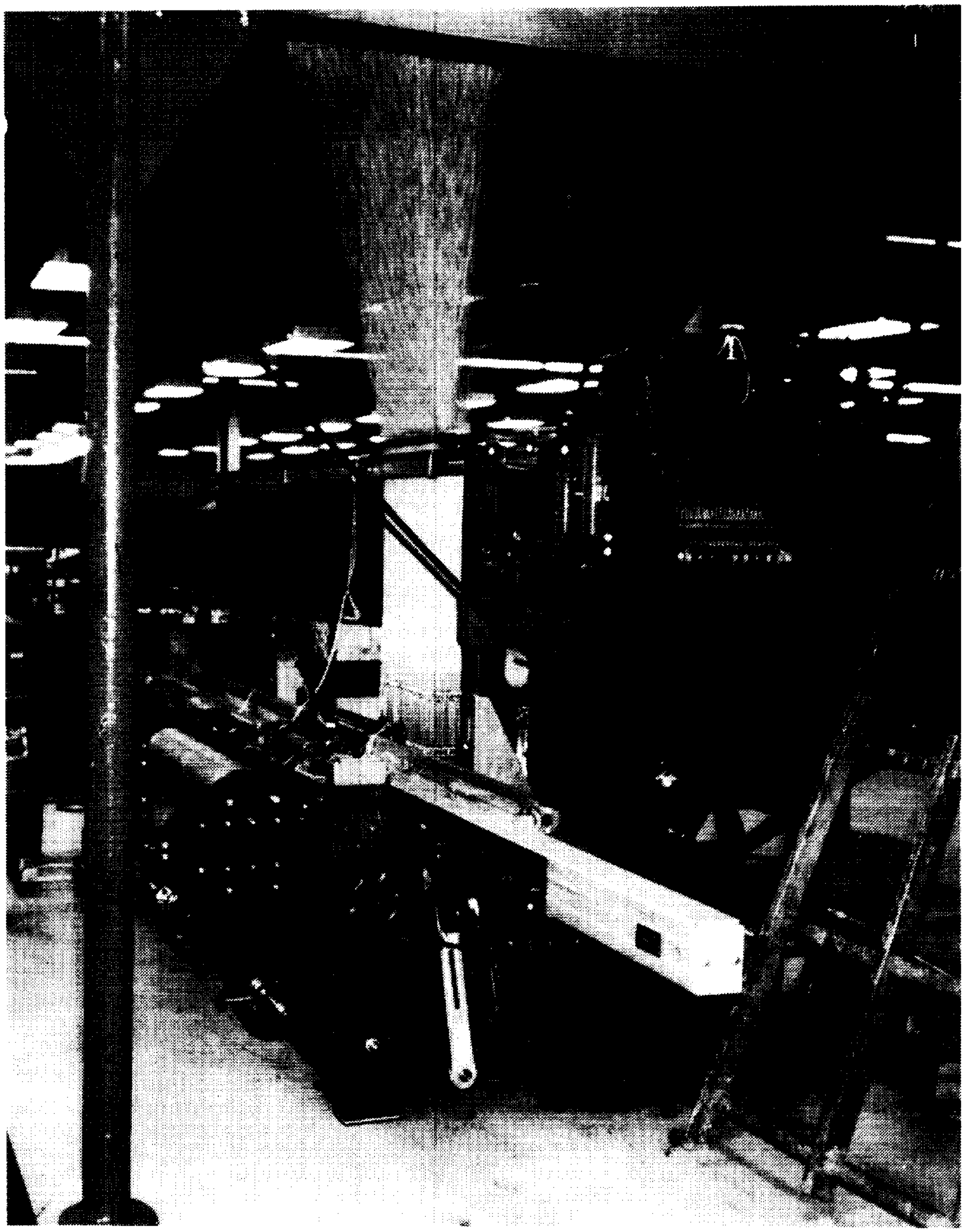
Consolidated Thickness Spread Sheet
Woven Commingled 3-D AS4/PPS I-Beam

HYBRID YARN FABRIC			FIBER	RESIN	TOTAL	
	I-BEAM WEB					
WARP	* END COUNT	(ENDS/IN)	128	128		
	* MANUFACTURER		HERCULES	BASF		
	* PRODUCT CODE		AS-4,3K	PPS		
	* DENIER	(GR/M)	1963	900	2863	
	YIELD	(YDS/LB)	2276	4965	1561	
	* DENSITY	(GR/CC)	1.73	1.34	1.58	
	AREAL WEIGHT	(GR/SQ M)	1099.1	503 .9	1603.1	47.24
	THICKNESS	(MILS)	25.0	14.8	39.8	^OZ/SQ YD^
	VOLUME FRACTION	(%)	41.9	24.8	66.7	
	WEIGHT FRACTION	(%)	45.7	21.0	66.7	
FILL	* END COUNT	(ENDS/IN)	64	64		
	* MANUFACTURER		HERCULES	BASF		
	* PRODUCT CODE		AS-4,3K	PPS		
	* DENIER	(GR/M)	1963	900	2863	
	YIELD	(YDS/LB)	2276	4965	1561	
	* DENSITY	(GR/CC)	1.73	1.34	1.58	
	AREAL WEIGHT	(GR/SQ M)	549.6	252.0	801.5	23.62
	THICKNESS	(MILS)	12.5	7.4	19.9	^OZ/SQ YD^
	VOLUME FRACTION	(%)	20.9	12.4	33.3	
	WEIGHT FRACTION	(%)	22.9	10.5	33.3	
TOTAL	AREAL WEIGHT	(GR/SQ M)	1648.7	755.9	2404.6	70.85
FABRIC	THICKNESS	(MILS)	37.5	22.2	59.7	^OZ/SQ YD^
	VOLUME FRACTION	(%)	62.8	37.2	100	
	WEIGHT FRACTION	(%)	68.6	31.4	100	
	DENSITY	(GR/CC)			1.58	

JACQUARD WEAVING MACHINE

This machine was purchased by TTI under NASA Contract NAS 1-18385. The machine features a mechanism which permits individual control of every yarn weaving across the width of a given fabric or preform. With a Jacquard head, weaving possibilities become infinite. It is this capability that permits the weaving of 3-D preforms.

The NASA machine has a 2500 warp end capability.



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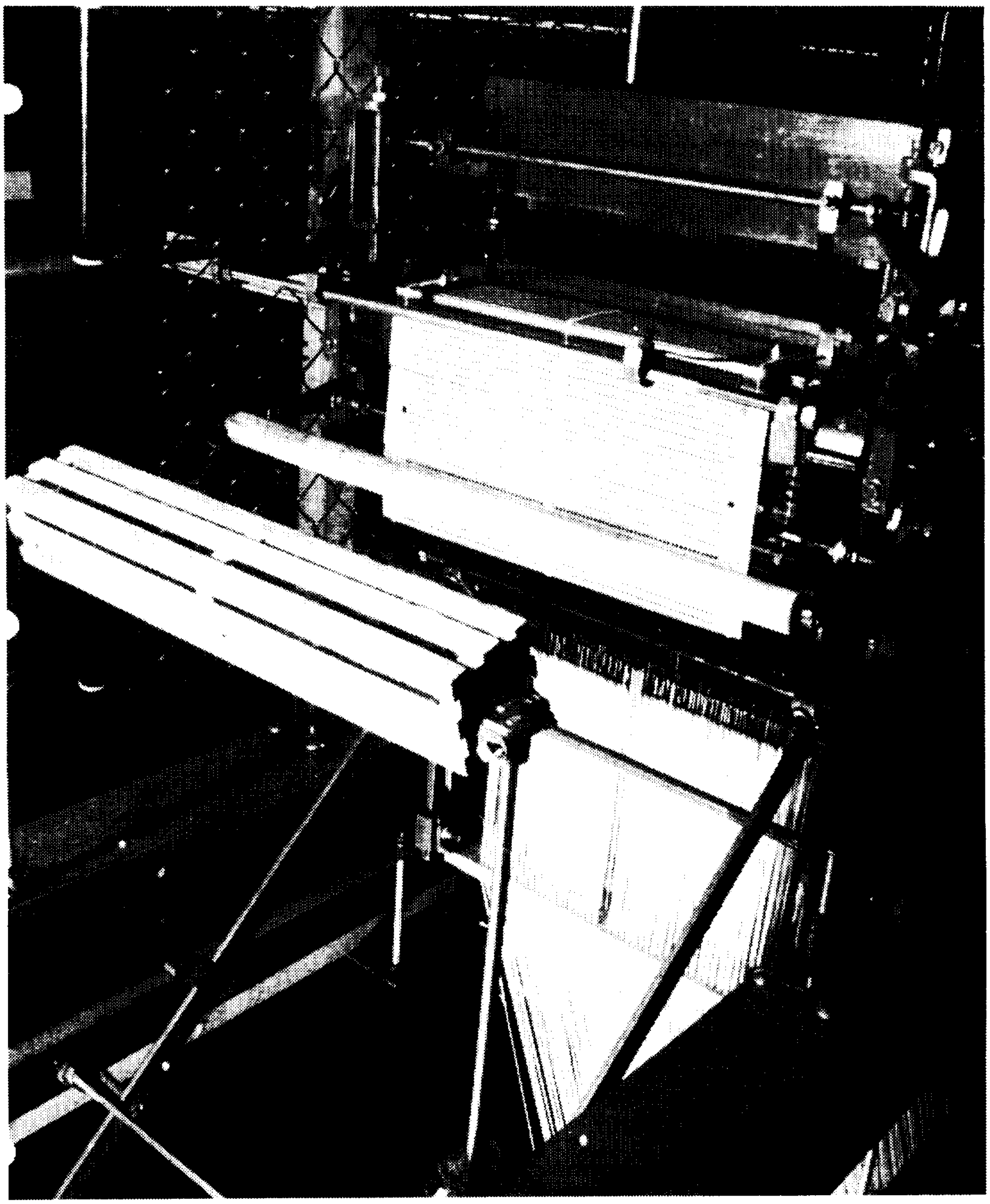
JACQUARD CARDS

Punched cardboard cards convey the fabric design or preform architecture to the Jacquard loom. The cards operate much like the rolls of perforated paper which control the operation of player pianos. The cards determine whether or not warp yarns are raised or lowered to accommodate the insertion of a fill yarn.



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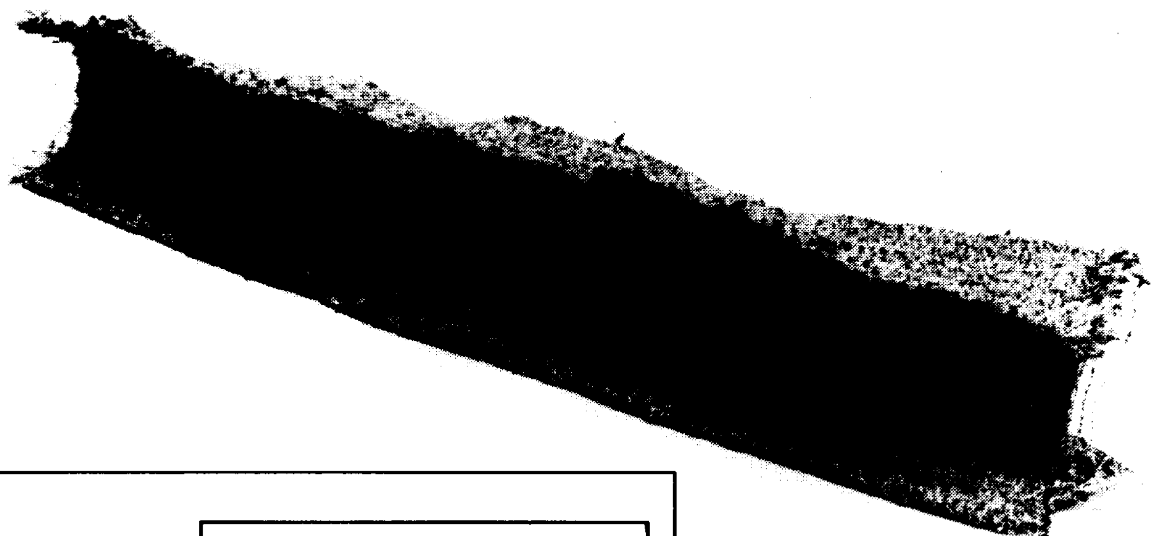
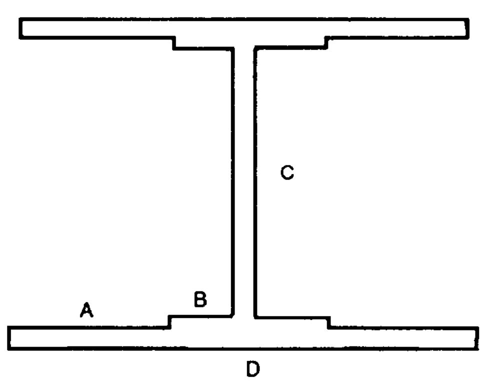
WOVEN COMMINGLED PREFORM

Three 40 in. (length) woven commingled AS4/PPS 0°/90° preforms were received from TTI. The visual appearances of the preforms were satisfactory; no floaters were detected in either the cap or web of the preform and the parts were tightly woven. (A floater is a warp weaver that has relatively long distances between successive interlacing fill yarns.)

The average thickness dimensions of the preforms were as follows:

Web:	0.627 in.
Outer Cap:	0.1251 in.
Inner Cap:	0.297 in.



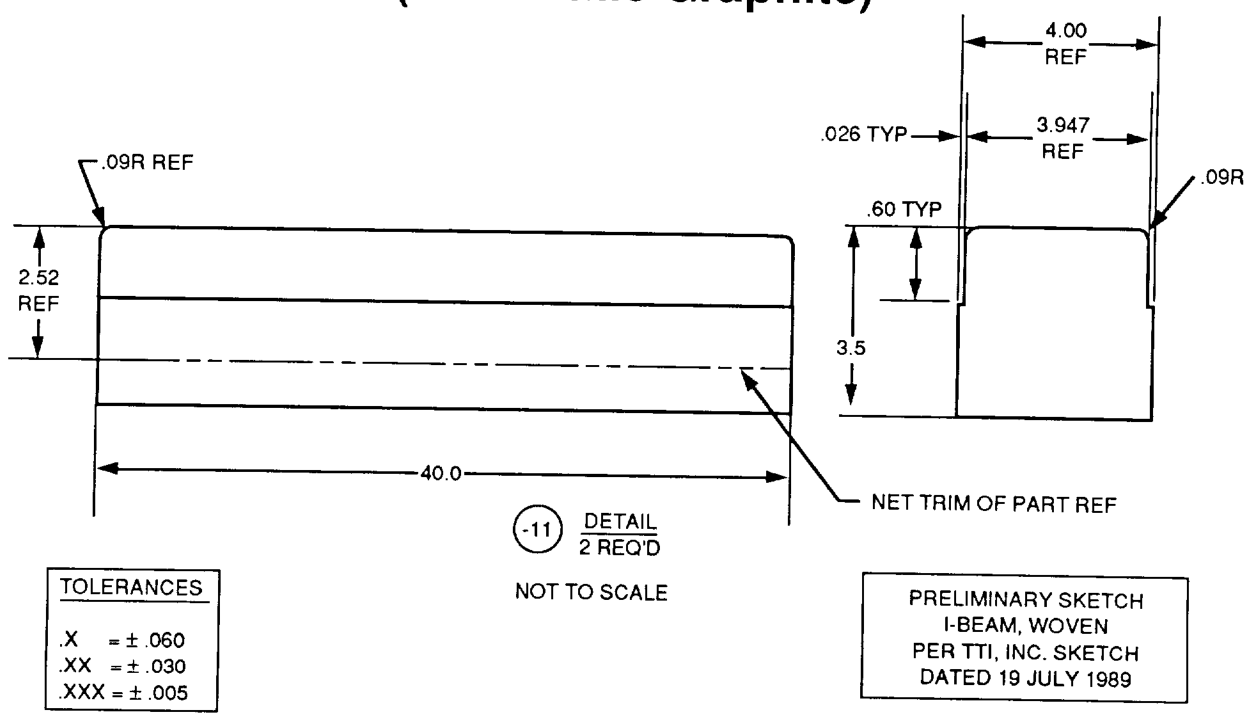


SECTIONS:	A	B	C	D
DIMENSIONS:	2.12	.6265	4.0	5.5
THICKNESS:	0.251"	0.297"	0.170"	(SEE A & B)

CONSOLIDATION/FORMING MANDRELS

It was decided to consolidate/form the commingled AS4/PPS I-beam preforms using matched monolithic graphite mandrels. The male tools would insure achievement of the required web height and thickness plus optimum forming/consolidation of the steps on the inner surfaces of the I-beam caps. Flat 0.125 in. thick aluminum caul plates were selected for use in consolidating the I-beam caps against the underlying monolithic graphite mandrels.

I-Beam Consolidation/Forming Tools (Monolithic Graphite)

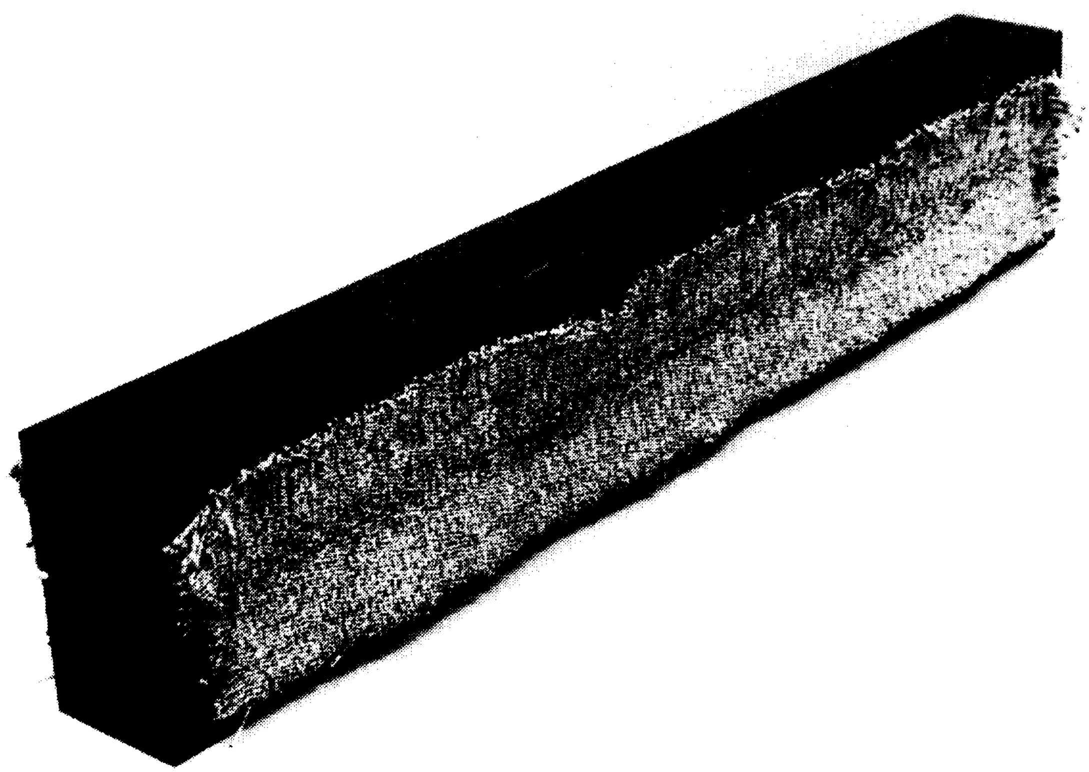


MONOLITHIC GRAPHITE TOOLING

Monolithic graphite was chosen as the material of construction for the tooling mandrels. The coefficient of thermal expansion (CTE) for this material ranges from 1.5 to 2.0 x 10^{-6} in./in./°F. This value compares favorably with the commonly used CTE range for Gr/Ep composite laminates, 1.0 to 1.5 x 10^{-6} in./in./°F. (The CTE value for consolidated woven 3-D commingled AS4/PPS 0°/90° structure is presently not available.) Corresponding CTE ranges for competitive tooling materials such as aluminum, steel and nickel alloy are 13.0-13.6, 6.1-6.7, and 6.6-7.4 x 10^{-6} in./in./°F, respectively. The thermal conductivity of monolithic graphite is greater than that of steel and nickel tool alloys (68 vs 26 and 34 BTU-ft/ft^2-hr-°F, respectively) but less than that of aluminum alloy (68 vs 117 BTU-ft/ft^2-hr- °F). Aluminum tool alloys, however, are not useful at temperatures above 700°F whereas monolithic graphite tools can be reliably utilized at temperatures up to 1000°F.

Monolithic graphite tools also have exceptional resistance to thermal shock at high temperatures due to the material's low CTE, high thermal conductivity, high tensile strength and relatively low modulus of elasticity.

Finally, monolithic graphite is very machinable and tools with precise tolerances (<0.003 in.) and smooth surfaces (<10 rms) may be cost effectively manufactured.

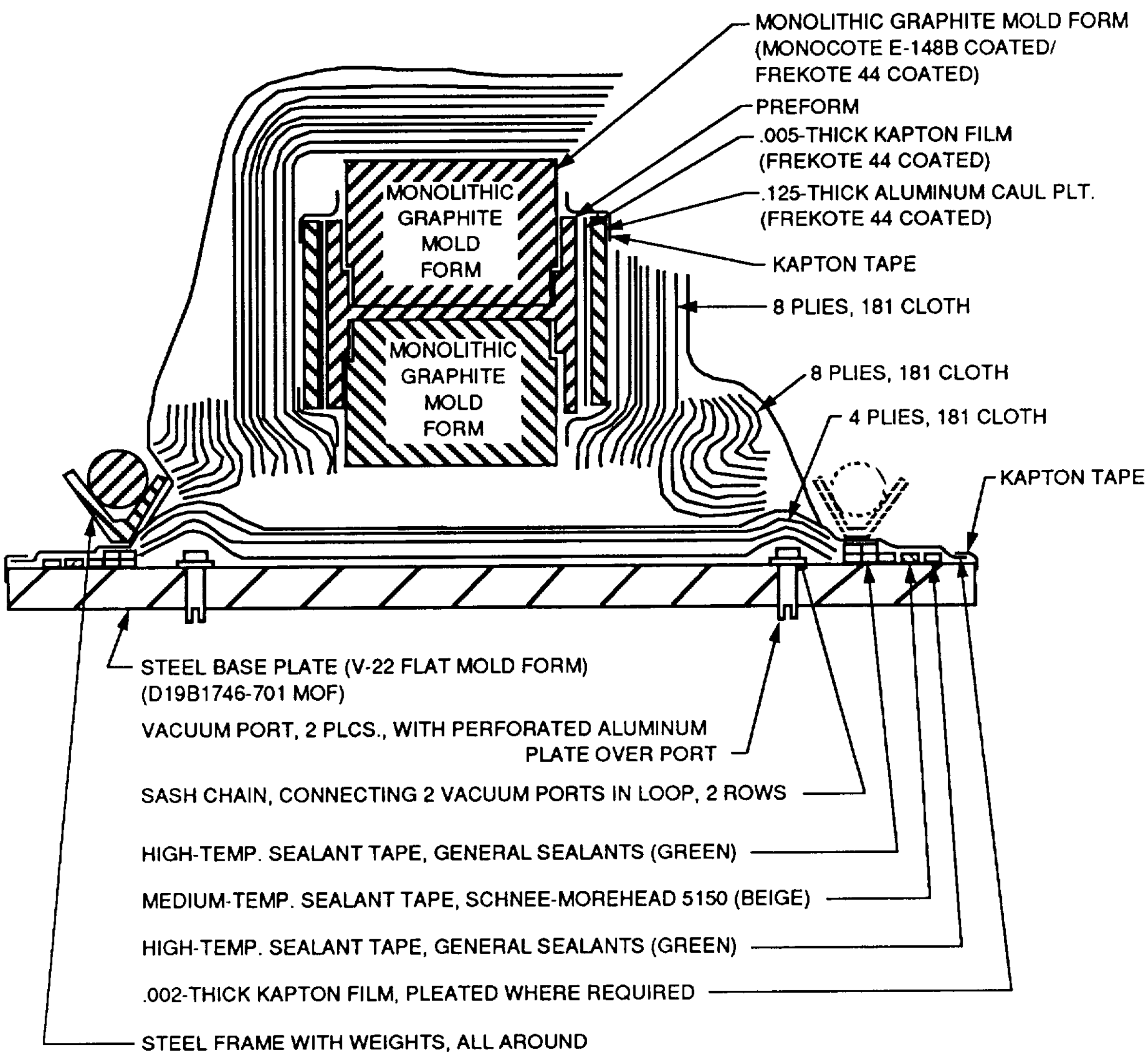


AUTOCLAVE VACUUM BAG ARRANGEMENT

The commingled AS4/PPS I-beams were consolidated using an autoclave/vacuum bag procedure. The workpiece (I-beam preform installed between matched graphite mandrels) was installed on a steel base plate. The workpiece was vacuum bagged to the baseplate using Kapton film material. A weighted steel frame, in combination with medium and high temperature sealant materials, was used to provide a vacuum tight bag over the workpiece.

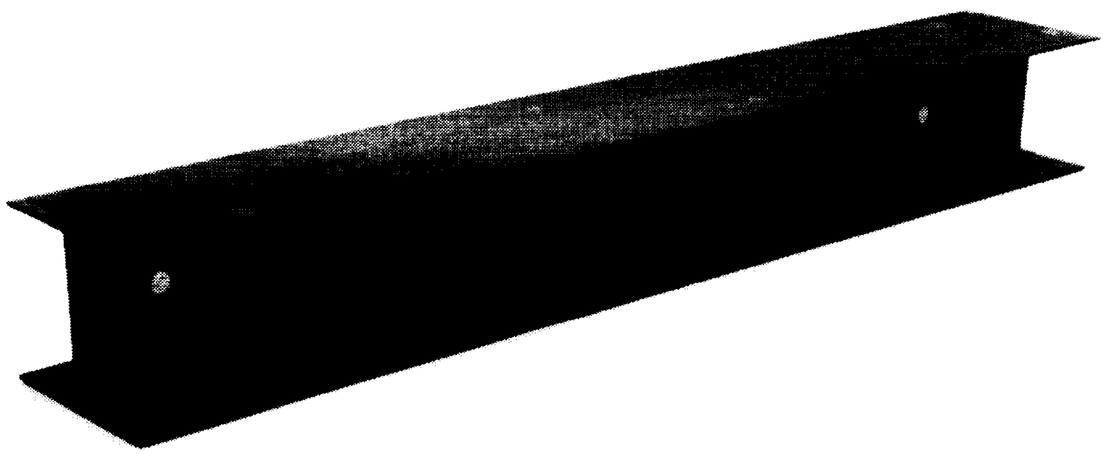
The commingled AS4/PPS preforms were consolidated for 30 minutes at 630°F and 200 psi.

Woven Commingled AS4/PPS 0°/90° I-Beam
Autoclave Vacuum Bag Arrangement



CONSOLIDATED I-BEAMS

The autoclave/vacuum bag consolidation procedure for I-beam -1 was unsatisfactory. The graphite mandrels hung up and did not properly close on the web of the preform. As a result, this I-beam did not pass ultrasonic or dimensional inspection. The layup procedure for the workpiece and the vacuum bagging arrangement were refinedto ensure optimum closure of the forming dies. I-beam preforms -2 and -3 were subsequently consolidated to provide I-beams that were acceptable with respect to ultrasonic and dimensional NDI. The trim drop-off from each of the I-beams was used to provide coupons for percent fiber volume analysis and edge photomicrographic inspection. Edge photomicrographic inspection indicated that I-beams -2 and -3 were free of porosity. The average percent fiber volume for these structures was approximately 57 percent.



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- Ultrasonic Inspection: No Defects
- Edge Photomicrographic Inspection: OK
- Percent Fiber Volume: 57%
- Final Web Thickness: 60% That of Preform

TARGET, PREFORM AND FINAL PART DIMENSIONS

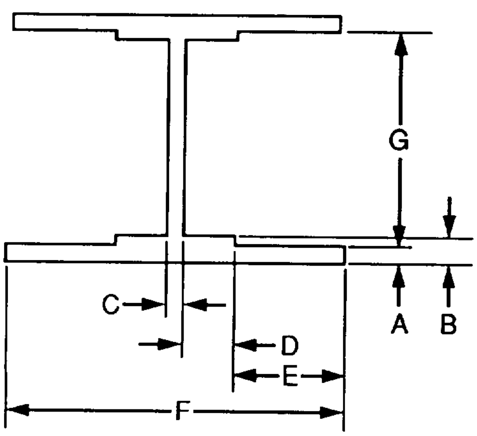
Target, as received preform and final consolidated dimensions are presented for each of the three I-beams. Emphasis is placed on final web thickness since a specific target value was given to TTI, i.e., 0.072 ± 0.006 in. As expected, the web thickness of I-beam -1 was unacceptable, 0.115 in. The web thicknesses of I-beams -2 and -3, however, were acceptable, i.e., 0.065 and 0.074 in., respectively.

Average percent consolidation values for the web and cap areas of the preforms are presented for I-beams -2 and -3. (Percent consolidation equals preform thickness – consolidated thickness divided by preform thickness multiplied by 100.) The average percent consolidation value for the webs was 56.5 percent.

The 56.5 percent consolidation value was used in the shimming operation for consolidation/forming of the AS4/PEEK 150g Y-spar preforms.

Woven Commingled AS4/PPS I-Beam

Target, Preform & Final Part Dimensions



	TARGET (IN.)	PREFORM (IN.)	CONSOLIDATED I-BEAMS 1 (IN.)	2 (IN.)	3 (IN.)	PERCENT CONS. (%)
A	>0.084	0.251	0.112	0.112	0.102	59.4
B	>0.120	0.297	0.144	0.140	0.144	51.5
C	0.066 -0.078	0.170	0.115	0.065	0.074	56.5
D	0.6	0.6	0.6	0.6	0.6	—
E	>2.0	2.2	2.2	2.2	2.2	—
F	>5.0	5.6	5.6	5.6	5.6	—
G	4.0	4.0	4.0	4.0	4.0	—

COMMINGLED AS4/PEEK 150G Y-SPARS

Three 40 in. (length) commingled AS4/PEEK 150g Y-spars are being fabricated by the autoclave consolidation of woven/stitched preforms. Cap details will be mechanically attached to the Y-spars to provide elements suitable for destructive testing.

Y-spar 0°/90° carcasses were woven by TTI using their Jacquard loom. Sewing Machine Exchange, Inc. (SMX), a TTI subcontractor, stitched woven commingled AS4/PEEK 150g fabric in 45°/135° orientations to the carcasses to provide woven/stitched 3-D Y-spar preforms.

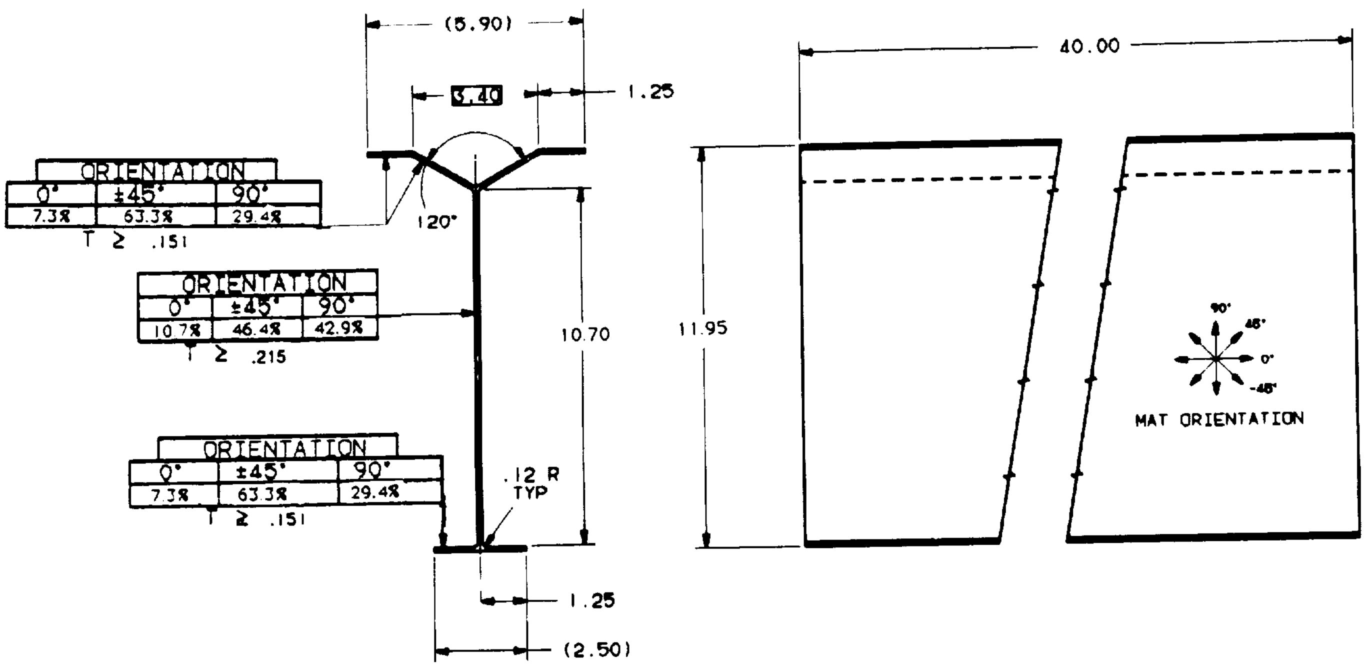
The Y-spar preforms are being sequentially consolidated by Grumman using vacuum bag processing in an autoclave. Grumman is presently evaluating non-autoclave consolidation procedures which have the potential to be more cost effective than the baseline process. These innovative processes include thermoforming and the Therm-X process. Since the primary goal of our program is to provide reliable engineering data and since a limited number of Y-spars are to be fabricated, it was decided to use the low risk autoclave process. Furthermore, the autoclave process had already been demonstrated by the successful consolidation of the commingled AS4/PPS I-beam preforms.

The Y-spar preforms are being sequentially consolidated using the following approach. The first Y-spar will be inspected using ultrasonic NDI and dimensional analysis. The Y-spar will be destructively sectioned and reinspected using dimensional and micrographic analysis. Design/Manufacturing/Quality Control personnel will review these data and refine the consolidation procedure accordingly. The second Y-spar will be consolidated and the above review process will be repeated. The third Y-spar will be consolidated using the refined process and then destructively tested using four-point beam bending.

COMMINGLED AS4/PEEK 150G Y-SPAR CONFIGURATION

TTI provided three woven/stitched commingled AS4/PEEK 150g Y-spar preforms which upon consolidation would meet modified configuration requirements of D19B8220-13. The percent fiber volume of the consolidated preforms was to be 60 percent.

Commingled AS4/PEEK 150G Modified Y-Spar Configuration

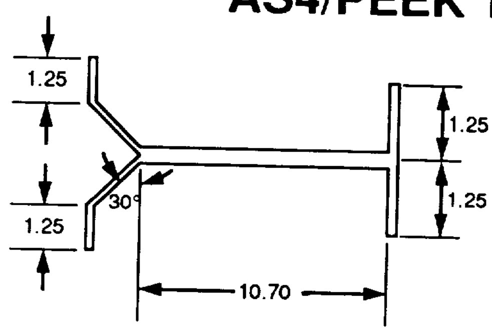


ARCHITECTURE OF PREFORMS

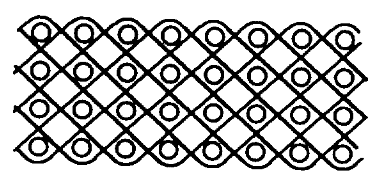
The architecture of the woven commingled AS4/PEEK 150g 0°/90° preforms is presented below. The preform webs consist of 76.59 percent fill yarns, 19.14 percent warp stuffers and 4.25 percent through the thickness warp weavers. The preform flanges consist of 75.00 percent fill yarns, 18.75 percent warp stuffers and 6.25 percent through the thickness warp weavers.

The critical dimension for the preforms was the web height as measured from the radius of the 90-degree flange to the radius of the Y-flange, i.e., 10.70 in. This dimension was made important by the decision to use male mandrels for consolidation of the preforms. Web and flange thicknesses were to be such that upon preform consolidation to a 60 percent fiber volume, modified D19B8220-13 target dimensions would be achieved. A 55 percent consolidation value was expected.

Architecture of Woven Commingled AS4/PEEK 150G 0°/90° Preform

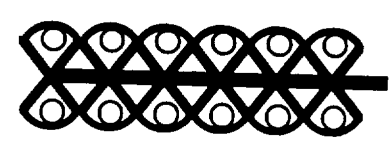


WEB SECTION



	YARNS/ INCH	% FIBER BY WEIGHT
WEB SECTION		
FILLING	72	76.59
WARP	18	19.16
THROUGH-THE THICKNESS	4	4.25
FLANGE SECTION		
FILLING	36	75.00
WARP	9	18.75
THROUGH-THE THICKNESS	3	6.25

FLANGE SECTION



MATERIAL TYPE: AS4/PEEK 150G COMMINGLED YARN

FRAMEWORK
Consolidated Thickness Spread Sheet - Web

The Framework print-out for the web of the commingled AS4/PEEK 150g 0°/90° Y-spar preforms is hown below. The 27 ends/in. end count for the warp fibers was composed of 22 warp stuffers and 5 hrough-the-thickness weavers. The denier value for the AS4 and PEEK 150g fibers making up the tows ised in the warp and fill directions were 3927 and 1800, respectively.

Target thickness and percent fiber volume values for the consolidated web were 0.071 in. and 61.0 percent, respectively.

Woven Commingled 3-D AS4/PEEK150 G 0°/90° Y-Spar Web Preform

HYBRID YARN FABRIC			FIBER	RESIN	TOTAL	
WARP	• END COUNT	(ENDS/IN)	27	27		
	• MANUFACTURER		BASF	BASF		
	• PRODUCT CODE		AS-4 6K	PEEK		
	• DENIER	(GR/M)	3927	1800	5727	
	YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	AREAL WEIGHT	(GR/SQ M)	463.8	212.6	676.4	19.93
	THICKNESS	(MILS)	10.1	6.5	16.6	^OZ/SQ YD^
	VOLUME FRACTION	(%)	14.3	9.2	23.5	
	WEIGHT FRACTION	(%)	16.1	7.4	23.5	
FILL	• END COUNT	(ENDS/IN)	88	88		
	• MANUFACTURER		BASF	BASF		
	• PRODUCT CODE		AS-4	PEEK		
	• DENIER	(GR/M)	3927	1800	5727	
	YIELD	(YDS/LB)	1138	2482	780	
	• DENSITY	(GR/CC)	1.80	1.29	1.60	
	AREAL WEIGHT	(GR/SQ M)	1511.7	692.9	2204.6	64.96
	THICKNESS	(MILS)	33.1	21.1	54.2	^OZ/SQ YD^
	VOLUME FRACTION	(%)	46.7	29.9	76.5	
	WEIGHT FRACTION	(%)	52.5	24.1	76.5	
TOTAL FABRIC	AREAL WEIGHT	(GR/SQ M)	1975.5	905.5	2881.0	84.89
	THICKNESS	(MILS)	43.2	27.6	70.8	^OZ/SQ YD^
	VOLUME FRACTION	(%)	61.0	39.0	100	
	WEIGHT FRACTION	(%)	68.6	31.4	100	
	DENSITY	(GR/CC)			1.60	

FRAMEWORK
Consolidated Thickness Spread Sheet - Flange

The Framework print-out for the flange of the commingled AS4/PEEK 150g 0°/90° Y-spar preforms is shown below. The 15 ends/in. end count for the warp fibers was composed of warp stuffers and through the-thickness weavers. The denier value for the AS4 and PEEK 150g fibers making up the tows used was again 3927 and 1800, respectively.

Target thickness and percent fiber volume values for the consolidated 0°/90° Y-spar web carcass were 0.036 in. and 61.0 percent, respectively.

Woven Commingled 3-D AS4/PEEK150 G 0°/90° Y-Spar Flange Preform

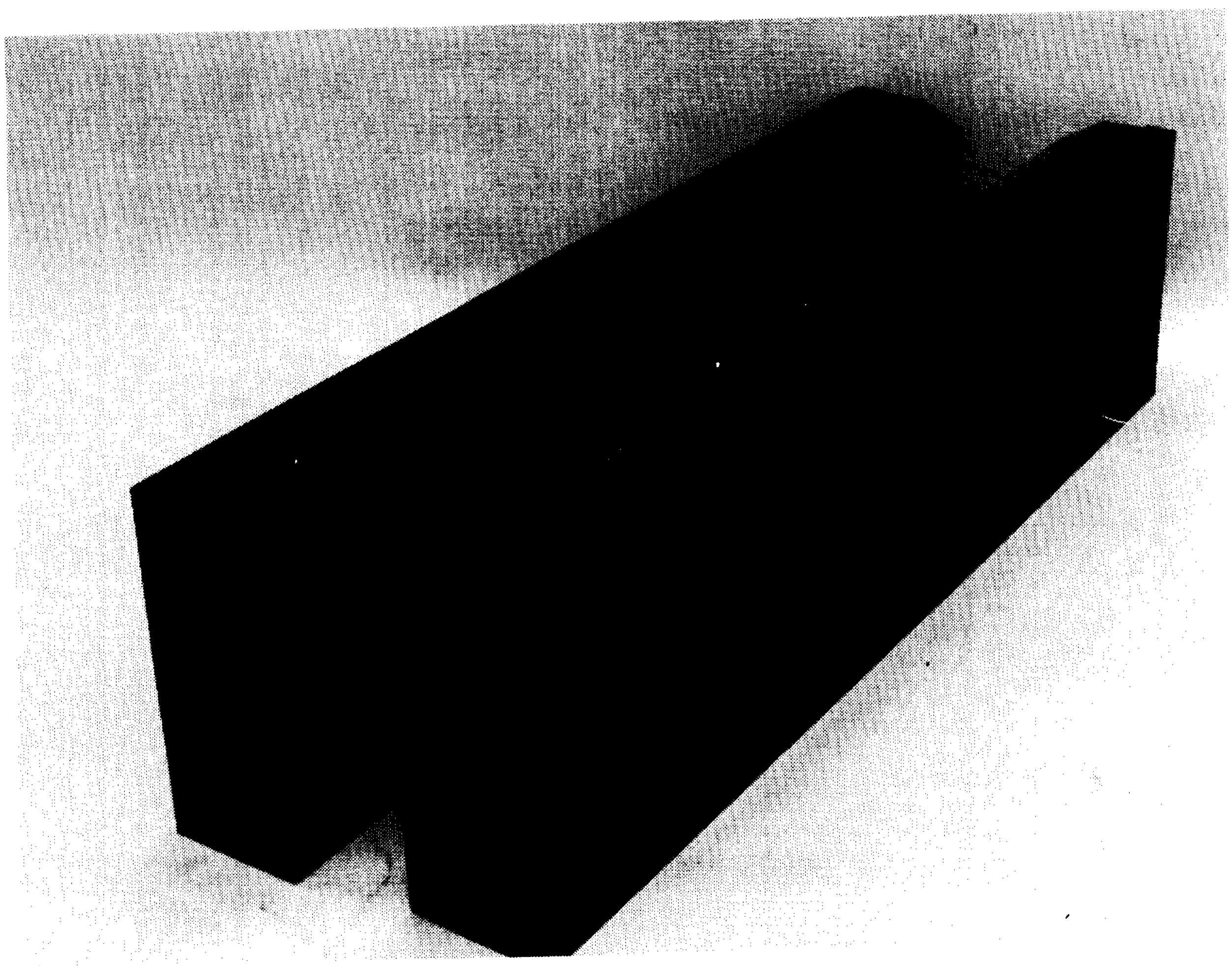
HYBRID YARN FABRIC			FIBER	RESIN	TOTAL	
WARP	* END COUNT	(ENDS/IN)	15	15		
	* MANUFACTURER		BASF	BASF		
	* PRODUCT CODE		AS-4 6K	PEEK		
	* DENIER	(GR/M)	3927	1800	5727	
	YIELD	(YDS/LB)	1138	2482	780	
	* DENSITY	(GR/CC)	1.80	1.29	1.60	
	AREAL WEIGHT	(GR/SQ M)	257.7	118.1	375.8	11.07
	THICKNESS	(MILS)	5.6	3.6	9.2	^OZ/SQ YD^
	VOLUME FRACTION	(%)	15.5	9.9	25.4	
	WEIGHT FRACTION	(%)	17.4	8.0	25.4	
FILL	* END COUNT	(ENDS/IN)	44	44		
	* MANUFACTURER		BASF	BASF		
	* PRODUCT CODE		AS-4	PEEK		
	* DENIER	(GR/M)	3927	1800	5727	
	YIELD	(YDS/LB)	1138	2482	780	
	* DENSITY	(GR/CC)	1.80	1.29	1.60	
	AREAL WEIGHT	(GR/SQ M)	755.9	346.5	1102.3	32.48
	THICKNESS	(MILS)	16.5	10.6	27.1	^OZ/SQ YD^
	VOLUME FRACTION	(%)	45.5	29.1	74.6	
	WEIGHT FRACTION	(%)	51.1	23.4	74.6	
TOTAL FABRIC	AREAL WEIGHT	(GR/SQ M)	1013.5	464.6	1478.1	43.55
	THICKNESS	(MILS)	22.2	14.2	36.3	^OZ/SQ YD^
	VOLUME FRACTION	(%)	61.0	39.0	100	
	WEIGHT FRACTION	(%)	68.6	31.4	100	
	DENSITY	(GR/CC)			1.60	

CONSOLIDATION/FORMING MANDRELS

It was decided to consolidate/form the commingled AS4/PEEK 150g Y-spar preforms using matched monolithic graphite mandrels. Monolithic graphite tooling was chosen because of the good performance of the mandrels used to consolidate the previously discussed commingled AS4/PPS 0°/90° I-Beams.

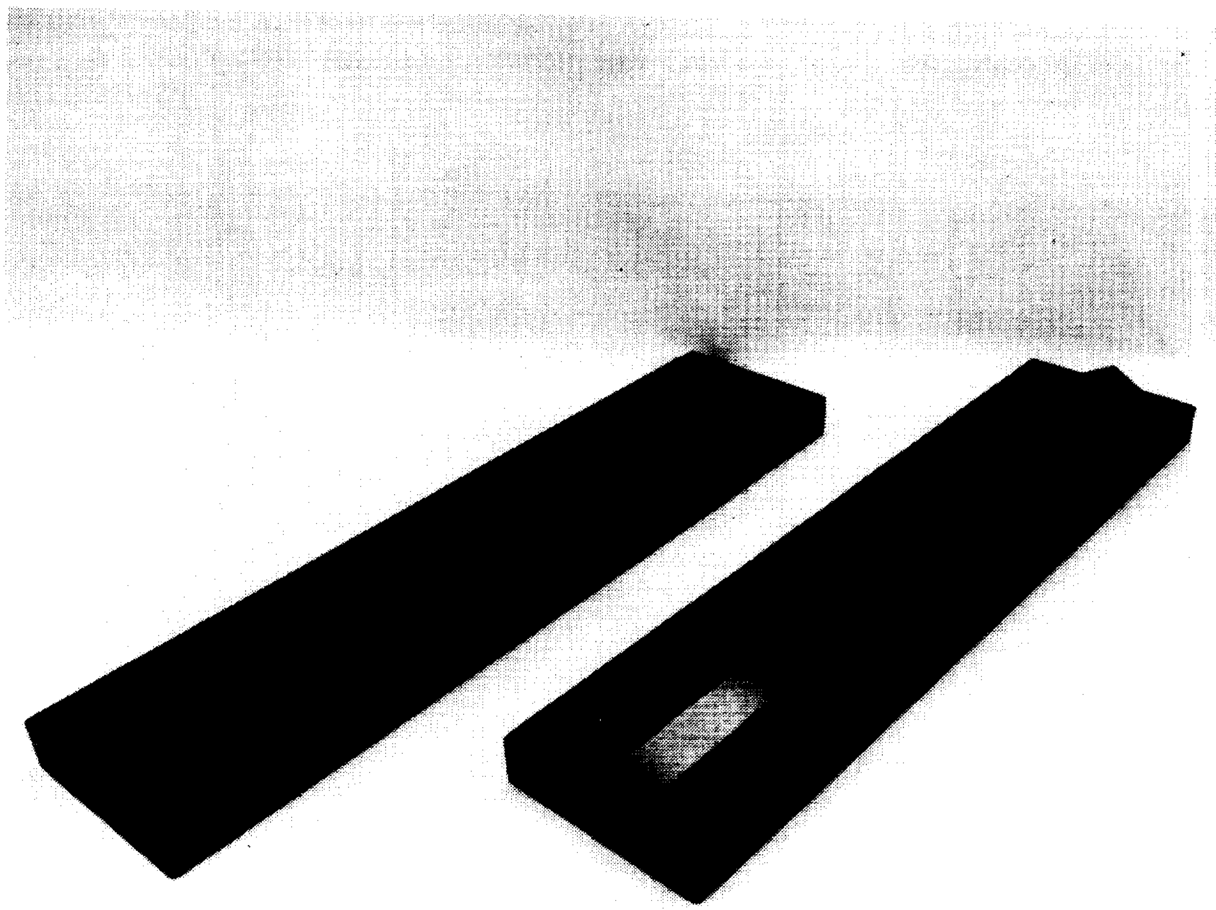
It was recognized that these mandrels are bulky and would act as heat sinks during autoclave consolidation of the Y-spar preforms. An optimum tooling approach would be to use integrally heated and cooled monolithic graphite mandrels. The cost of this type of tooling for the consolidation of three Y-spars was inconsistent with the scope of the subject program. It was considered more cost effective to use the relatively less expensive solid graphite tools with relatively longer autoclave consolidation cycles.

The figure below shows the matched monolithic graphite mandrels fabricated by Coast Composites, Inc. The tools are configured to accommodate Y-spar preforms with a web height of 10.70 in.



UPPER AND LOWER BASE PLATES

Monolithic graphite upper and lower base plates were provided to ensure optimum consolidation/forming of the Y and 90-degree flanges.



WOVEN 0°/90° Y-SPAR PREFORMS

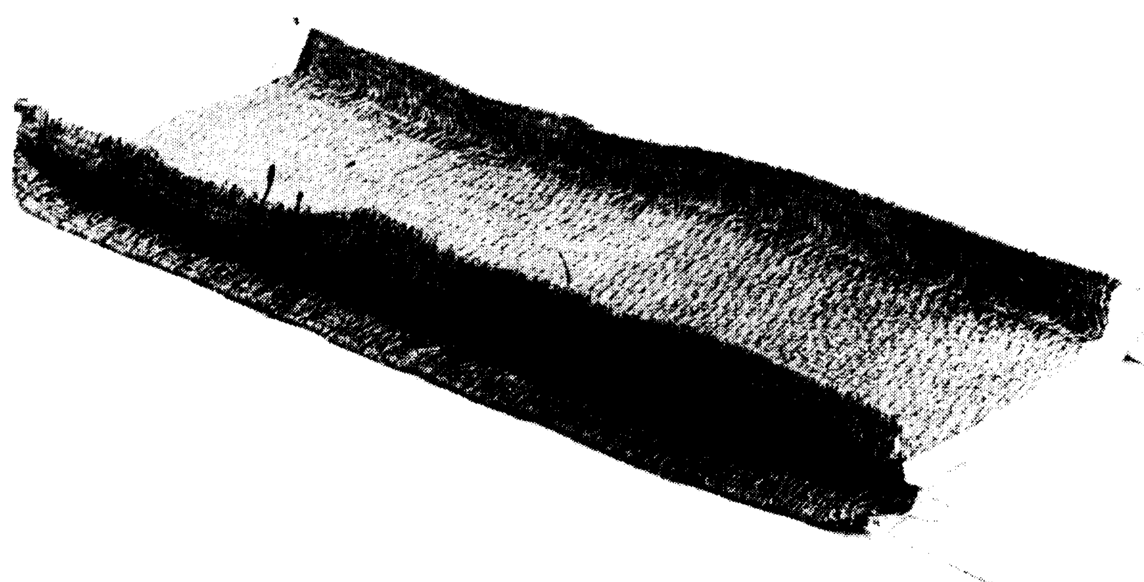
Three sections of 0°/90° Y-spar preforms (each in excess of 40 in. long) were woven by TTI using the web and flange architectures previously described. A shorter section of 0°/90° Y-spar preform was also provided for physical and mechanical properties characterization testing.

Visual inspection of the 0°/90° Y-spar carcasses revealed the presence of floaters (maximum length 2.5 in.) in the radii of the Y and 90-degree flanges. The floaters were due primarily to the use of 12K tows and the requirement that only 5 percent of the fiber reinforcement be used in the Z direction of the preform. The length and number of floaters could be reduced significantly by the use of 3K tows which would provide more fiber ends per in. (but at increased cost) in the Z direction to tie down the Y direction fibers. The percentage of fiber reinforcement in the Z direction could also be increased but with a corresponding reduction of in-plane mechanical properties.

Potential reduction in mechanical properties of the consolidated Y-spar due to the presence of floaters in the radii of those elements was minimized by the subsequent stitching operation for installation of 45°/135° fabric reinforcement.

The radii of the preforms (with 45°/135° fabric reinforcement located on the 0°/90° Y-spar carcasses) were stitched with three rows of stitches using an 1/8 in. row spacing. The remainder of the preforms were stitched using a cross hatch pattern with 1/4 in. row spacings.

The floaters are visible in the radius of the section of 0°/90° woven preform shown in the figure below.



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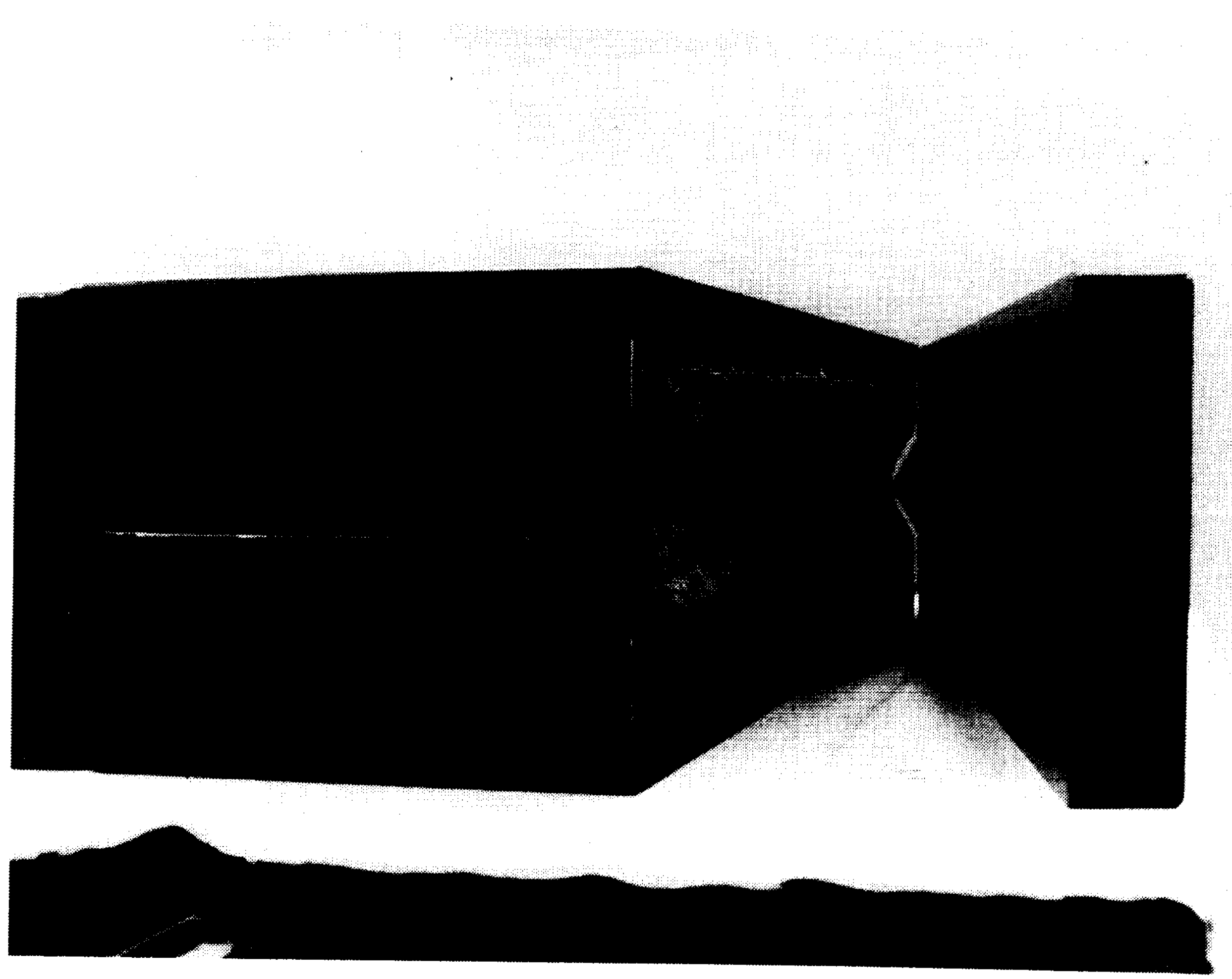
CONSOLIDATION OF SECTION OF 0°/90° Y-SPAR PREFORM

A section of woven commingled AS4/PEEK 150g 0°/90° Y-spar preform was consolidated for 120 minutes at 720 ±10°F and 200 psi in an autoclave. The section of preform was consolidated using the monolithic graphite tooling and the autoclave/vacuum bag process previously described for the commingled AS4/PPS 0°/90° I-beams.

The consolidated section of woven AS4/PEEK 150g 0°/90° Y-spar preform was visually excellent. A 16 in. (0° direction) by 6 in. section of the Y-spar web was cut and inspected using ultrasonic NDI. The section of Y-spar web was free of sonic discrepancies. The average thickness of the consolidated panel was 0.140 in. Based on an as-received web thickness of 0.340 in., the percentage reduction in preform thickness was 58.5 percent.

Resin content and fiber volume determinations for the consolidated panel were

Percent Fiber Volume:	55.8%
Percent Resin Volume:	43.6%
Percent Void Volume:	0.6%



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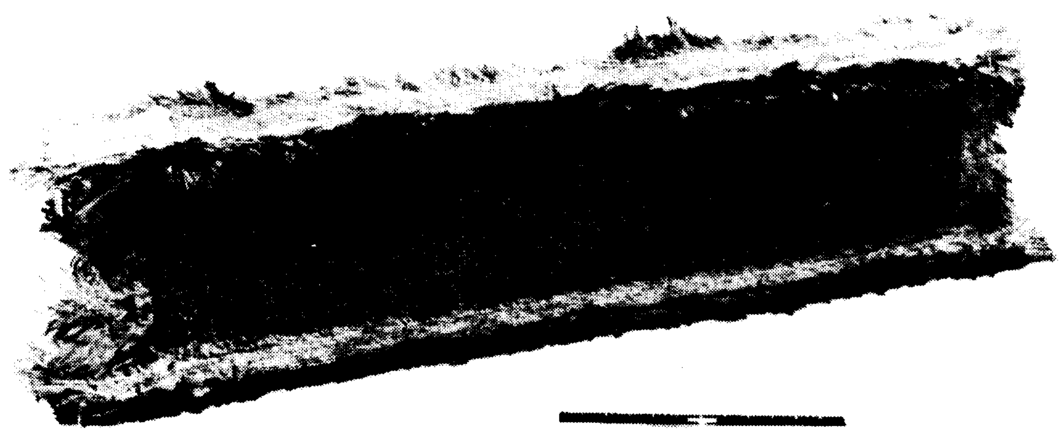
WOVEN/STITCHED Y-SPAR PREFORM

Required 45°/135° fabric reinforcement was stitched to the woven 0°/90° commingled AS4/PEEK 150g Y-spar carcasses by SMX. As stated earlier, the preform was stitched using a cross hatch pattern with a row spacing of 1/4 in. In the radius areas, however, three rows of stitches were installed with a row spacing of 1/8 in.

It was intended that the preform be stitched using only Toray T-900-100 50A carbon fiber; SMX, however, required the use of fiberglass loops in combination with the carbon fiber thread in the radii and flanges of the preform. The carbon stitching equipment was too large to be conveniently used for the Y-spar flanges. In addition, this equipment lacked the sensitive feeding characteristics required for the flange stitching operation. Ultimately, the Y-spar preform flanges were stitched manually.



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CONSOLIDATION OF Y-SPAR PREFORM S/N-1 Near Net Trimming

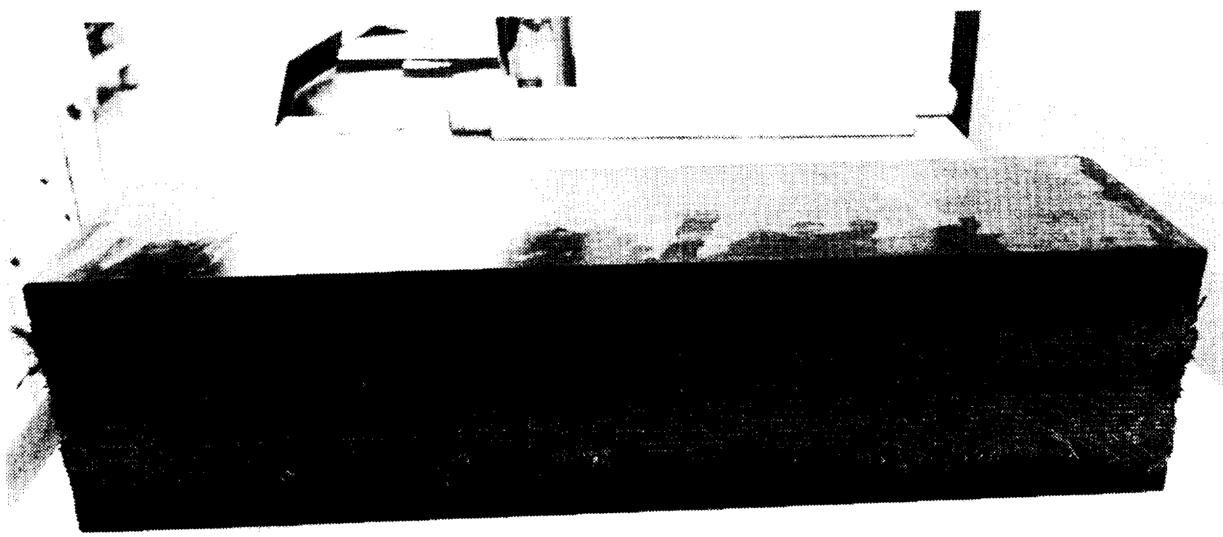
D19B8220-13 Y-spar Preforms S/N -2 and -3 will be fabricated using the procedures to be described for Preform S/N-1.

Preform S/N-1 was installed on one of the tool mandrels and manually trimmed to near net dimensions using scissors.

INSTALLATION OF Y-SPAR PREFORM BETWEEN TOOLING MANDRELS

The Y-spar preform is installed between the matched monolithic graphite mandrels. The mandrels are undercut to accommodate the flanges of the Y-spar preform. The width of each of these undercut surfaces is oversize with respect to the final trim of the corresponding Y-spar flange.

The 90° flange of Y-spar Preform S/N-3, as shown in the figure below, has been trimmed to a near net dimension that accommodates that of the tool but is larger than the final dimension of the consolidated Y-spar.



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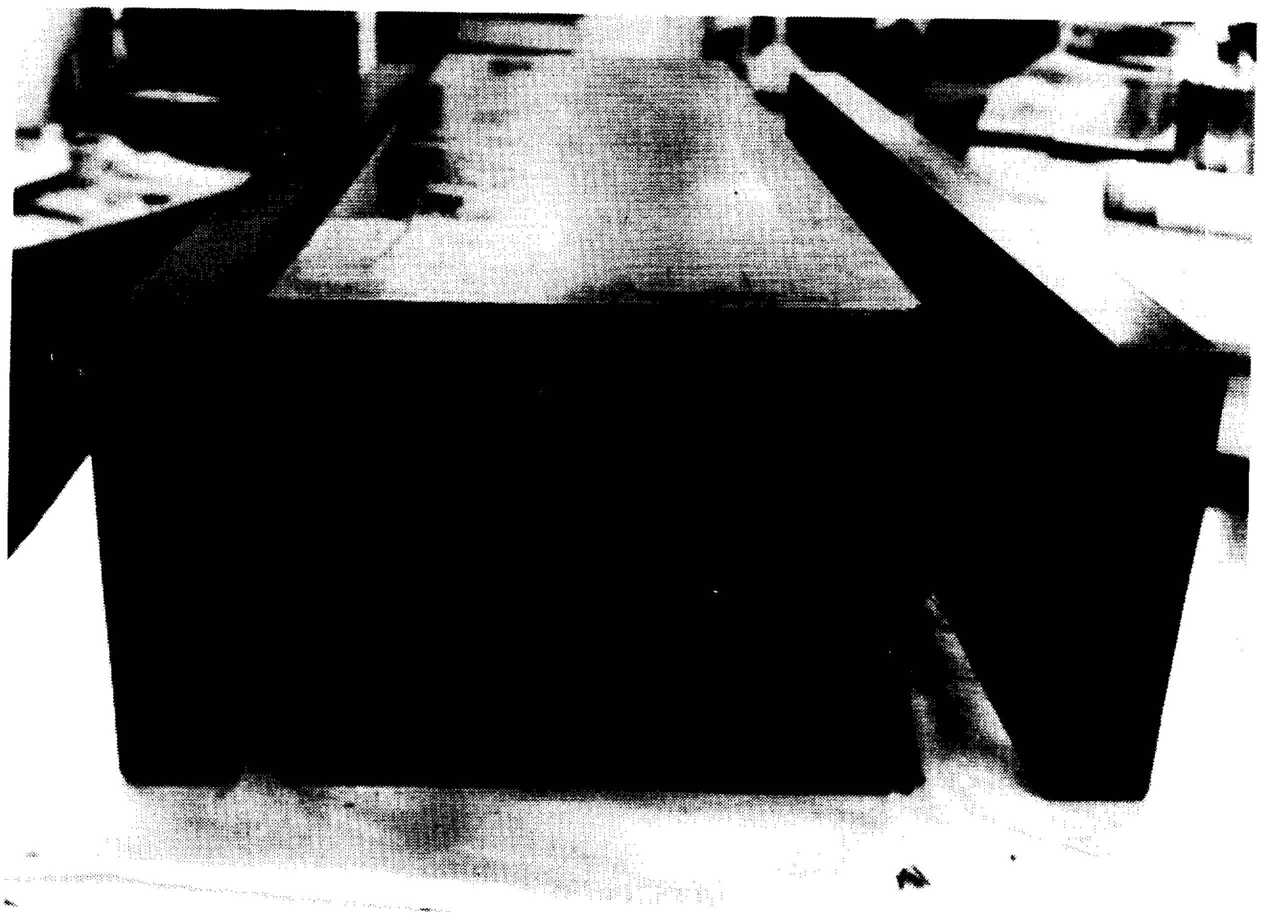
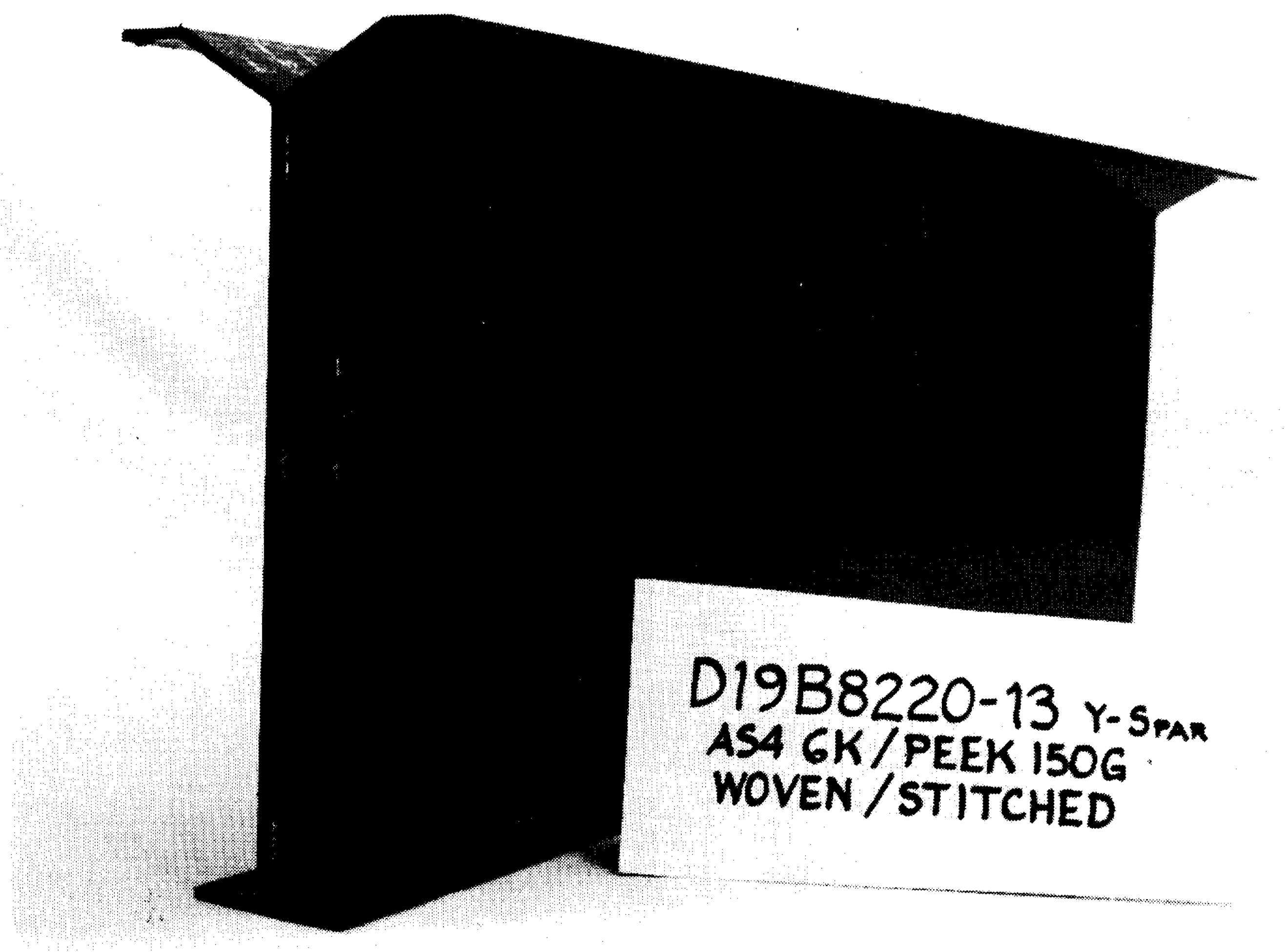
INSTALLATION OF UPPER AND LOWER TOOLING PLATES

The near net trimmed Y-spar preform is installed between the matched mandrels. As shown in the figure below, the mandrels are positioned on the autoclave table so that the web of the part is parallel to the surface of the autoclave table. The upper and lower closure plates are then placed against the outboard surfaces of the preform Y and 90° flanges.



CONSOLIDATED (TRIMMED) Y-SPAR

The consolidated commingled AS4/PEEK 150g woven/stitched Y-spar was consolidated for 4 hours at 720±10°F, 160 psi fluid pressure plus full vacuum bag pressure. The prolonged hold at elevated temperature was required to accommodate the relatively large mass of the monolithic graphite mandrels which acted as heat sinks. In production, integrally heated and cooled tools would be used in combination with cold-wall autoclave procedures to provide a low-cost consolidation methodology. The high-temperature autoclave run was performed without any processing difficulties. The consolidated Y-spar was visually acceptable. Tap testing indicated a satisfactory consolidation.



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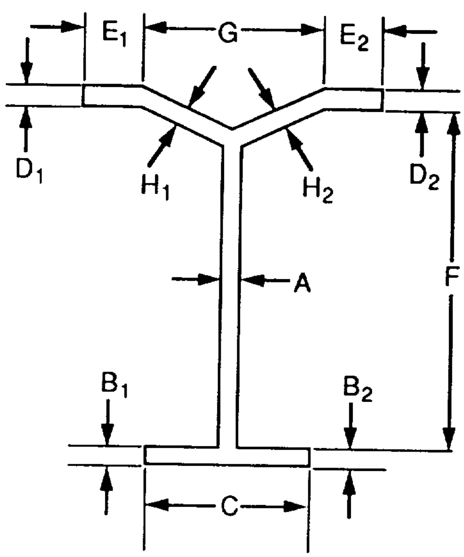
TARGET, PREFORM & FINAL PART DIMENSIONS OF WOVEN COMMINGLED 3-D AS4/APC-2 Y-SPAR 1

The results of a preliminary dimensional inspection (the Y-spar will be sectioned to provide in-depth dimensional analysis) are presented below. Target values for the consolidated oversize Y-spars were provided by TTI. These values are estimates based on corrective inputs to their Framework computer program to accommodate the greater mass of AS4 fiber used to fabricate the Y-spar preforms. (The Framework is an interactive computer program that predicts the thickness of a consolidated preform based on the physical characteristics of the fibers used in the fill and warp directions of the preform.) The table also provides initial preform thickness values and corresponding consolidated thickness measurements. Comparison of the last two measurement groups permitted calculation of percent reduction in preform thickness values.

Target values for the web (A) and outer sections of the Y-spar flanges (D_1 and D_2) were essentially realized by the consolidated structure. Target values for the inner sections of the Y-spar flanges (H_1 and H_2) and the 90° flanges (B_1 and B_2) were not achieved. Indeed, the consolidated thicknesses for the two inner Y-spar flanges were considerably different (0.170 vs 0.158 in.) indicating that the corresponding side mandrel may have hung up during consolidation. Percent consolidation values for these flanges support this hypothesis (H_1 vs H_2, 53.6 vs 60.2% and D_1 vs D_2, 58.2 vs 64.5%).

Woven Commingled 3-D AS4/APC-2 Y-Spar S/N-1

Target, Preform & Final Part Dimensions



	TARGET (IN.)	PREFORM (IN.)	CONS. Y-SPAR (IN.)	CONS. (%)
A	0.215	0.463	0.242	47.7
B_1	0.151	0.381	0.134	64.8
B_2	0.151	0.350	0.127	63.7
C	2.50	2.74	2.50	N/A
D_1	0.151	0.366	0.156	58.2
D_2	0.151	0.397	0.141	64.5
E_1	1.25	—	0.90	—
E_2	1.25	—	1.00	—
F	11.65	—	11.65	—
G	3.40	—	3.34	—
H_1	0.151	0.366	0.170	53.6
H_2	0.151	0.397	0.158	60.2

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