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RESEARCH CORPORATION

CARPINTERIA, CALIFORNIA

LARGE DIAMETER ASTROMAST DEVELOPMENT, PHASE I FINAL REPORT

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SECTION 1

INTRODUCTION

Coilable-longeron lattice columns called Astromasts® have been manufactured by Astro Research Corporation (Astro) for a variety of spacecraft missions. These flight structures have varied in diameter from 0.2 to 0.5 meter (9 to 19 in.), and the longest Astromast of this type deploys to a length of 30 meters (100 feet). Astro has also developed a double-laced diagonal Astromast design referred to as the Supermast™ which, because it has shorter baylengths than an Astromast, is approximately four times as strong. The longeron cross section and composite material selection for these structures are limited by the maximum strain associated with stowage and deployment. As a result, future requirements for deployable columns with high stiffness and strength require the development of both structures in larger diameters.

Astro is under contract with NASA Marshall Space Flight Center (MSFC) to develop large diameter Astromast technology. This report describes the design, development, and manufacture of a 6.1-m-long (20-ft), 0.75-m-diameter (30-in.), double-laced diagonal version of the Astromast. The manufacture of this model completes Phase I of this program. A 15-m-long (50-ft) model will be manufactured during Phase II which will be completed by the end of 1983.

Astromast®, U.S. and foreign patents
Supermast™, U.S. patent

SECTION 2
PROGRAM SUMMARY

2.1 DESIGN APPROACH

The purposes of this study are to develop large diameter Astromast technology and to manufacture two structural models. Since the potential applications in space involve a variety of structural performance requirements, Astro decided to attempt a design which would maximize all performance characteristics of a double-laced diagonal Astromast with a diameter of 0.75 m (30 in.). Previous Astromast designs, built to specific design requirements for each mission, have not been required to maximize all of these characteristics which include:

- o Highest stiffness-to-weight ratio for the fiber-reinforced composites
- o Maximum mast stiffness (axial, flexural, and torsional)
- o Maximum strength (bending, shear, torsion)

Experience gained in earlier Astromast projects was to be used to upscale existing designs properly to the larger dimensions of a 0.75-m-diameter (30-in.), self-deploying mast.

2.2 STUDY PLAN

The Phase I study plan originally consisted of two major activities: a longeron materials investigation and the manufacture of a 6.1-m-long (20-ft) model. Astro recognized that there were a number of high risk factors involved in the design approach. As a result, an internally funded IR&D project was established to manufacture a 3.8-m-long (12-ft) development model prior to the fabrication of the 6.1-m-long (20-ft) engineering model for NASA MSFC. In summary, the following tasks have been accomplished during Phase I:

- o A parametric design study
- o Pultrusion of three different longeron materials
- o Evaluation of longeron materials
- o Detailed design
- o Fabrication and testing of component parts

- Fabrication and testing of a 3.8-m (12-ft) development model
- Reinvestigation of the longeron design
- Fabrication and testing of a 6.1-m (20-ft) engineering model

2.3 PARAMETRIC DESIGN STUDY

An analytical parametric design study was conducted at the beginning of the program to establish preliminary sizing for Astromast designs incorporating several different composite longeron materials. The results of the study predicted the relative performance of masts employing these longerons materials. Both single- and double-laced diagonal configurations were considered. It was assumed that the longeron cross section would be square and of a maximum thickness established by the stowed strain of fiber material. Three fibers were considered for the unidirectional composite longeron material:

- S-2 fiberglass
- High-elongation graphite
- Hybrid combination of both fibers (see Figure 1)

In the case of the hybrid combination, it was assumed that the graphite fibers would be sandwiched between two layers of S-glass in order to maximize the strain capability of the longeron in one bending direction.

The results of this parametric study have been reported in Reference 1. The results indicate that S-glass is superior to graphite in this application because of its much higher strain limit. The analysis also shows that the hybrid design, as compared to the S-glass alone, would improve the stiffness of the masts if the sandwich material allowed the same strain limit as the S-glass alone.

2.4 PULTRUSION AND EVALUATION OF LONGERON MATERIALS

The pultrusion and evaluation of longeron materials are discussed in detail in Section 3 of this report. The hybrid longeron material was not acceptable because of a low strain limit. S-glass was selected for use in the longerons.

2.5 DETAILED DESIGN

A detailed design for the 0.75-m-diameter (30-in.) Astromast was developed using the largest allowable longeron and diagonal thicknesses, as discussed in Reference 1. Details of fittings were established on the basis of Astro's past experience in the design of single- and double-laced diagonal versions of the Astromast. A quasi-square longeron was selected to maximize strength and stiffness.

2.6 FABRICATION AND TESTING OF COMPONENT PARTS

Samples of each of the fittings were manufactured and tested as described in Section 4 of this report.

2.7 DEVELOPMENT MODEL

A 3.8-m-long (12-ft) development model was manufactured and retracted as described in Section 4 of this report. Two longerons failed before the mast was completely retracted.

2.8 REINVESTIGATION OF THE LONGERON DESIGN

As an extension of the IR&D project for the development model, Astro conducted an extensive investigation of the longeron material and design as summarized in Section 4 of this report. It was concluded that the square cross section, as compared with a round cross section, significantly increased the strain when the longeron is subject to the combination of bending and twisting which occurs in the transition section during deployment or retraction. It was also established that the longeron performance under these conditions could be improved by increasing the adhesive thickness at the pivot fittings.

2.9 ENGINEERING MODEL

As a result of the investigation described above, several design changes were incorporated in the 6.1-m-long (20-ft) engineering model. The longeron cross section was changed to an octagonal shape which could be fabricated by grinding the corners of the quasi-square pultruded material. In addition, the bond line thickness was increased at each pivot fitting. The original batten design was retained. This resulted in a higher ratio of batten stiffness to longeron stiffness than originally intended.

The mast was again retracted and deployed. The interference between the diagonal ball ends and the cups was reduced except at each end of the mast. We observed that substantial static friction existed between the bowed diagonals and battens. This tends to restrain the diagonals near the ends in a position where they cannot deploy properly. These same static friction effects counter the self-deploying forces in the mast, and it was necessary to apply torque to erect the ends of the mast.

2.10 DESIGN CHANGES

In order to ensure that the engineering model would self-deploy without damage to diagonal elements, it was necessary to reduce the stiffness of both diagonal and batten members. In order to learn as much as possible about the influence of these changes on the deployment and retraction, Astro made the changes in several steps and tested the mast between each step. The following configurations were tested:

- A single-laced diagonal configuration without changing the design of either the diagonals or battens - not self-deploying
- A single-laced diagonal configuration with three battens of reduced stiffness at each end - not self-deploying
- A single-laced diagonal configuration as above but with the diagonals reduced in diameter from 5.7 to 3.7 mm (0.22 to 0.145 in.), yokes of end battens modified to minimize interference with diagonals - self-deploying
- A double-laced configuration, as above - not self-deploying
- A double-laced configuration with all battens reduced to 50 percent of their original stiffness, end battens reduced to 25 percent of their original stiffness - self-deploying

The properties of the final version of the engineering model are presented in Table 1.

SECTION 3
MATERIAL SELECTION

3.1 CRITERIA

Because of the high-strain requirement, battens and diagonals were made of S-glass/epoxy composites. The battens would lend themselves to a hybrid S-glass/graphite combination; however, since the pertinent feature of the batten is its bending stiffness, as outlined in Reference 1, the relatively small gain in stiffness-to-weight ratio does not justify the increased manufacturing complexity and costs. The diagonals with their ball joints must be free to rotate about their axis and are, thus, preferably made from circular rods.

A circular cross section was also chosen for the battens because of manufacturing considerations. Circular dies for pultrusions are easier to fabricate and, thus, less expensive. Also, batten material can be centerless ground to a desired diameter with high precision. In fact, the pultruded batten material was centerless ground to a smaller diameter in order to eliminate a rough, resin-starved surface.

Pultrusion was selected as the manufacturing process for all the unidirectional composites because it offers better uniformity of the parts and better economy for medium to large quantities than a mold layup process.

In the past, when longerons have been produced by layup methods, either their length and cross section were limited because of tooling and autoclave size or excessive warping, or, as in the case of mandrel winding, a less efficient cross section had to be utilized in order to overcome stability problems inherent in precurved longeron material.

Even with the pultrusion process, the feasibility of larger cross section was in doubt. Because the resin must cure in a short time, uniform temperature and pressure over the whole cross section are essential - requirements which become more difficult to meet with increasing size of the pultruded cross section.

Therefore, one manufacturer was assigned the task to develop his pultrusion technique such as to produce longeron material of quasi-square cross section with a thickness of up to 12 mm (0.5 inch). S-glass fibers were to be combined with different matrix resins (vinyl ester, epoxy), and a glass/graphite sandwich using epoxy resin was to be produced in such a way that the graphite fibers would occupy the center third of the cross section. The efforts of Composite Products Technology Center (CPTC), a division of Goldsworthy Engineering, Inc., were compiled in a report which is presented in Appendix A.

3.2 MATERIAL EVALUATION

The three fiber/matrix combinations which CPTC supplied were evaluated by Astro for potential use as longeron material. Air Logistics manufactured the circular pultrusions for the battens and diagonals. Dimensions and material composition of all pultrusions are listed in Table 2.

A series of three tests was performed on each material and the results are compared. The tests were:

- o Bending to failure (ultimate strain)
- o Four-point bending (flexural modulus)
- o Burnout (percentage of fiber content)

The results of these tests are presented in Table 3. A brief description of each test procedure will be given, along with comments regarding each material as appropriate.

3.2.1 <u>Bending to Failure</u>

A typical test setup for longeron samples is shown in Figure 2. This test consisted of bending specimens of each material around successively smaller circular mandrels. A hydraulic bench press was used to apply the load smoothly. Mandrel sizes ranged from 356-mm (14-in.) radius to 127-mm (5-in.) radius in 1-inch increments representing strains of 1.5 to 4.2 percent with the 11.1-mm (0.437-in.) longeron material. Support points were placed far enough apart to avoid local shear failure. The specimens were cut long enough to provide considerable overhang and, thus, to avoid setup-induced neutral axis delaminations. Nevertheless, the S-glass with vinyl ester as matrix failed exactly in this mode, as shown in Figure 3. Representative failure modes for the other specimens are shown in Figures 4 and 5. The ultimate bending strain was computed by the well known relationship

$$\varepsilon = \frac{t}{(t + 2R)}$$

where t is the thickness of the specimen, and R is the radius of the mandrel.

3.2.2 Four-Point Bending

Astro's test fixture, SK 2241, is shown in Figure 6. The loads are applied by dead weights, and the deformation of the sample is measured at midspan by a dial indicator. A detailed explanation of its use and a sample calculation are presented in Appendix B. The primary data of loads and deflections were used to calculate the flexural modulus of elasticity. Because the data showed a slight nonlinearity when plotted, a best-fit straight line approximation was made using "CV," a curve-fitting program available on ROM for a Hewlett-Packard 41C calculator. Load-versus-deflection plots for two longeron samples are shown in Figure 7.

3.2.3 Burnout

This test was conducted by measuring the exact dimensions and weight of a sample of the composite and then placing it into a furnace at a temperature sufficient to burn out the resin leaving the fiber unaffected. This allows determination of the fiber content by weight as well as the fiber content by volume when the density of the glass is known. Results of these tests are shown in Table 3. The fiber content of both the vinyl ester/glass and epoxy/glass samples was slightly higher than that in longeron materials used by Astro previously. Unfortunately, this method cannot be applied for graphite/epoxy composites because the fibers oxidize, as well as the resin.

3.3 CHOICE OF MATERIAL

Of the three materials considered for use as longerons, S-glass/epoxy was chosen. It exhibited not only the best ultimate strain but also exceeded the hybrid glass/graphite composite in stiffness when the latter was bend tested in its weaker direction. The anisotropic characteristics of the hybrid composite were an additional concern; the material behaves similar to one with isotropic properties but a rectangular cross section. In the transition from stowed to deployed configuration the longeron is subjected to bending about both neutral axes. This may lead to instability when the bending stiffness about one axis is considerably higher than in the other direction.

The S-glass/vinyl ester composite was eliminated because the resin exhibited too low a shear capability as represented by repeated delaminations along the neutral axis.

The S-glass/epoxy exhibited a peculiar feature also. Ultimate strain tests differed when measured shortly after fabrication and five months later. The implications of this aging are discussed in a later section.

SECTION 4
DEVELOPMENT MODEL

Because of an upscaling factor of more than 1.5 from existing designs and the use of maximum member sizes, it appeared prudent to build and test a single joint as well as a short development model of the mast before manufacturing the 6.1-m-long (20-ft) engineering model. A few cups and shortened diagonals were built and mounted in a representative manner to a test fixture. This allowed application of pull forces to the diagonals as if they were in the deployed configuration (see Figure 8). The joint was tested to destruction. In one case (see Figure 9) one diagonal pulled out of its terminal at 5520 N (1240 lb) applied load which corresponds to 3017 N (678 lb) per diagonal or 8.9 MPa (1290 psi) shear stress in the EA 934 adhesive, indicating poor bonding. The cup broke at a considerably higher applied load of 8230 N (1840 lb) without damage to the diagonals (see Figure 10). This result could be used to determine the ultimate shear strength of the mast as 12600 N (2840 lb) taking into account the double lacing, although this value is rather academic because a load of this amount could hardly be applied to the mast without damaging other parts.

Funded by Astro's internal research and development program, the development model was to incorporate all the features of the engineering model except its length which was 3.75 m (12 ft) or eight full baylengths. Table 1 lists the pertinent dimensions and performance values (in the first column as planned and in the second column as measured or as predicted based on the measurements made on the material). Figures 11 and 12 show the model as assembled in vertical position and cantilevered from its baseplate, respectively. A 3/16-inch-diameter steel cable was used as a control lanyard; it was attached to the center of the tip plate, routed through the center of the mast and the baseplate, over a pulley, and to a hand-operated winch.

During the first retraction attempt, the initial torque was applied manually to the tip plate, but as soon as the longeron started coiling, the lanyard was employed to continue retraction (see Figure 13). Although the lanyard force did not exceed 900 N (200 lbs) (as measured on a dynanometer at the tip plate), one of the longerons broke just below the third pivot from the top (see Figure 14). Shortly afterwards, a second longeron fractured at the same station. The mast was subsequently redeployed with manual assistance (see Figure 12), and although two longerons were fractured completely across their thickness, the mast still could sustain the lateral load of the tip plate weight of approximately 27 kg (60 lb) as shown in Figure 15.

As a result of this failure, the longeron material was subjected to a series of additional strength tests, and the strains in the transition section of the longerons were analyzed more precisely. It was found that:

- The original strain limit (measured shortly after delivery from the manufacturer) could not be reached anymore. In fact, it was reduced to about 75 percent of the original value.
- When tested with a pivot bonded on, the strain limit was reduced even further to 43 percent of the originally measured value.
- With a glue line increased from 0.18 to 0.43 mm (0.007 to 0.017 in.), 50 percent of the originally measured strain value could be reached.
- Changing the adhesive from Hysol EA 934 A/B to EA 9320 increased the strain limit once more to about 63 percent of the original value.

Additional tests were performed with the longeron samples being wrapped helically around circular tubes in order to establish failure criteria for combined bending and torsion. The results are plotted as an interaction diagram with ultimate shear angle γ versus ultimate bending strain ε in Figure 16. In the same figure, strain combinations are plotted as they have been calculated for the transition section of a quasi-square longeron and an octagonal longeron of the same thickness. The arrows indicate the direction along the longeron from stowed to deployed configuration while the subscripts 1, 2, and 3 refer to the location of the strains in the cross section as indicated by the inset. Test points of longeron material used in previous Astromast designs are included in Figure 16 for reference and comparison purposes.

A comparison between longerons used in the development model and those used in previous Astromasts is presented in Table 4. Subsequent modifications to the longeron design are discussed in the next section.

SECTION 5

ENGINEERING MODEL

5.1 DESIGN MODIFICATIONS

The design of the 6.1-m-long (20-ft) engineering model was modified as a result of the experience with the development model. The following changes were made to the design before fabrication:

- o The quasi-square longeron blanks were gound to an octagonal cross section of the same thickness of 11.1 mm (0.437 in.)
- o The pivots were modified by replacing the square broach hole with a circular hole of 12.3-mm diameter (31/64-in.) and increasing the chamfer from 0.5 to 1.0 mm (0.02 to 0.04 in.).
- o Hysol EA 9320 was substituted for EA 934 A/B as bonding adhesive for the longeron fittings.

Obviously, the major modification is the change of the cross-sectional shape of the longerons. This reduces not only the strain level in the transition section but also the axial and flexural stiffness of the longeron. The actual mast performance is, therefore, also reduced as follows:

- o Axial and bending stiffness by a factor of 0.83
- o Bending and compression strength which rely on the bending stiffness of the longeron (buckling) by a factor of 0.69

In regards to the substitution of adhesives, it should be noted that the manufacturer (Dexter Hysol Division) lists a narrower service temperature range for EA 9320 (-55 to +110°C) than for EA 934 A/B (-260 to +175°C). However, the epoxy used in the longeron material has an even lower heat resistance of 90 to 100°C depending on the mixture ratio of the catalyst, and the pultruded material of Air Logistics should not be exposed to temperatures above 90°C when it is strained as in the stowed mast.

5.2 RETRACTION AND DEPLOYMENT TESTS

The engineering model was successfully retracted without the problems experienced with the development model. However, during deployment, interference was observed between the diagonal ball ends and the cups, and several diagonals were broken at each end of the mast. The aluminum washers behind the cups were also distorted.

The mast was disassembled, and the following changes were made:

- o The cups were modified to provide more space for the right-hand diagonal terminals when they have to rotate from the stowed to deployed configuration.
- o The special washers on the back of the cup and the keeper plates at the end clevises were replaced with hardened stainless steel (410) washers and plates.

The mast was again retracted and deployed. The modification to the cups substantially eliminated the interference between the diagonals and the cups except at the end of the mast. It was observed that the very stiff diagonals were developing substantial static friction loads among themselves and the battens. This condition prevented the diagonals from moving to a position where they would not be damaged by the batten yoke fittings. These same strain friction forces were sufficient to overcome the self-deploying forces of the mast. Photographs of the fully deployed and fully retracted mast appear in Figures 17 through 20.

It became apparent that two design changes were necessary in order to ensure satisfactory self-deploymennt of the mast:

- o The diagonals must be reduced in diameter to a size that is closer to the scale used in the past (they were originally about twice that diameter).
- o The batten stiffness must be reduced, at least at the ends of the mast, to increase the self-deploying force.

In order to learn as much as possible about the influence of these changes on the retraction and deployment, Astro made the changes in several steps and tested the mast between each step. The following configurations were tested:

- o The mast was disassembled so that every other batten and corresponding set of diagonals could be removed. The reassembled single-laced Astromast was tested for deployment and retraction. Like the double-laced version, this mast would not self-deploy, and there were indications of considerable interference between the diagonals and the battens at each end of the mast during deployment and retraction.
- o The last three battens at each end were modified to reduce their stiffness by 50 percent, and the mast was retested with the same results.

- All diagonals were replaced by diagonals of a smaller diameter, 3.7 instead of 5.7 mm, and the yokes of the end batten assemblies were modified to minimize interference with the diagonals. This version of the single-laced Astromast self-deployed and packaged satisfactorily.
- The mast was reassembled as a double-laced diagonal Astromast with the same size members as above. The mast would not self-deploy the last bays.
- The batten assemblies were removed and modified so that all central batten assemblies were reduced in stiffness by 50 percent compared with the original design and that the end battens were reduced to 25 percent of the original stiffness. This version of the Supermast was self-deploying and packaged satisfactorily.

5.3 PREDICTED PERFORMANCE OF THE ENGINEERING MODEL

The revised values of predicted performance are listed in the third column of Table 1. Thanks to the much higher-than-nominal modulus of the longerons, the bending stiffness of the mast with reduced longeron cross section should be equal the originally planned value. The shear and torsional properties were reduced due to smaller diagonals. The reduction in cross sections also lowered the mass per unit length to 3.32 kg/m.

SECTION 6
CONCLUSIONS AND FUTURE DEVELOPMENT

The design at its present stage still has to be tested extensively to verify its performance. Future development will be aimed at the improvement of the strain margin for the longerons. The high fiber content of the present longeron material appears to render it very sensitive to local shear forces, a characteristic not observed on other longeron material which appeared, in general, of lower quality than the quasi-square material produced by CPTC. Also, the apparent decrease in strain capacity associated with aging needs verification. Inquiries with the resin manufacturer disclosed that the amount of catalyst used may affect the long-time curing properties of the composite. CPTC indicated that to achieve a more flexible composite, 5 pph of catalyst were used instead of the normal 3 pph. Shell maintains that as high as 12 pph of catalyst are feasible to increase flexibility.

The experience gained thus far with the resin system suggests that fiber content and catalyst percentage are two independent variables, each capable of affecting the developed properties of the final product significantly. For this reason, in Phase II we plan to evaluate enough combinative samples to establish both the independent effects, as well as the interactive effects of each variable. This could be accomplished by varying the amount of fiber bundles (ends), e.g., from 91 to 83 for the quasi-square cross section, while varying the catalyst mixture ratio from 3 to 12 pph, thus establishing a matrix of sample variations. Testing of these samples in bending and bending/torsion combinations should shed light on this issue.

The final development of the 0.75-m-diameter (30-in.) Supermast will be achieved as a result of the modifications described in Section 5 and through further improvement of the longeron material as previously described. In addition, prior to the fabrication of the 15-m-long (50-ft) model for Phase II, a lanyard-controlled deployment and retraction system will be developed. In order to make the mast erect from one end, pushoff mechanisms will be installed on one endplate. These spring-loaded units will push out through the stack of battens by applying a force at each of the pivot fittings located at the first half bay. The retraction system will consist of three bridles connected to the central lanyard. The bridles will be attached to the mast one baylength from the tip and will be capable of providing a torque to initiate the retraction process through a system of pulleys. Deployment and retraction will be controlled with a gear motor.

REFERENCES

1. Preiswerk, P.R.; and Knapp, K.: The Influence of Composite Material Selection on the Structural Performance of Continuous-Longeron Astromasts. Astro Research Corporation, ARC-TN-1108, 29 March 1982.

TABLE 1. PROPERTIES OF 0.75-M-DIAMETER SUPERMAST.

PARAMETER	AS PLANNED	DEVELOPMENT MODEL	ENGINEERING MODEL
Longeron cross section	Quasi-square	Quasi-square	Octagonal
Longeron material	S-2 glass/Shell RSL 387*	S-2glass/Shell RSL 387*	S-2 glass/Shell RSL 387*
Batten, diagonal material	S-glass/epoxy**	S-glass/epoxy**	S-glass/epoxy**
Nominal diameter, D	0.75 m	0.751 m	0.751 m
Baylength, ℓ	0.4688 m	0.4688 m	0.4688 m
Batten stiffness ratio, $\frac{(EI)_b}{(EI)_\ell}$	0.24	0.226	0.24
Longeron thickness, d	11.25 mm	11.11 mm	11.11 mm
Radius, r	1.25 mm	1.50 mm	- - -
Batten diameter, d_b	8.85 mm	8.78 mm	8.78 x 7.49 mm
Diagonal diameter, d_d	5.63 mm	5.74 mm	3.68 mm
Bending stiffness, $(EI)_m$	1.37×10^6 N-m^2	1.63×10^6 N-m^2	1.37×10^6 N-m^2
Shear stiffness, $(GA)_m$	2.08×10^6 N	2.67×10^6 N	1.1×10^6 N
Torsional stiffness $(GJ)_m$	0.146×10^6 N-m^2	0.188×10^6 N-m^2	0.077×10^6 N-m^2
Longeron buckling load, P_{cr}	12.1×10^3 N	13.86×10^3 N	9.50×10^3 N
Bending strength, M_{cr}	6800 N-m	7800 N-m	5350 N-m
Shear strength	1090 N	1220 N	887 N
Torsional strength	410 N-m	458 N-m	333 N-m
Linear mass	4.59 kg/m	4.01 kg/m	3.32 kg/m

*Pultruded by CPTC
**Pultruded by Air Logistics

TABLE 2. LONGERON, BATTEN, AND DIAGONAL MATERIALS EVALUATED FOR USE IN THE 0.75-m-DIAMETER SUPERMAST.

APPLICATION	CROSS SECTION	DIMENSIONS	FIBER	MATRIX RESIN	CATALYST	PULTRUDER
Longeron	Quasi-square	11.1 x 11.1 mm (0.437 x 0.437 in.) 1.50-mm radius (0.059 in.)	S-2 glass Owens Corning OCF463 AA250	Vinyl ester Ashland Hetron 902	0.5% Percadox 16-N +1.5% Benzoyl peroxide	CPTC
			S-2 glass	Epoxy Shell RSL 387	5% CA 9350	CPTC
			S-2 glass & graphite	Epoxy Shell RSL 387	CA 9350	CPTC
Batten	Circular	9.30-mm dia. (0.366 in.)	S-2 glass	Epoxy	Proprietary	Air Logistics
Diagonal	Circular	5.74-mm dia. (0.266 in.)	S-glass	Epoxy	Proprietary	Air Logistics
Diagonal	Circular	3.68-mm dia. (0.145 in.)	S-glass	Epoxy	Proprietary	Air Logistics

TABLE 3. LONGERON, BATTEN, AND DIAGONAL MATERIALS TEST RESULTS

APPLICATION	MATERIAL	BEND RADIUS MINIMUM (in.)	ULTIMATE STRAIN (%)	MODULUS OF ELASTICITY @0.01% STRAIN (GPa)	FIBER BY WEIGHT (%)	FIBER BY VOLUME (%)
Longeron	S-glass/vinyl ester	14	1.5	61.9	80.5	64.3
	S-2 glass/epoxy	6 (as received)	3.5	63.4	79.0	62.9
		8 (5 months later)	2.7			
	S-2 glass/graphite epoxy	10	2.1	54.3	N/A	N/A
		N/A		78.5	N/A	N/A
Batten	S-2 glass/epoxy	5.0	3.2	59.95	74.8	57.6
Diagonal	S-2 glass/epoxy	3.5	3.1	63.9	77.4	60.3

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TABLE 4. SUMMARY OF LONGERON PROPERTIES AND PERFORMANCE.

PROJECT	MOONBEAM	L-SAT	DRA (SPERRY)	18-IN. SUPERMAST	0.75-m SUPERMAST
Mast diameter, D (in.)	10	10	18.5	18	29.53
Baylength ratio, ℓ/D	0.5698	0.5698	0.56	0.645	0.625
Lacing type	Single	Single & double	Single	Double	Double
Deployment mode	Canister	Canister	Self	Self	Self
Longeron Data:					
Cross section, (in, in^2)	0.135 x 0.135	0.135 x 0.135	0.227 x 0.222	0.270 dia.	0.437 x 0.437
Type of fabrication	Mandrel layup and grinding	Mandrel layup and grinding	Mold layup and grinding	Pultruded	Pultruded
Prebend radius, R_o (in.)	16	23	∞	∞	∞
Material	S901/E792	FE-2/S-2	FE-2/S901		S-2/RSL 387
Manufacturer	U.C. Polymeric	Ferro Corp.	Ferro Corp.	Air Logistics	Goldsworthy
Density (lb/in^3)	0.0710	0.0741	0.0732	0.0705	0.0717
Fiber content (by weight), (%)	81.6 to 83.1	83.1	79.4	77.7	79.0
Flex modulus, E (psi)	7.9×10^6	8.46×10^6	8.9×10^6	8.3×10^6	9.06×10^6
Type of flex test	4-point bending	4-point bending	Buckling	3-point bending	4-point bending
ϵ_{stowed} (%)	0.93	1.03	1.20	1.49	1.46
ϵ_{max} (%)	>3.0	>3.3	>2.75	2.7	>3.5
ϵ/γ performance	0.93/0.83	2.05/1.66	1.84/0.65	2.1/0.66 2.18/1.09	1.65/1.08
References	Notebook 96 ST-81/12-1 ST-82/3-1 1011-5	1018-79 ST-81/12-1 ST-82/3-1	PRP's 3-ring binder	1002-50	1016

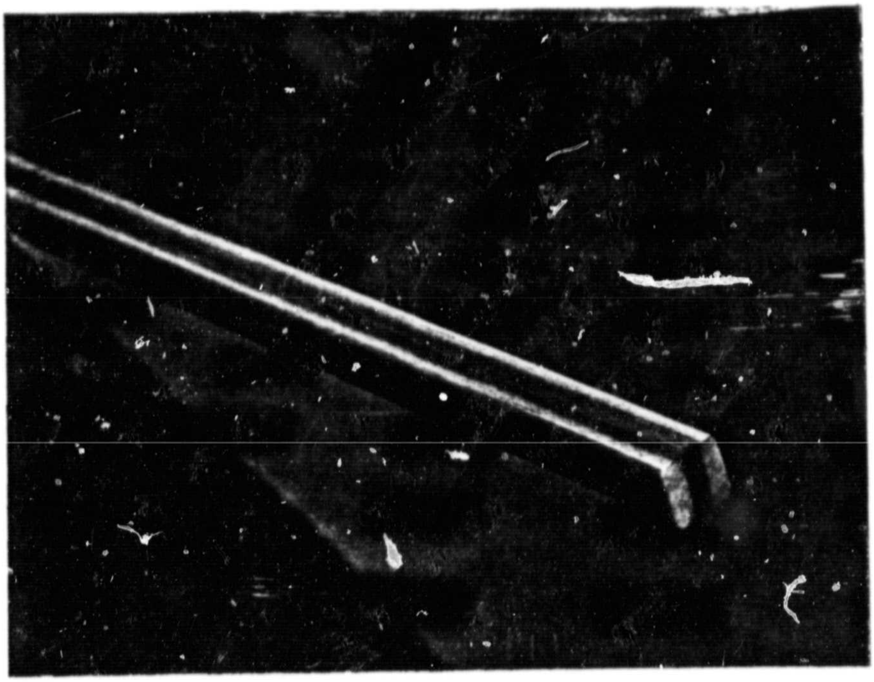

Figure 1. Hybrid longeron material, glass/graphite with epoxy matrix.

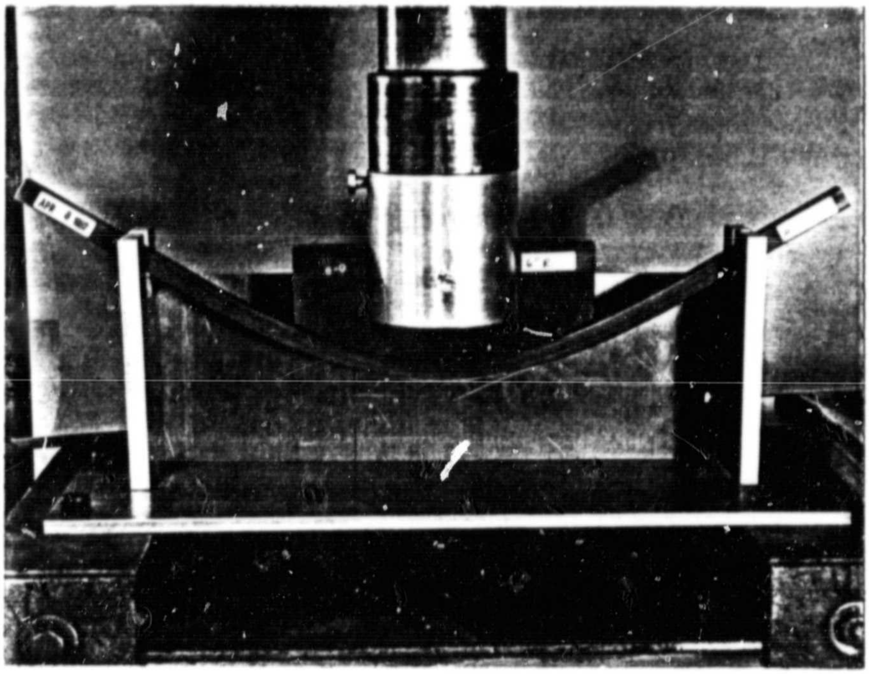

Figure 2. Ultimate strain test fixture (sample shown is S-glass/epoxy undergoir , i 3.51% strain).

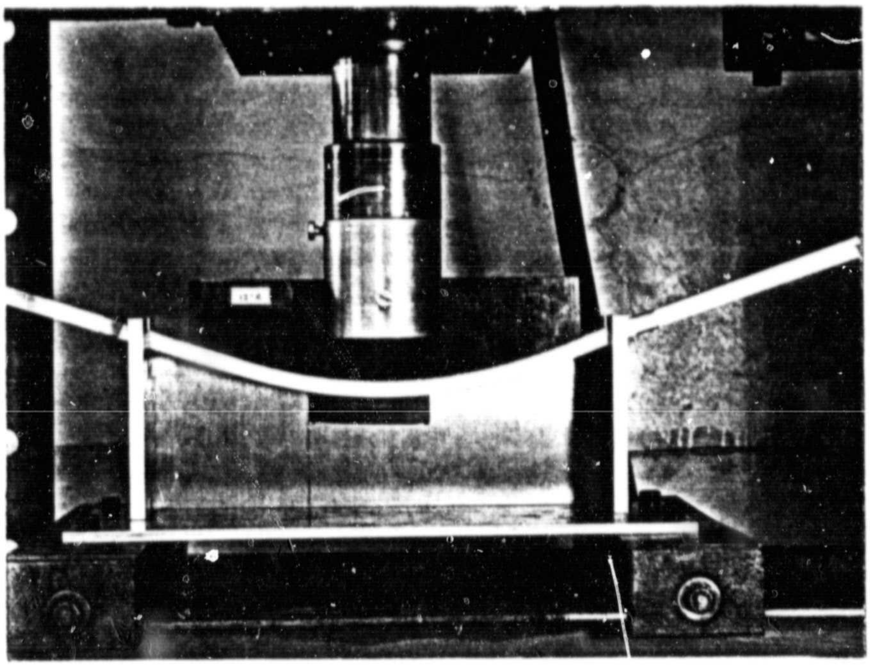

Figure 3. Vinyl ester failure mode (strain = 1.8%).

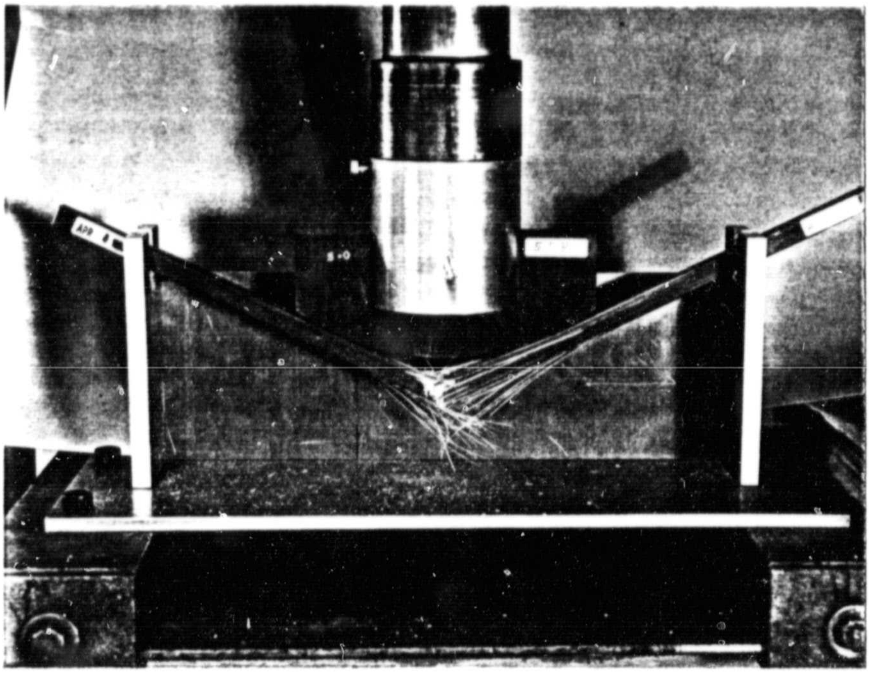

Figure 4. S-glass/epoxy failure mode (attempting 4.2% strain).

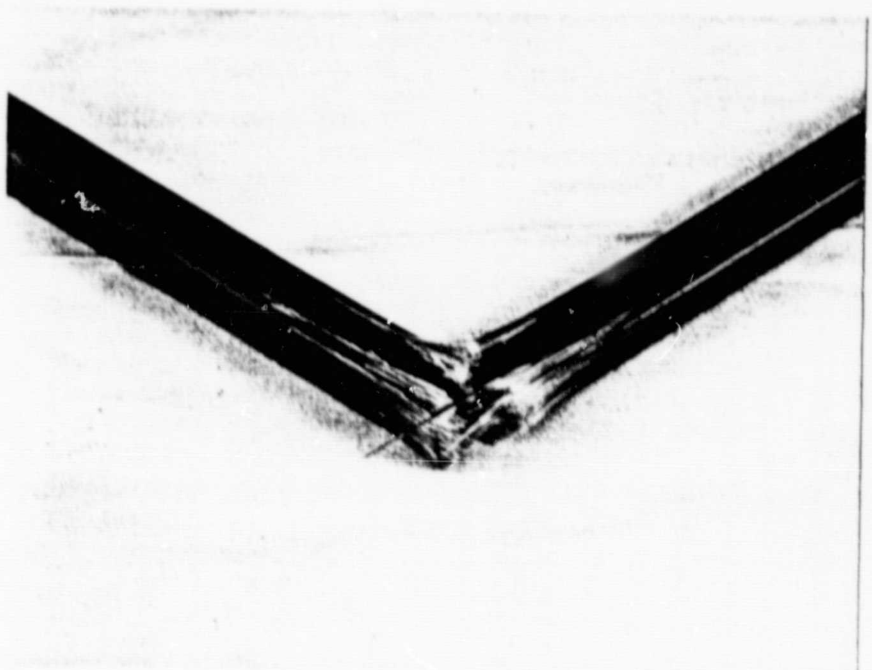

Figure 5. Hybrid (graphite/glass/epoxy) material failure mode.

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Figure 6. Four-point bending test fixture (SK2241).

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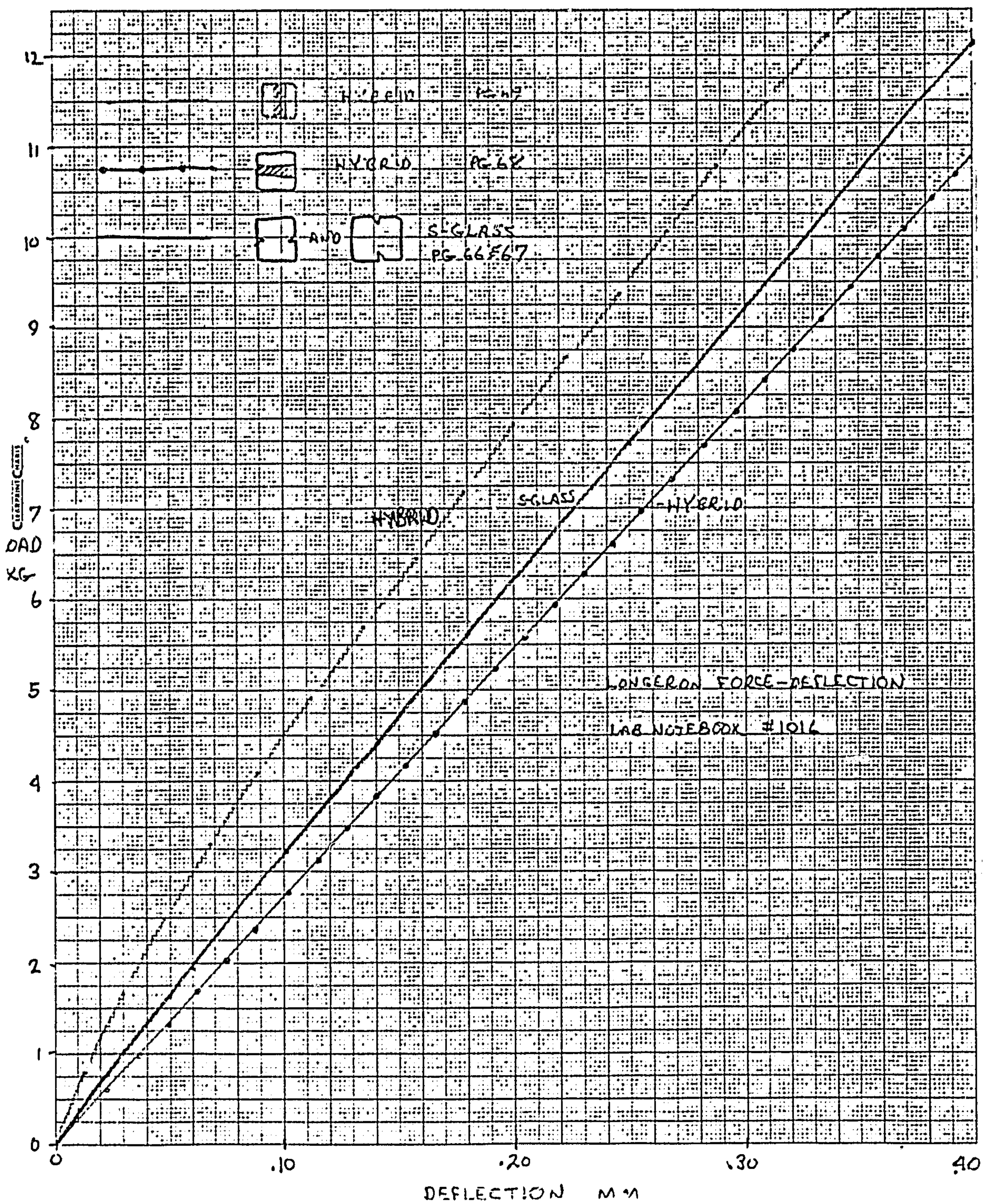

Figure 7. Longeron material, four-point bending tests.

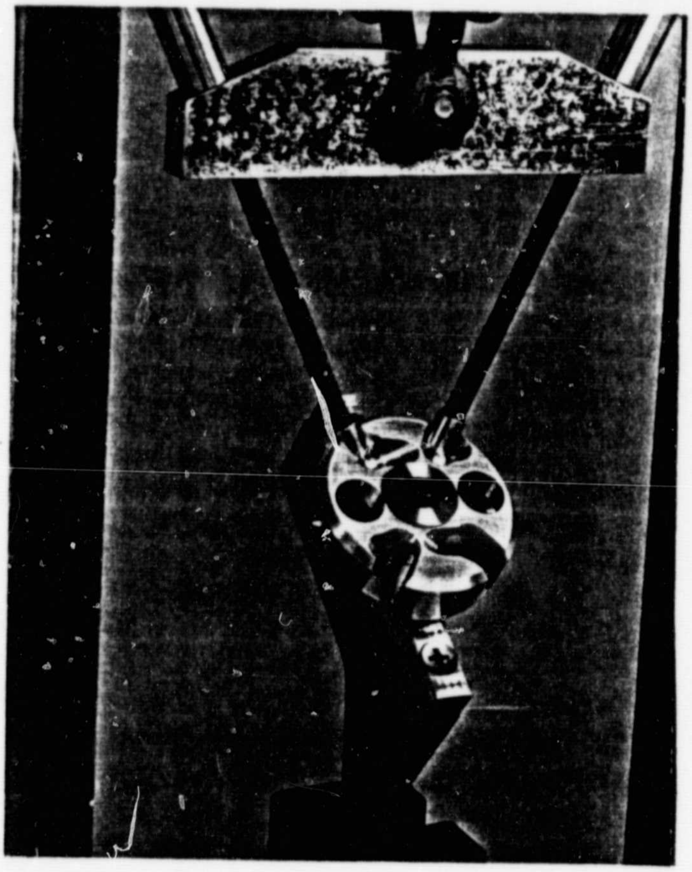

Figure 8. Diagonals/cup pull test setup.

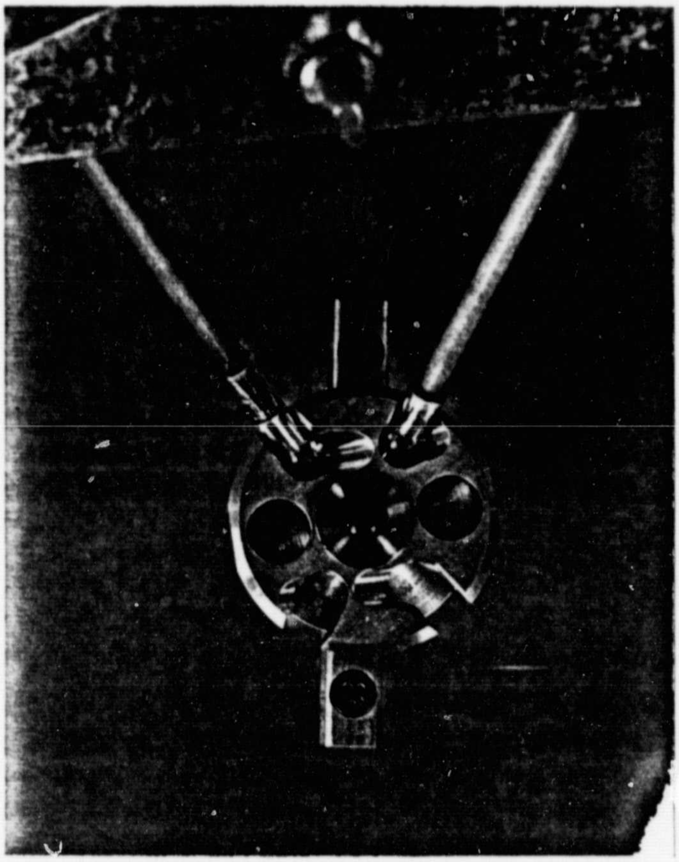

Figure 9. Cup/diagonal pull test setup.

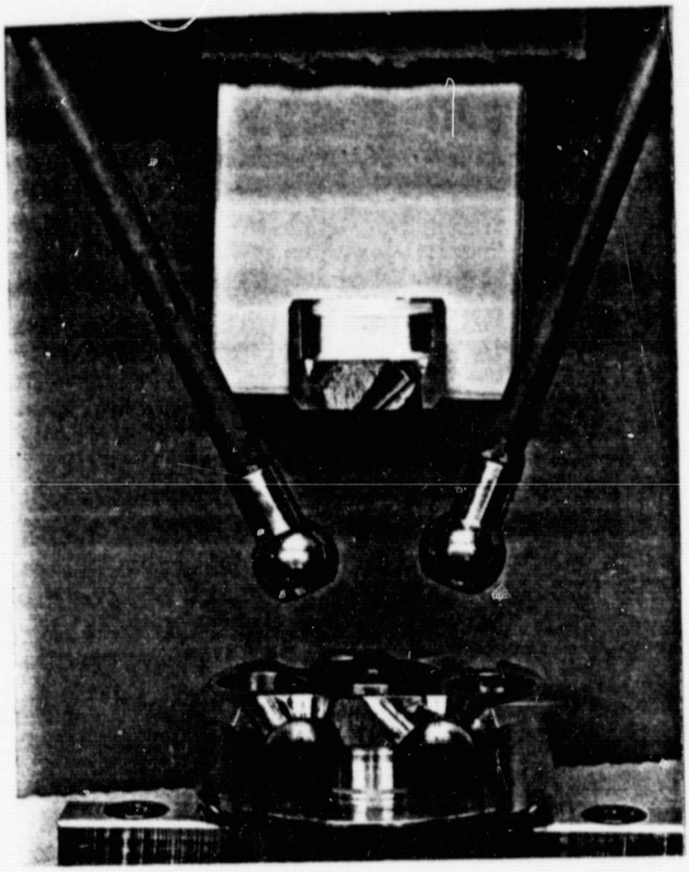

Figure 10. Cup failure.

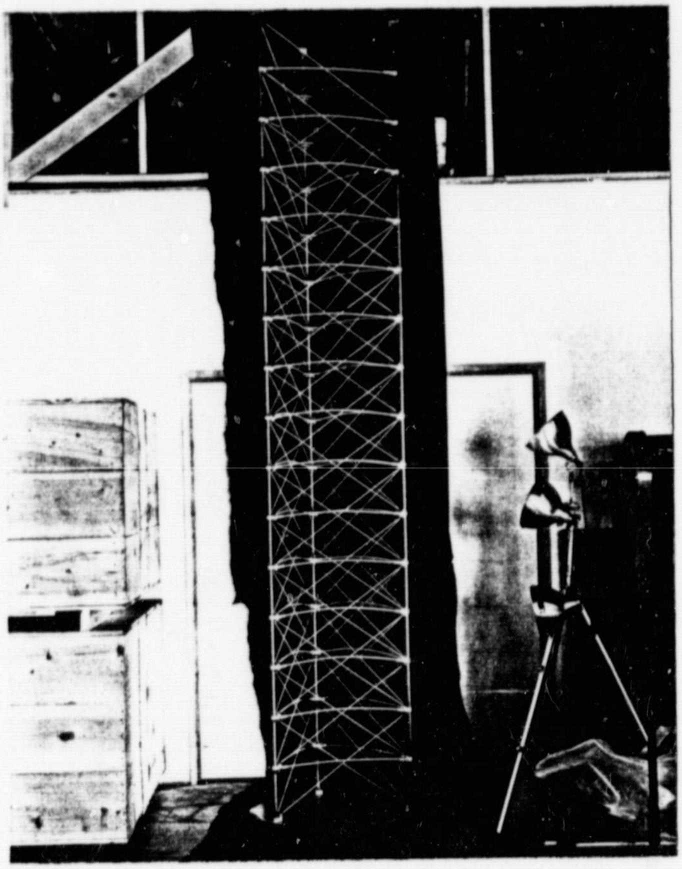

Figure 11. Twelve-foot model Supermast (SK2258) as assembled.

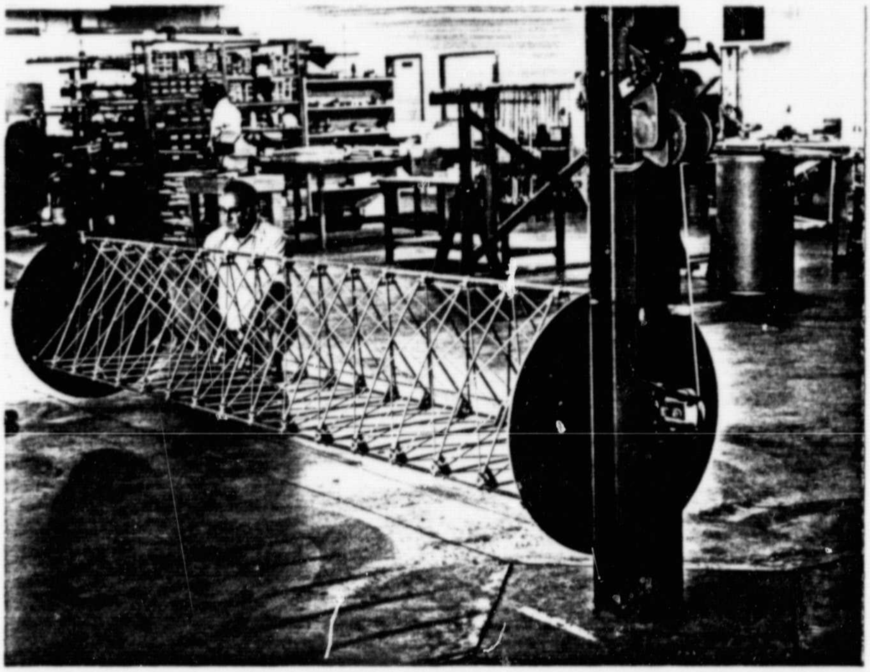

Figure 12. Twelve-foot model Supermast test setup.

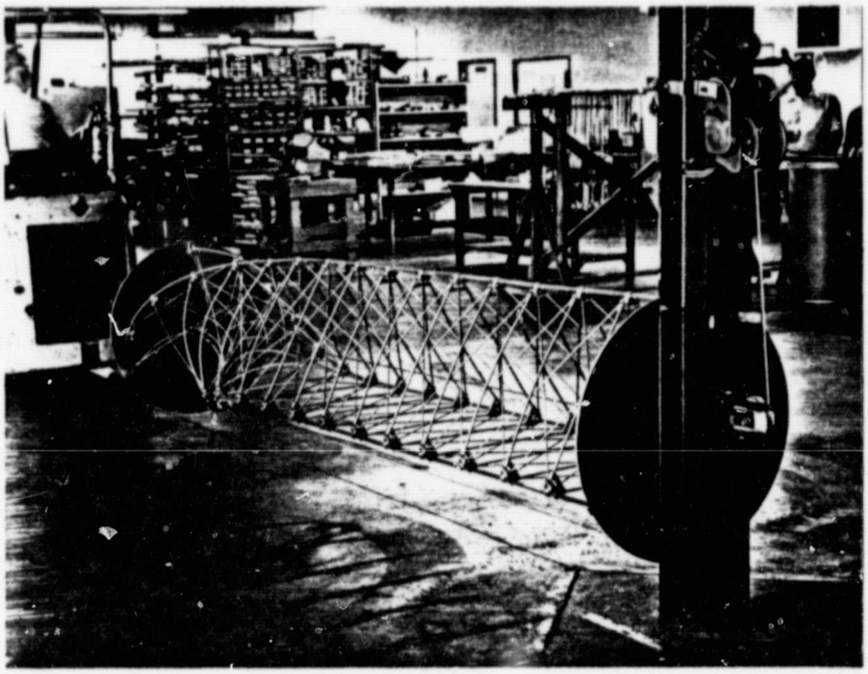

Figure 13. Twelve-foot model Supermast retraction with lanyard tension only.

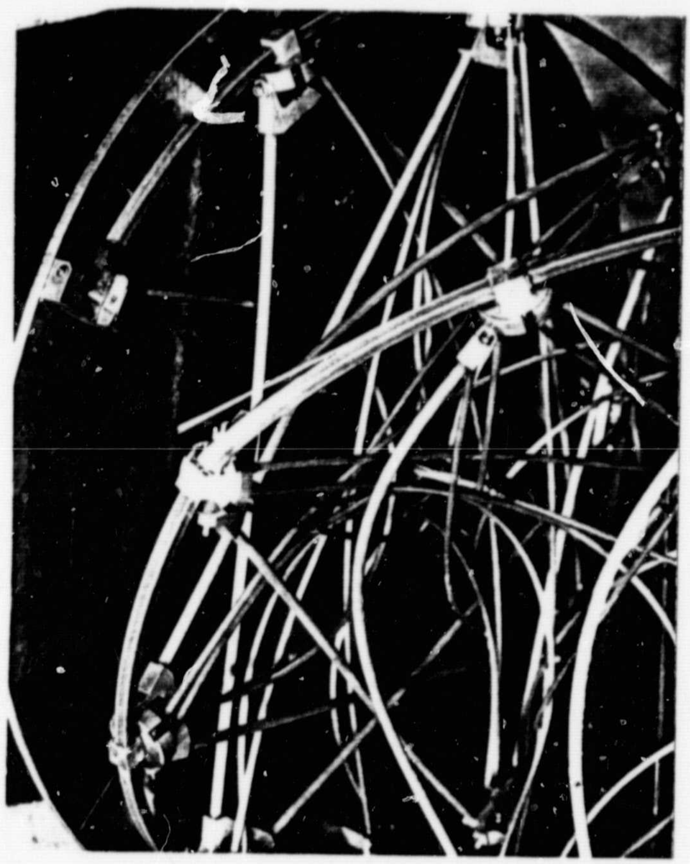

Figure 14. Twelve-foot model Supermast showing many broken fibers in first-failed longeron.

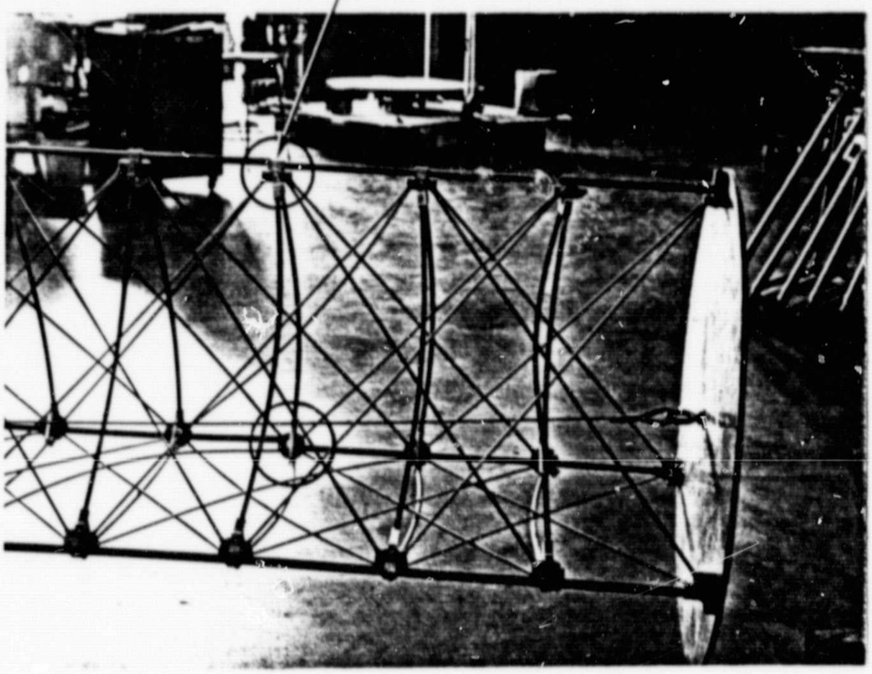

Figure 15. Cantilevered tip plate after failure of two longerons.

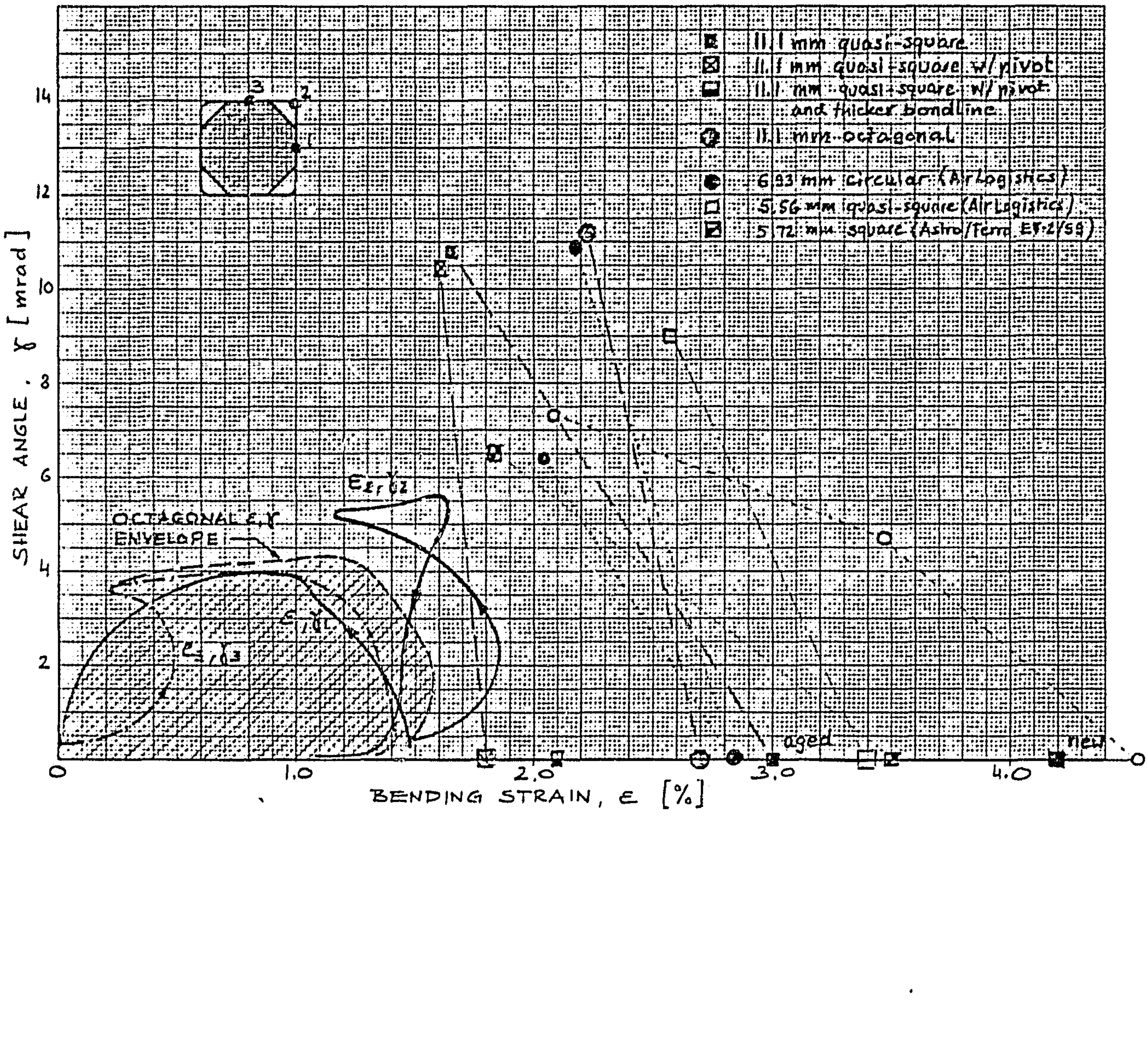

Figure 16. Strain interaction diagram.

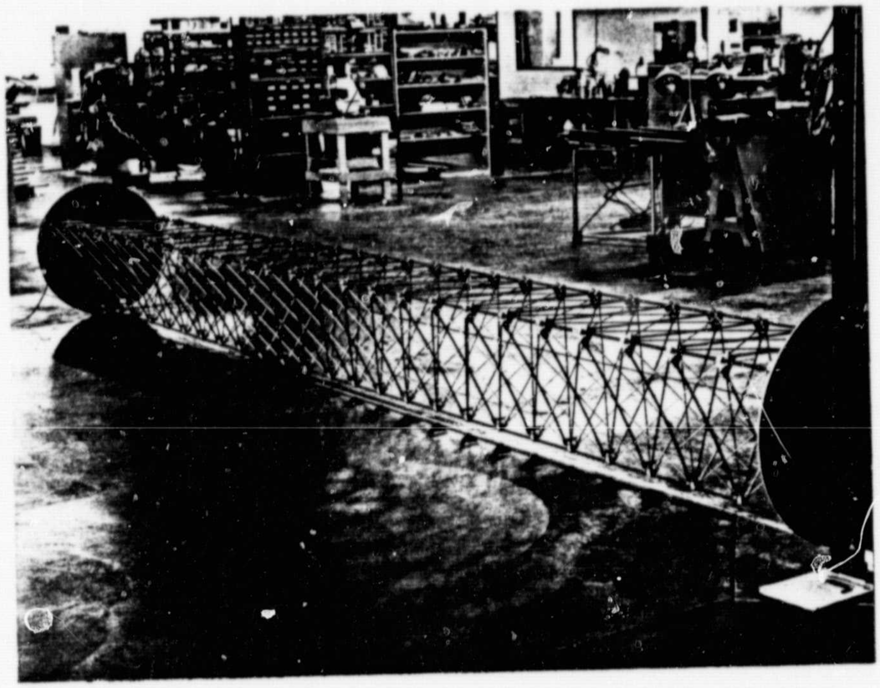

Figure 17. 0.75-m-diameter Supermast, 6-m long.

Figure 18. 0.75-m-diameter mast test setup.

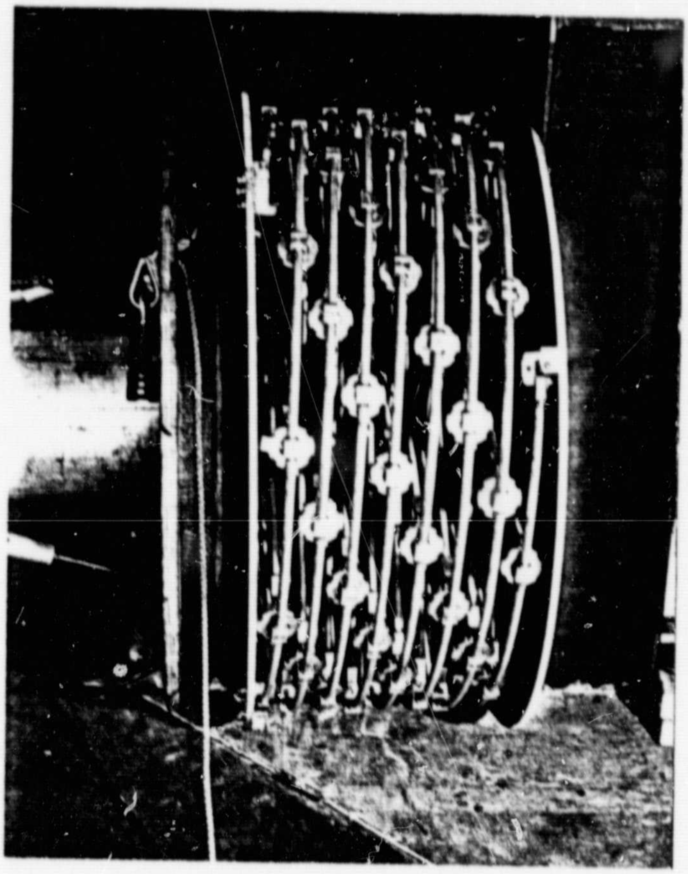

Figure 19. 0.75-m-diameter retracted Supermast, 0.4-m long.

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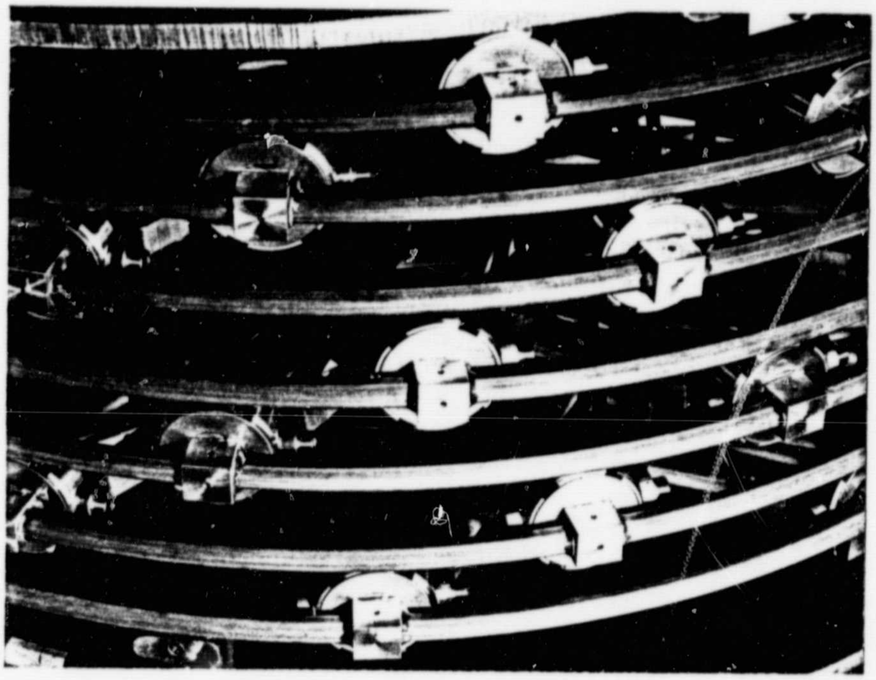

Figure 20. 0.75-m-diameter Supermast retracted detail.

APPENDIX A

PULTRUSION OF SQUARE S-GLASS RODS REPORT

PULTRUSION OF SQUARE S-GLASS RODS FOR THE DEVELOPMENT OF LARGE DIAMETER ASTROMASTS

PHASE I - FINAL REPORT

APRIL 15, 1982

COMPOSITE PRODUCTS TECHNOLOGY CENTER
23930 Madison Street
Torrance, CA 90505

April 14, 1982 CPTC# 81-8

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Astro Research Corporation
6390 Cindy Lane
Carpinteria, CA 93013

Attn: Dr. Karl Knapp,
Mr. Roger Lagerquist

Dear Sirs:

With the conclusion of Phase I of the Goldsworthy/CPTC pultrusion program, I'd like to present the attached summary of laboratory results. At Goldsworthy we are quite pleased with the program results and look forward to starting Phase II after your testing is complete.

In order to initiate Phase II we ask for an addenda to the initial purchase order #6139 and 50% of the phase price. Reference back to the CPTC quote dated November 18, 1981 note that we have asked for one extra production day if the Shell "fast cure" epoxy is the approved resin. At this time I suggest that such precaution may not be necessary. I would advise that Astro Research/Goldsworthy proceed on the basis of 3 days @ $836/day as quoted. Consequently, Goldsworthy requests $1,856.50 or one-half of the anticipated program price to initiate work. If the program were to require an additional one day effort to complete production of 500 feet/S-glass rod, Goldsworthy will present that cost at final billing. I will continue to assess Astro Research of the program status along the way.

It would be most convenient to our production schedule if the test based decisions, to proceed with Phase II, be made as rapidly as possible. If possible, we wish to avoid breaking down the pultrusion set-up for another task and then re-setting up later.

We look forward to any questions, or results you might have.

Best regards,

Rob Sjostedt

Rob Sjostedt
R & D Manager

Enc: as noted above

PULTRUSION OF SQUARE S-GLASS RODS FOR THE DEVELOPMENT OF LARGE DIAMETER ASTROMASTS

PHASE I - FINAL REPORT

I. CONCEPT

Pultrusion would appear to be an ideal process for the production of quasi-square S-glass/epoxy rods to be used as longeron members in lightweight extendible space structures. The need for uniform mechanical properties throughout long material lengths, low void content, and evenly tensioned fibers should be fully accomplishable with the pultrusion process. Furthermore, the high degree of fiber packing (72 to 75% by weight) required to achieve the specified 7.5 million composite modulus can easily be accomplished by pultrusion.

The recent availability of a new family of developmental "fast cure" epoxy resins by Shell Chemical, further added to the probability of producing high-performance rods by pultrusion. Shell was able to recommend an epoxy resin with both excellent properties and good processability.

II. PROGRAM OBJECTIVES

Following the design and manufacturing of the pultrusion die and related material guidance tooling, three lab trials were accomplished.

1) Pultrusion of 100 ft. S-2 glass rod with Ashland Hetron 902 vinyl ester resin.

2) Pultrusion of 100 ft. S-2 glass rod with Shell developmental "fast-cure" epoxy resin.

3) Pultrusion of 100 ft. hybrid sample S-2 glass and intermediate strength carbon fiber core/epoxy rod. The carbon core comprised 1/3 of the rod cross section area.

All pultrusions were processed in a manner consistent with recognition of the high strain loading of the rod. This involved efforts to correctly wet-out and orient the fiber prior to the pultrusion die. Secondly, all pultrusions were attempted at minimum resin filler loadings possible. Thirdly, radio frequency pre-heat was used in the glass pultrusions, just prior to the die entrance, insuring full and uniform cure of the composite cross section.

III. SIGNIFICANT DETAILS

1) Pultrusion die design - the 0.443" square pultrusion die was designed with an improved mating surface seal. Most of the die mating surface was relieved, such that a narrow 0.25" contact land was left for sealing. This was important for pultrusion of the Shell "fast-cure" epoxy as any leakage at the seam line will cause the product to seize. The epoxy is particularly prone to this phenomena since the resin undergoes a large viscosity drop before cure.

2) All resin mixes and processing details are available in the attached laboratory log sheets.

However, in summary the following optimum processing conditions were observed for each sample group respectively.

1) S-2 glass/vinyl ester - Hetron 902
   a) Die temperature - 240°F
   b) RF pre-heat (internal - 1" prior to die entrance) - 150°F
   c) Line speed - 18 in/min.

2) S-2 glass/epoxy - Shell Epon resin RSL 387 Curing Agent CA9350.
   a) Die temperature - 350°F
   b) RF pre-heat - 205°F
   c) Line speed - 6 in/min.

3) S-2 glass carbon hybrid/epoxy - Shell Epon resin RSL 387 with curing agent CA9350.
   a) Die temperature - 400°F
   b) No RF (due to conductivity/carbon fibers)
   c) Line speed - 4 in/min.

IV. RESULTS AND CONCLUSIONS

Approximately 130 to 150 feet total of each of the three sample types were produced. A low filler loading (5-10% by resin weight) was required in all cases to yield good surface finish and continuous running. The product samples were sent to Astro Research for testing and early indications were that the epoxy S-2 glass rod fully met Astro's requirement. Complete test results are to follow at a later date. The relatively low performance results of the vinyl ester samples are attributable to a high fiber loading. If future runs are attempted it would be worthwhile to reduce the glass content to 72% by weight with vinyl ester resin.

Another improvement to the process lies in the packaging form of the S-2 glass rovings. The tangential wrapped spools used in Phase I developed a twist in the roving as the pultruded length increased. The twist is probably affecting the ultimate properties of the rod. Removeable tube (no twist) centerpull S-2 glass roving doffs are commercially available from Owens-Corning Fiberglass. The tangential wrapped spools were used in Phase I to keep costs down.

Goldsworthy/CPTC maintains that the current process is fully developed and production of 500 foot lengths can commence immediately.

I will be pleased to respond to any questions regarding the above report.

P.S. Please see attached burn-out tests.

PULTRUSION REPORT

JOB NO. 1267

RUN NO. 1
DATE: 3/30/82
BY: HECTOR/SRUF

FIBER

Manufacturer ______
Quantity 90/96

Type ______
Calc. v/o Fibers ______

RESIN

Manufacturer ASHLAND
Viscosity ______

Type HETRON 902
Hardener ______
Catalyst 0.5% PERCADOX 16-N +1.5% BENZOYL PEROXIDE
Diluent ______
Filler N/A
Mold Release 1.5% MOLGARD

PROCESSING

Bath Temp. AMBIENT
Die Temp. 210-240
Post Cure N/A

Viscosity ______
Pull Rate 6-18"/MIN
Die Size .443² x 48

TEST RESULTS

V/o Fiber 96 ROVINGS - 80.3%
90 ROVINGS - 77.5%

% Voids ______

TEMPS. ARE °F

RF TEMPS. ARE MEASURED IN CENTER OF MATERIAL 2 in. BEFORE ENTERING DIE

JOB NO. 1267

P2

RUN NO. 1

DATE: 3/30/82

BY: HECTOR/STC

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/MIN)
1227	N/A	210 START	N/A	6
1234	150	"	"	"
FULLY CURED MAT'L EXITING DIE				
1247	"	"	ON	"
RF GENERATOR OVERLOADS & IS TURNED OFF WHILE FUSES ARE CHANGED - 2 ROVINGS ADDED TOTAL ROVING COUNT - (92)				
1251	200	"	"	"
1304	"	"	"	"
92 ROVINGS EXITING DIE - 2 ADDITIONAL ROVINGS ADDED - TOTAL ROVING COUNT - (94)				
1315	"	"	"	"
RF GENERATOR OPERATIONAL - MATERIAL SHOWING SIGNS OF POSSIBLE INTERNAL CRACKING				
1320	"	"	ON	"
(93) ROVINGS EXITING - FINISH GOOD - NO MEASURABLE INCREASE IN PULL LOADS				
1325	"	"	100	"
(94) ROVINGS EXITING DIE				
1336	325	220	125+	6-12
MATERIAL BEGINS TO GEL AHEAD OF DIE ENTRANCE DUE TO EXCESS R.F. PRE-HEAT - LINE SPEED INCREASED TO 12"/MIN.				

JOB NO. 1267

P3

RUN NO. 1

DATE: 3/30/82

BY: HECTOR/S[illegible]

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TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1344	325	220	160	12
1353	225	"	140	"

2 ROVINGS ADDED IN TANK

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1404	"	"	"	"
1409	"	"	"	"

(96) ROVINGS EXITING DIE

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1410	275	"	"	"

LAST SECTION OF DISORIENTED FIBERS NOW EXITING DIE

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1430	"	"	VARYING	"
1437	800	"	"	24
1440	"	"	"	18
1450	300	240	150	"
1455	400	"	"	"

BEGIN RUN #1 - PIECE #1 240° DIE/150° RF/18"/MIN

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1510	310	"	"	"

BEGIN PIECE #2 - 240/150/18

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1526	"	"	"	"

BEGIN PIECE #3 - 240/150/18

HYDRAULIC PRESSURE REDUCED TO AVOID DAMAGING MATERIAL IN CLAMPS

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1543	"	"	"	"

BEGIN PIECE #4 240/150/18

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1600	"	"	"	"

BEGIN PIECE #5 240/150/18

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE ("/M)
1614	"	"	"	"

BEGIN PIECE #6 240/150/18

JOB NO. 1267 P 4 RUN NO. 1

DATE: 3/30/82

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BY: HECTOR/STEIK

TIME	LOAD	DIE TEMP.	BL. TEMP.	PULL RATE ("/min)
1629	200	240	150	18
		BEGIN PIECE #7	240/150/18	
1644	"	OFF	OFF	Ø

END PIECE #7 END RUN #1

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PULTRUSION REPORT

JOB NO. 1267

RUN NO. 5
DATE: 4/05/82
BY: HECTOR/STEVE

FIBER

Manufacturer ______
Quantity 90

Type ______
Calc. v/o Fibers ______

RESIN

Manufacturer SHELL
Viscosity ______

Type RSL 387
Hardener CA 9350 (5PPH)
Catalyst ______
Diluent ______
Filler ASP400 (2%)
Mold Release Calcium Stearate (3PPH)

PROCESSING

Bath Temp. AMBIENT
Die Temp. 350°F
Post Cure N/A

Viscosity ______
Pull Rate 60"/MIN
Die Size $0.443^2 \times 48$

TEST RESULTS

v/o Fiber 77.%

% Voids ______

RUNS 2,3&4 FAILED DUE TO PROBLEMS ASSOCIATED WITH LACK OF FILLER - (SURFACE SLOUGHS & ACOMPANYING HIGH PULL LOADS

JOB NO. 1267

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RUN NO. 5

DATE: 4/05/82

BY: HECTOR/STEI

TIME	LOAD (LBS)	DIE TEMP (°F)	RF. TEMP. (°F)	PULL RATE (in/min)
1404	350	360	ON	6
1415	550	350	100	6
MATERIAL EXITING CURED				
1420	750	320	200	6
1430	600	350	205	6
MATERIAL ENTERING DIE @ 350°DIE/205°RF/6"MIN				
1439	650	350	205	6
MATERIAL EXITING DIE APPEARS FULLY CURED & NO APPARENT CRACKING - PEAK EXOTHERM IS 16" INSIDE (UPSTREAM) OF DIE EXIT				
1449	"	"	"	"
BEGIN PIECE #1				
1530	600	"	"	"
BEGIN PIECE #2				
1610	"	"	"	"
BEGIN PIECE #3				
1650	"	"	"	"
BEGIN PIECE #4				
1730	"	"	"	"
BEGIN PIECE #5				
1810	"	"	"	"
BEGIN PIECE #6				
1850	"	"	"	"
BEGIN PIECE #7				
1930	"	"	"	"
END PIECE #7 - RF OFF - RUN STOPPED				

PULTRUSION REPORT

JOB NO. 1267

RUN NO. 6
DATE: 4/13/82
BY: HECTOR/STEVE

FIBER

Manufacturer OCF/
Quantity ______

Type ______
Calc. v/o Fibers ______

RESIN

Manufacturer SHELL
Viscosity ______

Type RSL 387
Hardener CA 9350
Catalyst ______
Diluent ______
Filler ASP 400 (5%)
Mold Release Calcium Stearate (3 PPH)

PROCESSING

Bath Temp. AMBIENT
Die Temp. 400°F
Post Cure N/A

Viscosity ______
Pull Rate 6"/MIN
Die Size .443² x 48

TEST RESULTS

V/o Fiber ______

% Voids ______

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JOB NO. 1267

RUN NO. 6
DATE: 4/13/82
BY: HECTOR/STEVE

TIME	LOAD	DIE TEMP.	RF. TEMP.	PULL RATE
1415	N/A	400	N/A	6
	MATERIAL ENTERING DIE			
1426	250	"	"	"
	PRODUCT EXITING DIE - APPARENT GOOD PRODUCT			
1439	"	"	"	"
	CARBON FIBERS DISORIENTED @ OUTSIDE EDGES - 10 MIL. SHIMS ADDED @ ENTRANCE BETWEEN LAYERS TO AID IN ORIENTATION			
1500	500	"	"	"
	INCREASE IN SURFACE SLOUGH & PULL LOADS			
1505	600	"	"	4
	LOADS INCREASING - SPEED TO 4"/MIN			
1507	600	"	"	"
	SLOUGH INCREASING - DECISION MADE TO ADD 5% ASP 400 FILLER (BRINGING TOTAL TO 10%)			

END.

PULTRUSION REPORT

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JOB NO. 1267

RUN NO. 7

DATE: 4/14/82

BY: HECTOR/STEVE

FIBER

Manufacturer OCF/

Quantity ____

Type ____

Calc. v/o Fibers ____

RESIN

Manufacturer SHELL

Viscosity ____

Type RSL 387

Hardener CA 9350

Catalyst ____

Diluent ____

Filler ASP 400 (10%)

Mold Release Calcium Stearate

PROCESSING

Bath Temp. AMBIENT

Die Temp. 400°F

Post Cure N/A

Viscosity ____

Pull Rate 4 in/min

Die Size .443² x 48

TEST RESULTS

v/o Fiber ____

% Voids ____

JOB NO. 1267

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RUN NO. 7

DATE: 4/14/82

BY: HECTOR/STEVE

TIME	LOAD	DIE TEMP	[illegible] TEMP.	PULL RATE
0911	N/A	400	N/A	6
		MAT'L ENTERING DIE		
0920	900	"	"	"
		EXITING DIE - LIGHT SLOUGH		
0936	700	"	"	4
		REDUCE SPEED TO 4 in/min		
0947	600	"	"	"
0955	650	"	"	"
		BEGIN PIECE #1.		
1100	"	"	"	4
		BEGIN PIECE #2 - ROVINGS TWISTING BEFORE ENTERING TANK		
1153	700	"	"	"
		BEGIN PIECE #3		
1247	750	"	"	"
		BEGIN PIECE #4		
1340	"	"	"	"
		BEGIN PIECE #5 - TWISTING OF FIBERS IS SHOWING IN OUTER SURFACE OF PRODUCT AS APPARENT CRACKS		
1430	"	"	"	"
		BEGIN PIECE #6		
1514	3000	"	"	Ø

ROVING DISORIENTATION DUE TO ATTEMPTED SPLICE INCREASES LOADS UPON ENTERING DIE

END

Burn-Out Tests

04-05-82

Sample N° 1 96 Rovings

Resin = HETRON 902
Percadox 16N = 0,5%
BZP = 1,5%
Molgasd = 1,5%

Burn out results

weight cup + sample = 49,1103
weight cup − 40,0517
grs. sample 9,4113

Weight sample + cup after burn = 47,610
weight cup 40,0517
7,5583 grs dry sample

grs. sample 9,4113 → 100 %
grs dry S. 7,5583 — X

X = 80,37 % Fiber glass

Sample N° 2

N° Rovings = 90

% Fiber glass = 77,52

04-06-82

Sample N° 1
Epoxy Resin = RSL 387
CA 9350 = 5pph
Calcium(ST) = 3 pph
ASP400 = 7 %

Burn out Results

% Fiber glass plus ASP 400 = 78,77

APPENDIX B

FOUR-POINT BENDING TEST PROCEDURE

TEST PROCEDURE

BENDING MODULUS OF ELASTICITY BY THE FOUR POINT METHOD.

PURPOSE.

This test determines the bending modulus of elasticity for slender elements such as the longerons, battens and diagonals used in Astromast deployable structures.

EQUIPMENT.

Test Fixture SK 2241, including the Test Article Support and Weight Hanger.

Metric Dial Indicator, Brown & Sharp #8261-911 (Yellow Dial).

Set of Metric Weights.

Table with Cast Iron Grating Top.

DESCRIPTION OF THE TEST.

The test article is placed on supports that are a fixed distance apart. Bending loads are applied by a weight hanger that has knife edges separated by a fixed distance. A series of metric weights provides incremental loading.

Deflections at the center of the test article are converted to modulus of elasticity by an equation that uses the test article crossectional dimensions, test fixture geometry, applied loads and observed deflections. See "DATA REDUCTION".

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PREPARATION.

Weigh the weight hanger unit (SK 2241), including the nuts and washers used for installation.
Add nuts and/or washers to make the tare weight a round number.
Attach a sticker to the weight hanger, indicating the tare weight.

Remove the horizontal bar from the weight hanger and bring the threaded rods down through the cast iron grating. Re-attach the horizontal bar and tighten the jam nuts, making sure the bar is equally distant from both knife edges.

Position the test article support (SK 2241) on the grating beneath the weight hanger. Center the weight hanger over the test article support and move the test article support until both threaded rods clear the grating. Clamp the test article support to the grating.

Cut the test article to a minimum length of 18 inches (24 inches maximum). Lift the weight hanger and slide the test article onto the supports. Center it. Use rubber bands to hold the test article against the front sides of the knife edge slots: Wrap a rubber band around the test article outboard of each knife edge and attach it to a screw on the front side of the fixture.

Mount the dial indicator above the center of the test article so the plunger is just above the lowest point in its travel. Push against the test article support and dial indicator to check for excessive play. Make sure the dial indicator is centered by measuring from both knife edges.

Identify the weights by affixing a numbered sticker to each one. Record the size of each weight and its sticker number.

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TEST PROCEDURE.

Support the weight hanger on blocks so it doesn't touch the test article. Zero the dial indicator by rotating its face. Tap lightly on the dial indicator to remove friction. Readjust the zero if necessary. Preload the test article by lowering the weight hanger and applying the maximum load. Then remove all of the weights and support the weight hanger on blocks. Check the dial indicator zero and readjust it if necessary. Record the load (zero) and deflection (zero). Lower the weight hanger onto the test article and record the load (weight hanger tare) and deflection (indicated by the dial indicator). Add metric weights one at a time and record the loads and deflections. Record the sticker numbers of the weights used.

DATA REDUCTION.

Secant Modulus.

The flexural modulus of elasticity (E) may be found by using the following equation to evaluate data taken with test fixture SK 2241:

$$E = \frac{2.500 \times W}{I \times Y} \times 10^{-9} \text{ gigapascals}$$

where W is the Applied Weight in kilograms.

I is the moment of inertia of the test article crossection in meters^4,

and Y is the Deflection in millimeters.

Tangent Modulus.

The tangent modulus is obtained by substituting the local slope of the force-deflection curve at a given strain level in place of W/Y in the above expression. To find the modulus at near zero loads, the force-deflection curve should be smoothed by making a least squares fit to a curve of the form $Y = A \times X^{B}$. This can be done with HP-41C Standard Applications program "POW".

The modulus E can be obtained with HP-41C program "FFFF". This program finds the moment of inertia of a round, square or rectangular crossection including the effect of corner radii. (It also finds the corner radii of a square section, given the side and diagonal measurements). The program accepts crossection measurements in inches and gives the moment of inertia in english units. Then it converts the moment of inertia to SI units and calculates E in gigapascals.

SAMPLE CALCULATION.

Assume the following data were obtained from a four point bending test:

Crossection Dimensions - .4362" x .4360" x .5686" diagonal.

Corner Radius - .0581"

Crossection Moment of inertia - 2.893×10^{-3} in^{4},

or 1.204×10^{-9} m^{4}.

Load (including tare) - 7.738 kg.

Deflection - .230 mm.

The modulus of elasticity is:

$$E = \frac{2.500 \times 10^{-9} \times 7.738 \text{ kg}}{1.204 \times 10^{-9} \text{ m}^{4} \times .230 \text{ mm}}$$

or $E = 69.86$ gigapascals