THERMALLY STABLE DEPLOYABLE STRUCTURE

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ABSTRACT

A deployable structure which meets stringent thermal and strength requirements in a space environment has been developed. A mast with a very low coefficient of thermal expansion was required to limit the movement from thermal distortion over the temperature range of -200 °C to 80 °C to .064 cm (.025 in.). In addition, a high bending strength over the temperature range and weight less than 18.1 kg (40 pounds) was needed. To meet all of the requirements, a composite, near-zero CTE structure was developed. The measured average CTE over the temperature range for the mast was .70 x 10^{-6}/°C (.38 x 10^{-6}/°F). The design also has the advantage of being adjustable to attain other specific CTE if desired.

INTRODUCTION

ABLE's FASTMast (Patent 4,599,832) was used as a basis for the design (Figure 1). The FASTMast is built up from many pieces and its component nature allowed the design to be tailored to meet the strength and CTE requirement while minimizing the weight. The buckled bow rods shown in Figure 1 serve to preload the structure and remove play at the joints due to manufacturing tolerances which would also contribute to the deflection at the top of the mast. A lanyard deployment system was chosen over a canister deployment system to minimize both the weight and stowed volume. The mast and deployment system for a 230 cm (90 inches) high mast was kept below a weight of 18.1 kg (40 pounds) and a stowed height of 20.3 cm (8.0 inches).

CTE tests and strength tests were done to determine the optimum longeron design. A prototype model of the mast was built using aluminum and S-glass/epoxy to check the mast design and deployment mechanism.

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Bow Rods

Square Frame

Longerons

Diagonals

Graphite/Epoxy
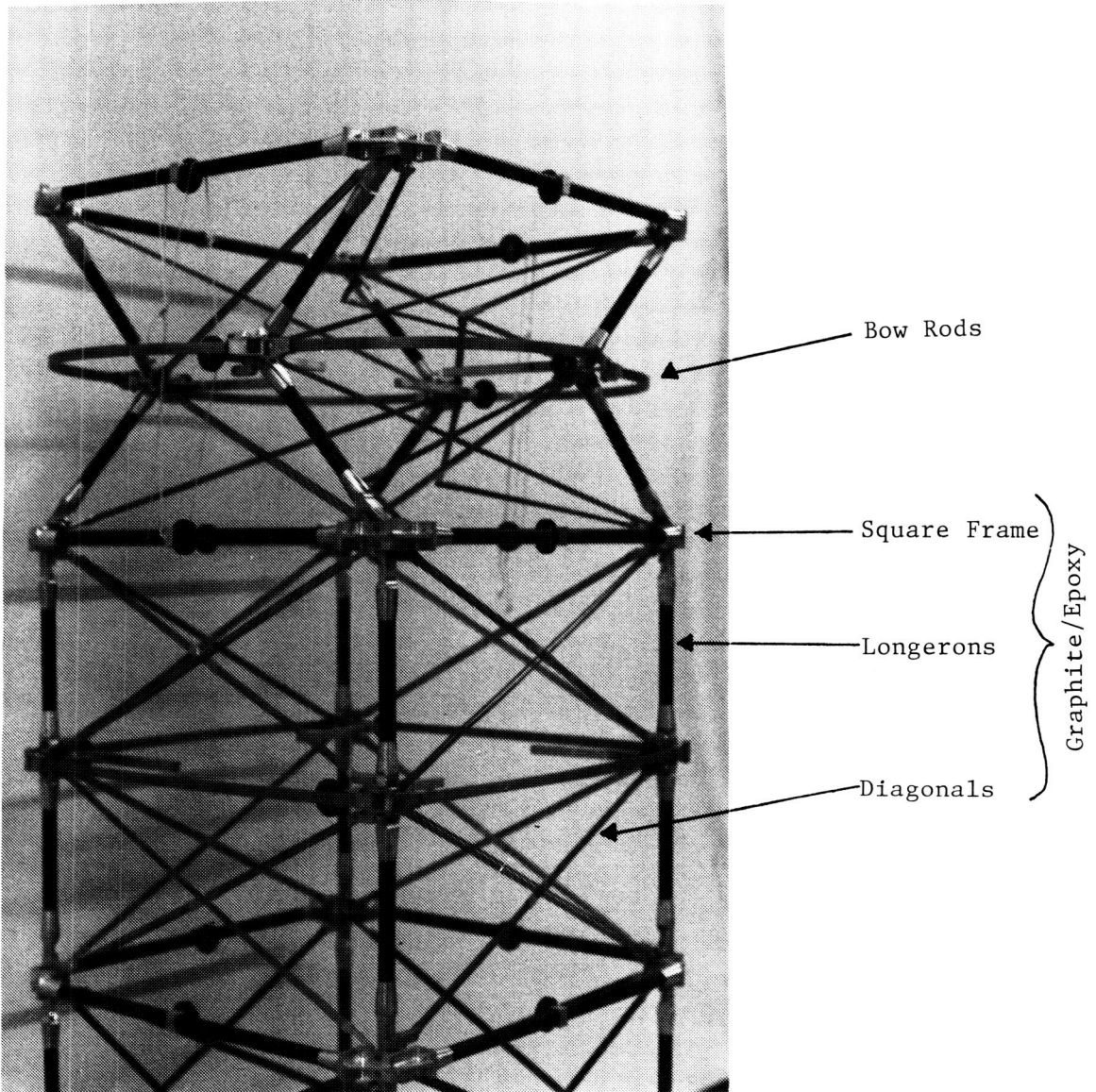
Figure 1. ABLE FASTMast

DESIGN CONSIDERATIONS

Thermal Distortion

The low CTE was required to limit the thermal distortion caused by the large temperature differences which can occur in structural elements in space. The two orientations of the mast to the sun shown in Figure 2 will cause the largest thermal differences and thus distortions. In one case the sun is shining directly onto one longeron while the longeron behind it is shaded. In the second case, the sun is shining directly onto one set of diagonals while the adjacent sets are shaded. The worst-case sun orientation is when both longeron shading and diagonal shading occur simultaneously. To meet the distortion requirement for this condition over the -200 °C to 80 °C temperature range, the mast could have a maximum CTE of 1.0×10^{-6}/°C (.56 $\times 10^{-6}$/°F).

Strength and Stiffness

Each longeron had to have a strength of 10,700 N (2,400 lb) for the mast to have 6,770 N-m (60,000 in.-lb) bending strength. Full strength was required over the temperature range so the differences in CTE's between mating parts were critical. The stiffness was designed to be tunable; by using tubes for longerons, the inside diameter could be adjusted to change the stiffness without redesigning the mast.

Materials

P75 graphite epoxy was chosen for the primary members in the mast because of its low CTE of -1×10^{-6}/°C ($-.55 \times 10^{-6}$/°F) and low density of 1.6 g/cm^3 (.058 pounds/inch^3). In addition, it has a high strength of 8.6×10^8 N/m^2 (125,000 psi) and a high stiffness of 17×10^{10} N/m^2 (25×10^6 psi). It was used for the longerons, square frame and diagonals, as shown in Figure 1. Titanium was used for the large corner pieces because of its density and high strength. Titanium has a relatively large CTE of 8.3×10^{-6}/°C (4.6×10^{-6}/°F), but the corner pieces have a small effect on the overall CTE of the mast. S-glass/epoxy was used for the flexible bow rods which preload the structure but make no contribution to thermally-induced displacements.

Metal end fittings bonded to the graphite/epoxy were used because manufacturing the graphite with end fittings was expensive and limited the design flexibility. The longeron strength was limited by the strength of the metal to graphite bond so thermal compatibility between the two materials was important. Titanium was considered but analysis showed that its CTE would increase the overall CTE of the mast above the required value, and the strength of a titanium-to-graphite bond would be too low at -200 °C due to the differential CTE between the two materials. For a bond strength of 10,700 N (2,400 pounds), a minimum bond length of 2.3 cm

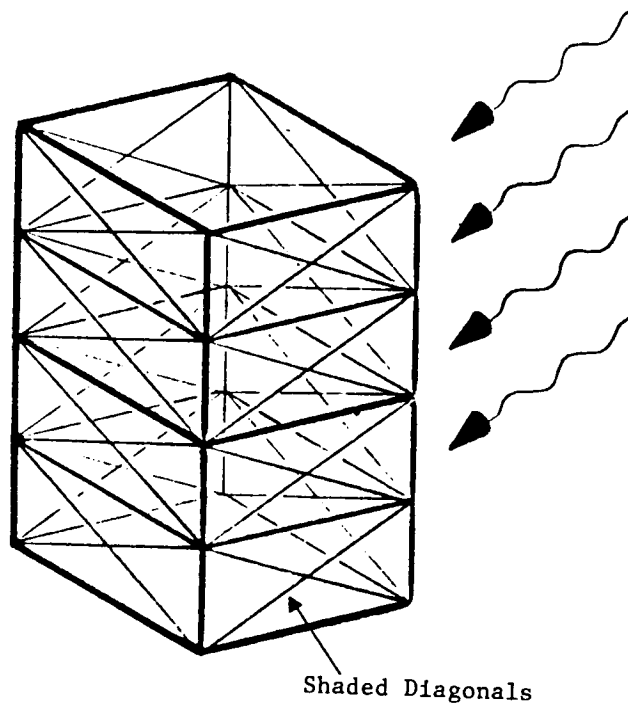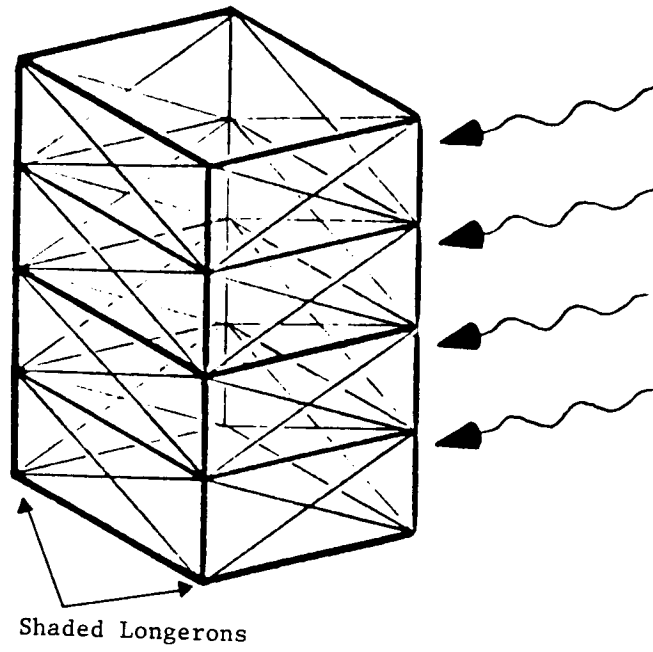Shaded Longerons

Shaded Diagonals

Figure 2.   Mast to Sun Orientations

(.9 inches) was required. However, analysis indicated that at low temperatures, the differential CTE between the two materials along that length would cause shear failure in the bond. Invar was also considered because of its low CTE, $1.6 \times 10^{-6}/°C$ ($.9 \times 10^{-6}/°F$), although its density is almost twice that of titanium. The effective CTE and strength of the mast with each metal bonded to graphite had to be determined.

MATERIAL TESTS

CTE Tests

Samples of the two material options, titanium-invar-graphite and titanium-graphite, were made up as shown in Figure 3. Due to symmetry, it was only necessary to simulate a longeron for one half of a bay. The samples were sent to a CTE-measuring lab and the CTE's over the temperature range were determined.

The results of the CTE testing for the titanium-invar-graphite sample are shown in Figure 4. The CTE of invar varies with temperature[1] as shown in Figure 5, and the CTE data for the test sample tracks the characteristic curve for the thermal expansion of invar. The near-zero CTE between -60 °C and -10 °C lowers the average CTE over the temperature range to $.68 \times 10^{-6}/°C$ ($.38 \times 10^{-6}/°F$) and a smaller temperature range could result in an even lower CTE. The predicted CTE of $.25 \times 10^{-6}/°C$ ($.14 \times 10^{-6}/°F$) for the longeron agreed fairly well with the tested CTE. A CTE of $.68 \times 10^{-6}/°C$ ($.38 \times 10^{-6}/°F$) would result in .044 cm (.017 inch) movement at the top of the mast over the temperature range, which is less than the .064 cm (.025 inch) movement allowed.

Figure 6 shows the CTE test results for the titanium-graphite sample. A CTE of $2.56 \times 10^{-6}/°C$ ($1.42 \times 10^{-6}/°F$) was predicted and the tested CTE was $3.28 \times 10^{-6}/°C$ ($1.82 \times 10^{-6}/°F$) which would result in .21 cm (.082 inch) movement at the top of the mast over the temperature range. Further design work would be necessary if titanium were to be used since .21 cm (.082 inch) exceeded the maximum allowed movement. The CTE test results are summarized in Table 1.

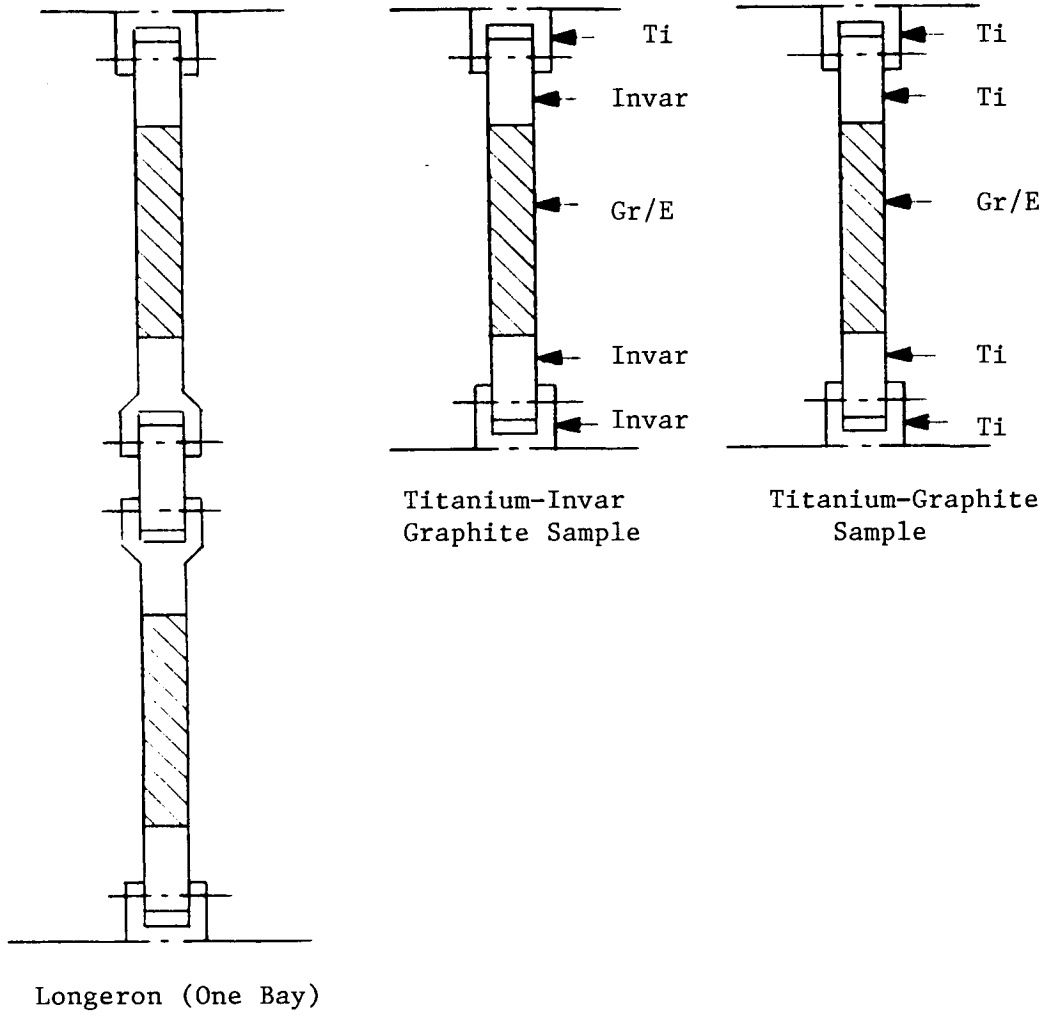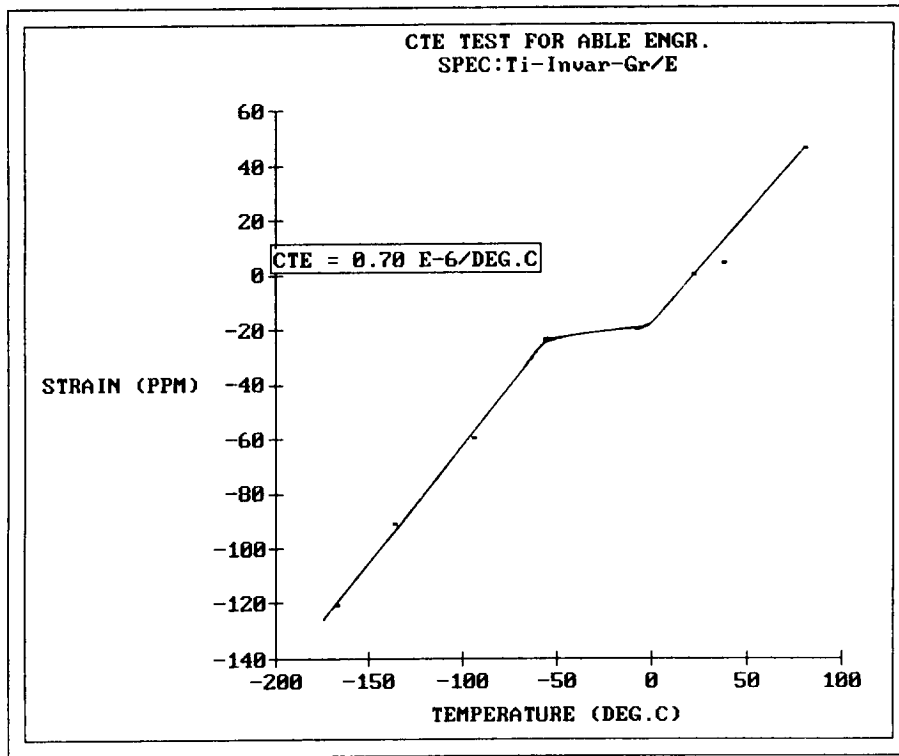1.   American Society for Metals, Metals Handbook, Vol. 2, 8th ed., 1961

Longeron (One Bay)

Titanium-Invar
Graphite Sample

Titanium-Graphite
Sample

Figure 3. CTE Test Samples

CTE TEST FOR ABLE ENGR.
SPEC:Ti-Invar-Gr/E

CTE = 0.70 E-6/DEG.C

STRAIN (PPM)

TEMPERATURE (DEG.C)

Figure 4.   Titanium-Invar-Graphite Test Results

Change in Length

A   B   C   D   E   F

Temperature

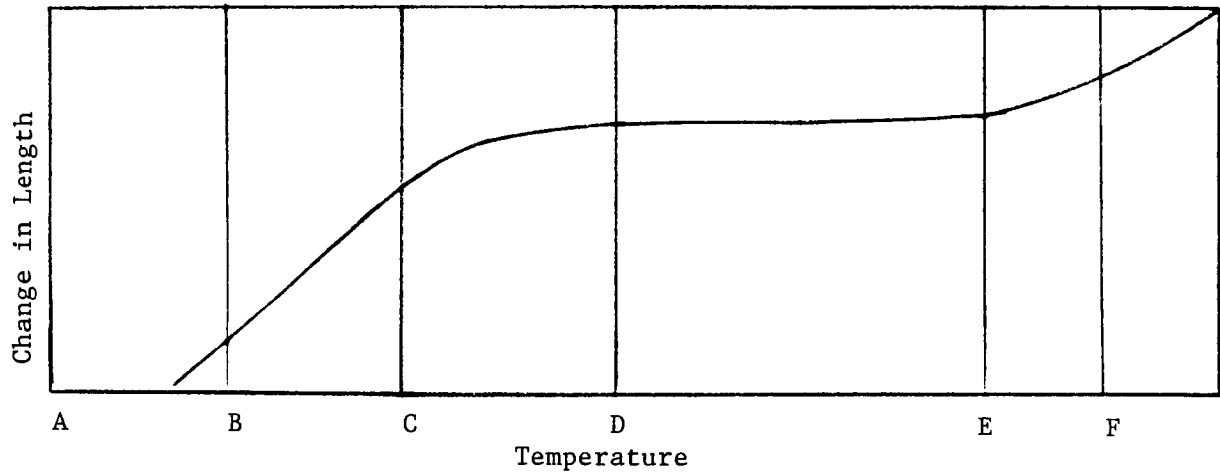Figure 5.   Change in Length with Temperature of a Typical Invar
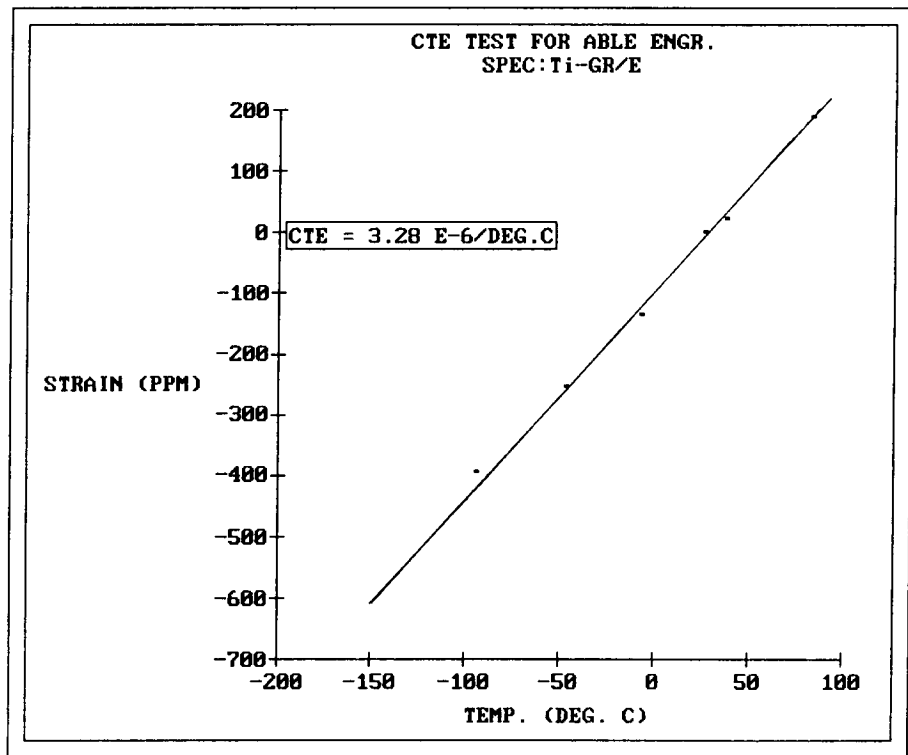
Figure 6. Titanium-Graphite Test Results

Titanium-Invar-Graphite		
CTE Actual	$.68 \times 10^{-6}/^\circ C$	$(.38 \times 10^{-6}/^\circ F)$
Predicted	$.25 \times 10^{-6}/^\circ C$	$(.14 \times 10^{-6}/^\circ F)$
Calculated Movement	$.044$ cm	$(.017$ in.$)$
Titanium-Graphite		
CTE Actual	$3.28 \times 10^{-6}/^\circ C$	$(1.82 \times 10^{-6}/^\circ F)$
Predicted	$2.56 \times 10^{-6}/^\circ C$	$(1.42 \times 10^{-6}/^\circ F)$
Calculated Movement	$.21$ cm	$(.082$ in.$)$

Table 1. CTE Test Results Summary

Bond Strength Tests

The strength of the epoxy bond between the graphite and metal end fittings was tested using the fixture shown in Figure 7. The fixture was placed inside a thermal chamber. Liquid nitrogen was sprayed into the chamber to achieve a low temperature of -190 °C and a hot air gun was used to raise the temperature to 80 °C. Thermocouples were used to monitor the temperature of the metal end fittings and the graphite. The LN_2 was regulated by a controller and the duty cycle was adjusted so that the temperatures for the graphite and metal end fittings were kept to within 2 °C of each other. A tensile load of up to 15,100 N (3,400 pounds) on the test samples could be applied with the gaged tensioning system. A bond strength of 10,700 N (2,400 pounds) was needed to meet the strength requirement for the mast.

Two bond configurations were tested and they are shown in Figure 8. With the tapered bond, the OD of the graphite bonding surface and the ID of the metal end fitting had a slight taper. The taper increases flexibility in the least loaded sections which encourages a more even transfer of load along the length of the bond. Bonding along the taper also meant that bonding occurred to some of the internal longitudinal fibers as well as those along the outside of the tube. The parallel bond, with the bond line parallel to the axis of the tube, was the second configuration. With this bond, the OD of the graphite and the ID of the metal fitting remain parallel with the axis of the parts but the inside of the graphite and the outside of the metal fitting are tapered to provide the same load transfer advantage as with the tapered bond. This type of bond has the advantage of the epoxy being entirely in shear where it has its greatest strength, and the overall length of the made-up tube is easier to control.

Test samples simulating the tapered bond proposed for the mast were fabricated from graphite tubing and both titanium and invar end fittings and tensile tests were conducted. At the same time the effect of thermal cycling was also tested by storing the test samples in the thermal chamber while the tests were being run. As a result, the untested samples were thermally cycled between room temperature and -190 °C. Test results are shown in Figure 9. The failure mode for all of the samples was a shear failure at the bond. The invar-to-graphite bond had strength well over the required 10,700 N (2,400 pounds), even at -190 °C. The strength of the titanium-to-graphite bond degraded rapidly as the temperature dropped and at -190 °C had a strength of only 1,780 N (400 pounds).
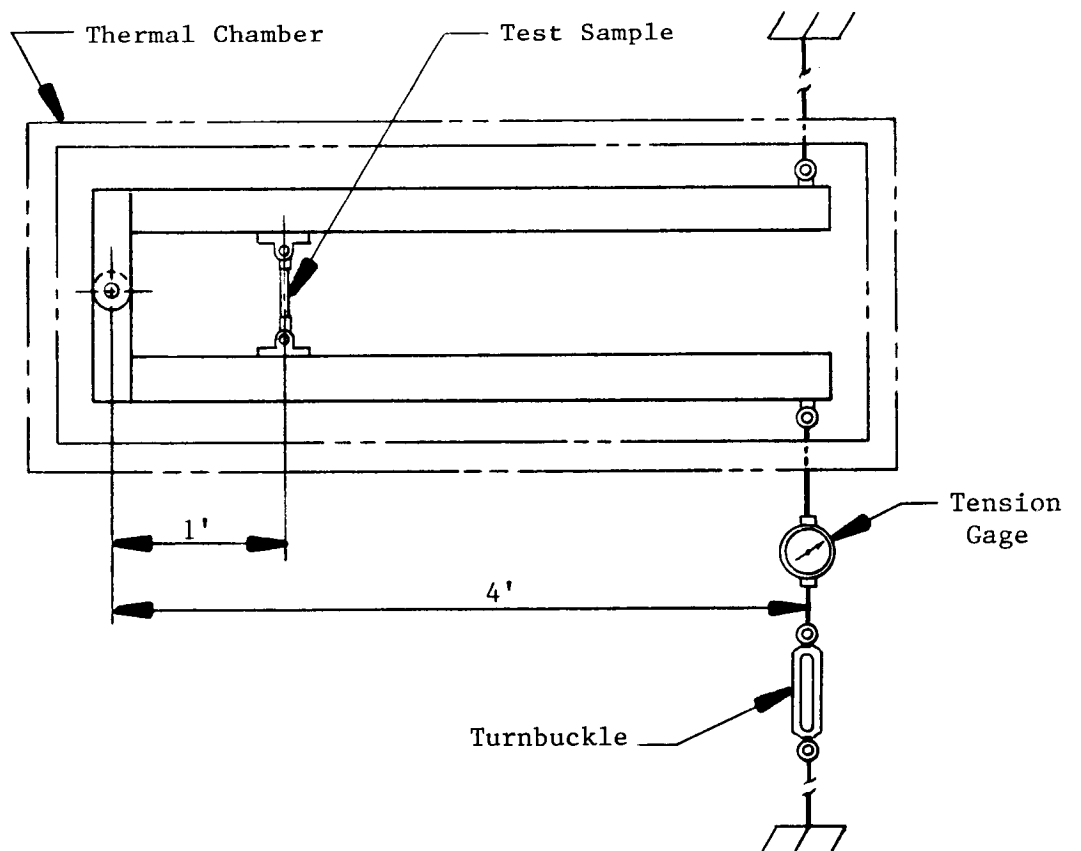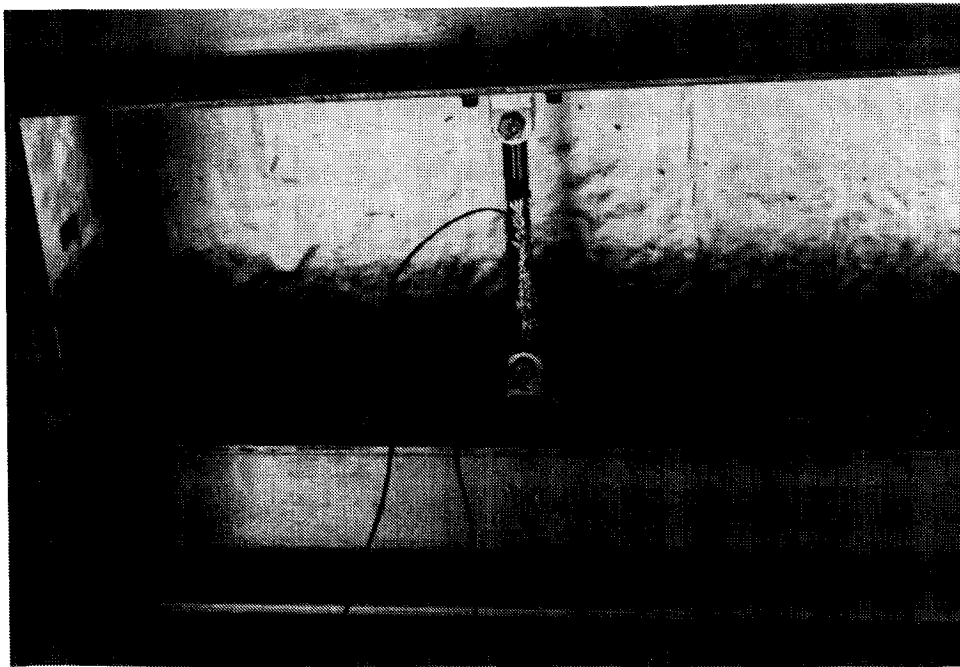
Figure 7. Graphite to Metal End Fitting Bond Test

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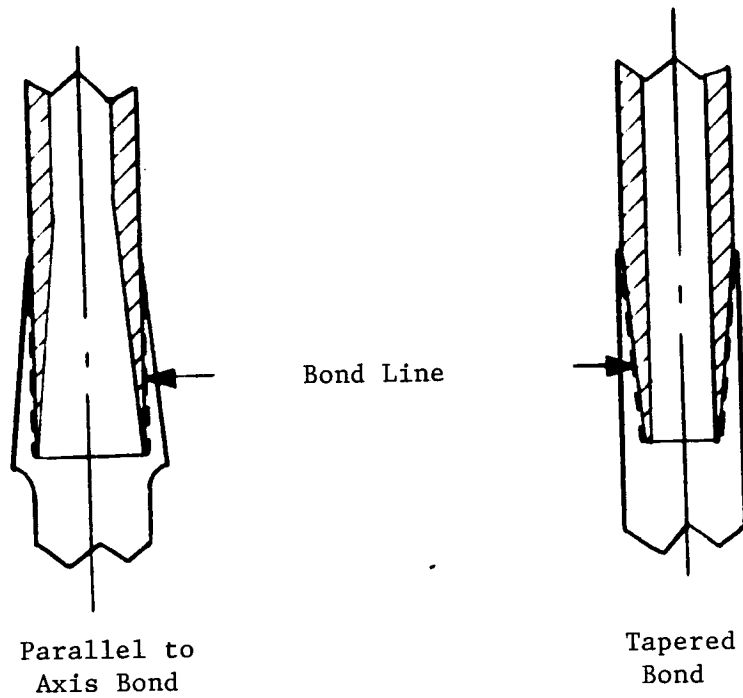Parallel to
Axis Bond
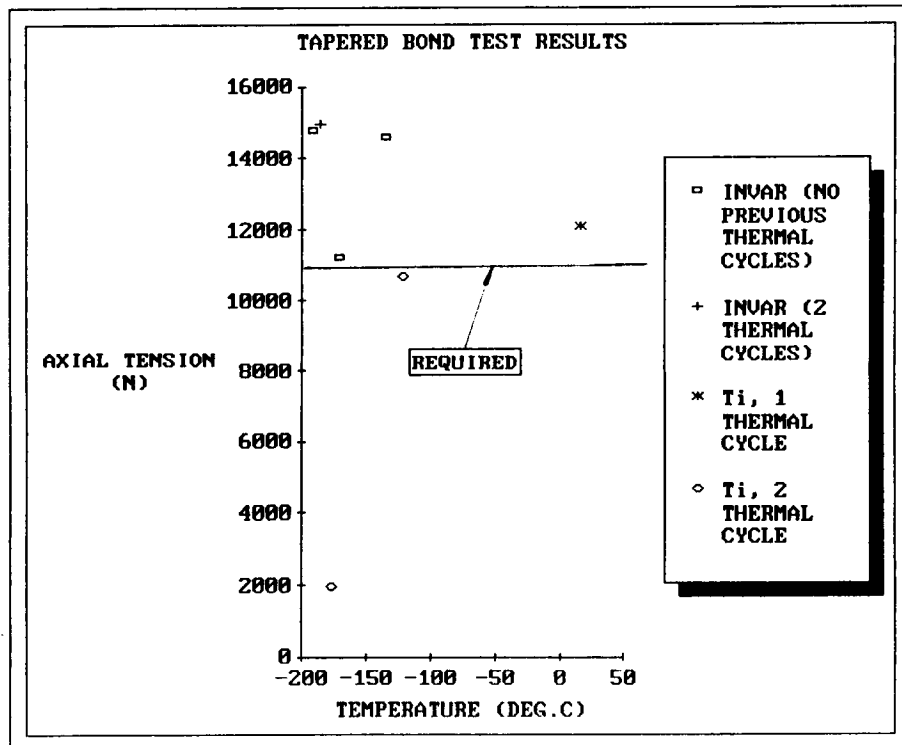
Tapered
Bond

Figure 8. Bond Configurations

Figure 9. Tapered Bond Test Results

Titanium-graphite test samples with a parallel bond line were fabricated in an effort to improve the strength of the titanium-to-graphite bond. Axial slots were cut in the end fitting to allow the metal to more easily conform to the radial contraction of the graphite since the radial CTE of graphite is fairly high, $32 \times 10^{-6}/°C$ ($18 \times 10^{-6}/°F$). The results are included with the results from the tapered bond test in Figure 10. The strength of the parallel bond was only slightly improved over that of the tapered bond at -190 °C and was lower than the tapered bond strength at the higher temperatures, potentially due to the decrease in bond area resulting from the axial cuts.

Conclusion from Testing

The trade study between invar and titanium end fittings showed that invar was the better material choice. The overall mast CTE was too large and the bond strength too low with titanium end fittings. Using invar instead of titanium increased the weight by 1.91 kg (4.2 pounds).

SUMMARY

CTE tests and bond tests verified that the FASTMast design could be tailored to fill the need for a deployable mast with a very low CTE and high strength over the temperature range of -200 °C to 80 °C. By combining materials with inherently low CTE, invar and graphite, for the primary mast members and judicious use of high CTE material with high strength, titanium, the CTE of the mast can be kept to a minimum while retaining high strength and low weight. Table 2 contains a summary of the requirements and the thermal and strength characteristics for the thermally stable mast which was developed.

The mast development is being continued. Improvements are being made to the lanyard deployment mechanism and the device which sequences the bay deployment.
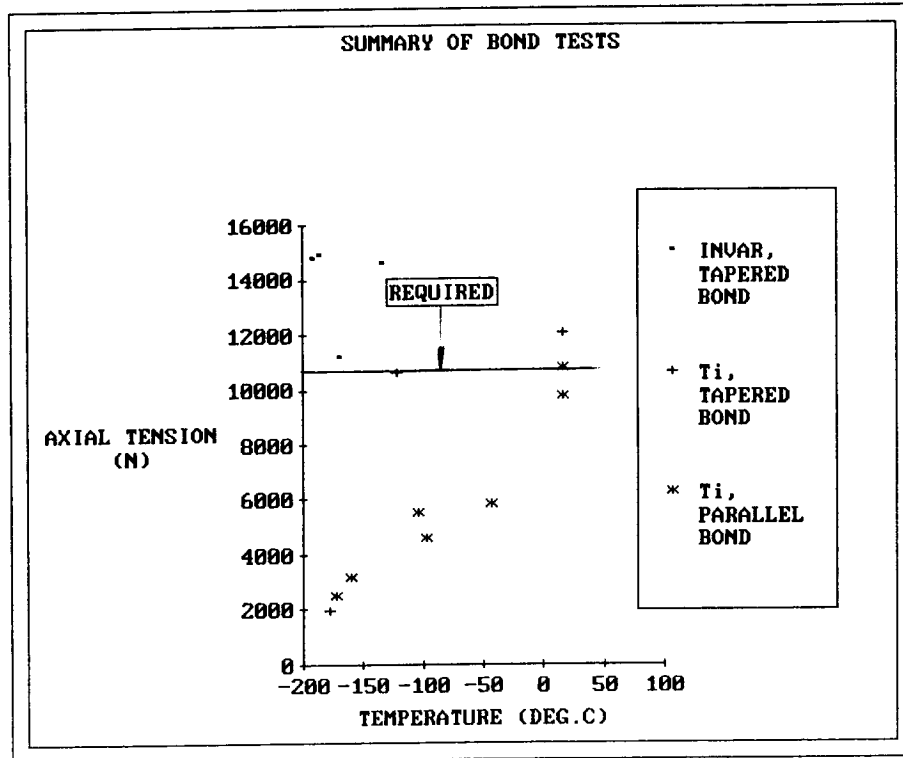
Figure 10. Bond Test Results Summary

	Required	Actual
CTE	$1.0 \times 10^{-6}/°C$ $(.56 \times 10^{-6}/°F)$	$.70 \times 10^{-6}/°C$ $(.38 \times 10^{-6}/°F)$
Maximum Distortion	.064 cm (.025 in.)	.044 cm (.017 in.)
Bending Strength	6770 N-m (60,000 in.-lb)	7950 N-m (70,500 in.lb)

Table 2. Summary of Requirements and Mast Characteristics