SPACE STRUCTURES CONCEPTS AND MATERIALS

Contract No. NAS8-37257

PHASE 2 FINAL REPORT

SMALL BUSINESS INNOVATION RESEARCH

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PROJECT SUMMARY

The primary objective of this Phase 2 SBIR program was to produce a thermally-stable truss assembly capable of enhanced structural performance in the space environment.

This objective has been achieved by designing and manufacturing an all metal matrix tubular truss assembly. The tubular components were developed from continuous graphite-reinforced aluminum. End fittings and assembly sleeves were made from discontinuous ceramic-particulate reinforced aluminum.

Thermal stability was incorporated in the truss assembly by utilizing high stiffness, negative coefficient of thermal expansion (CTE) P100 graphite fibers in a 6061 aluminum matrix, crossplied to provide minimized CTE in the assembled truss. Tube CTE was designed to be slightly negative to offset the effects of the end fitting and sleeve, CTE values of which are approximately one half that of aluminum.

In the design of the truss configuration, the CTE contribution of each component was evaluated to establish the component dimensions and layup configuration required to provide a net zero CTE in the subassemblies which would then translate to a zero CTE for the entire truss bay produced.

The complete truss was installed in a test chamber at Composite Optics, Inc., San Diego, California, and the CTE of the bay assembly was measured with the following results:

CTE = -.208 PPM/°F over the temperature range -150 to +150°F

CTE = -.0428 PPM/°F over the temperature range of -100 to +150°F

The above results demonstrate the viability of designing and building dimensionally stable G/Al composite space structures.

During the CTE testing, rotational distortion of the truss was detected to be less than 1/4-degree.

MMC bay assemblies such as that demonstrated in this development effort could form the basis for satellite, space antenna and space station structures which are essentially tailorable to provide thermal stability over a wide range of space environmental conditions. The MMC construction also provides enhanced capability for joining (e.g. metallic joints), high thermal conductivity for minimizing temperature gradients, improved survivability, and no outgassing or susceptibility to nascent oxygen.

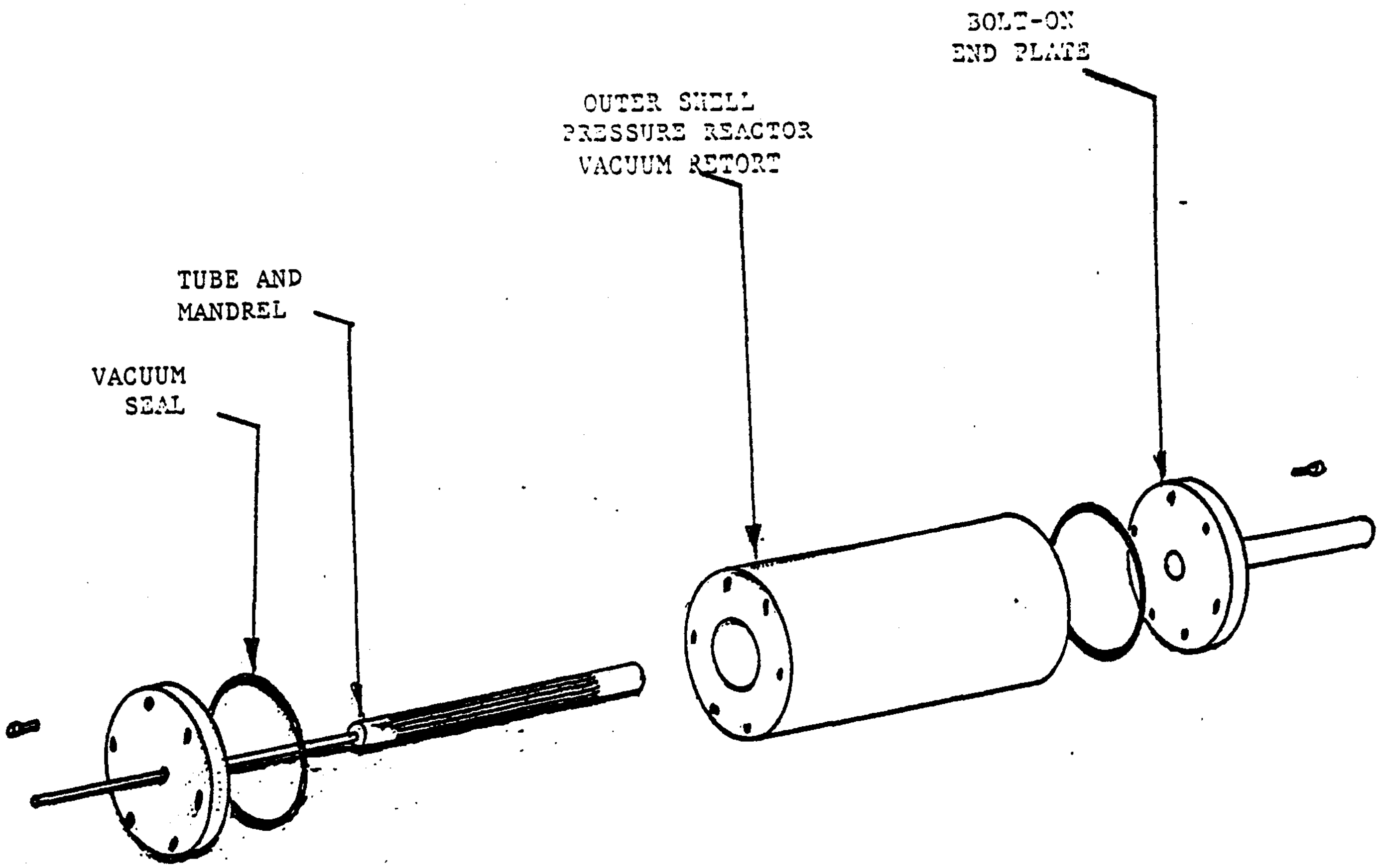
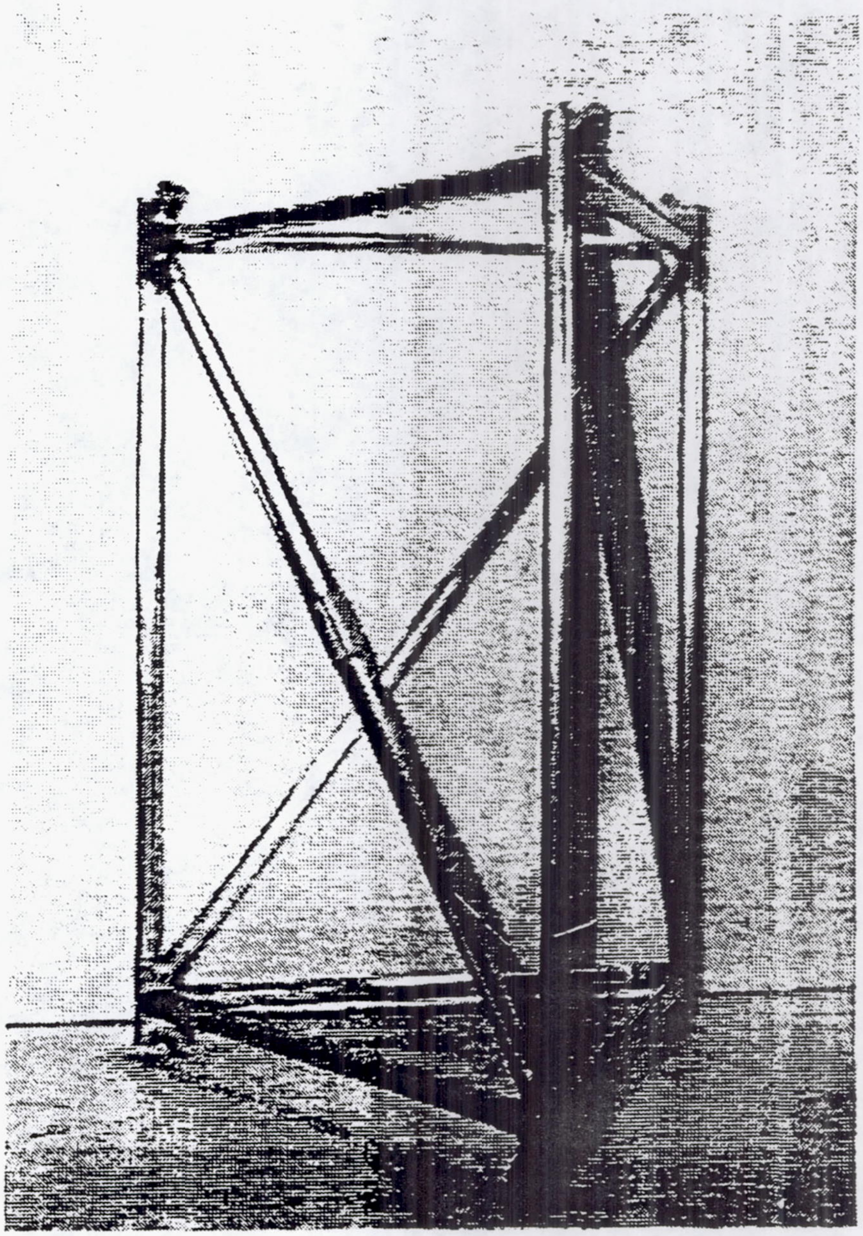


Figure 7. Pressure Vessel/Retort System for DWG Tube Fabrication.



MMC Truss Structure
(G/Al ±12° Thin Wall Tubes
B_4C/Al Net Shape Forged End Fittings)

Measured Truss CTE -.208 PPM/°F
over -150 to +150°F.

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1.0 INTRODUCTION

This program is an extension of successful Phase 1 research involved in evaluation of graphite/aluminum metal matrix composites (MMC) for space structures application. The composites were made by the proprietary DWG process. This effort resulted in demonstration of a near zero CTE truss end fitting concept. The research was extended to a Phase 2 program to fabricate a tubular DWG graphite/aluminum truss assembly having the structural integrity and thermal stability needed for space application. The scope of this work involved the following program tasks:

a. Establish design requirements for space-truss structure components in terms of CTE, strength, stiffness, weight and configuration.

b. Design MMC end fittings and tube elements to meet the established design requirements.

c. Characterize the MMC materials to be used for fittings and tubes.

d. Demonstrate fabricability and thermal stability of tubes/end fittings assembly.

e. Fabricate sufficient hardware to assemble a single truss structure for testing.

f. Prepare summary report including alternate future use of this technology.

g. Deliver the dimensionally stable space truss assembly to NASA.

2.0 TECHNICAL DISCUSSION

In this Phase 2 evaluation of Space Structures Concepts and Materials, it was elected to use the metal matrix composites DWG and DWAl 20® to build a generic demonstration truss assembly with structural integrity and to show by CTE testing that the truss is thermally-stable. DWG is a proprietary thin ply continuous graphite reinforced aluminum composite from which the tubular components were fabricated. The truss end fittings were constructed using the discontinuous ceramic particulate reinforced MMC DWAl 20®. The Program Plan is depicted in Figure 1.

2.1 TRUSS CONFIGURATION

Candidate truss assembly configurations that were considered are illustrated in Figure 2, viz., a cubical bay, an equilateral triangle with square sides, and a tetrahedral shape. In the final analysis, the triangular shape with square sides was selected since it is not excessively complicated, it is well within the scope of work, it demonstrates fully the required assembly

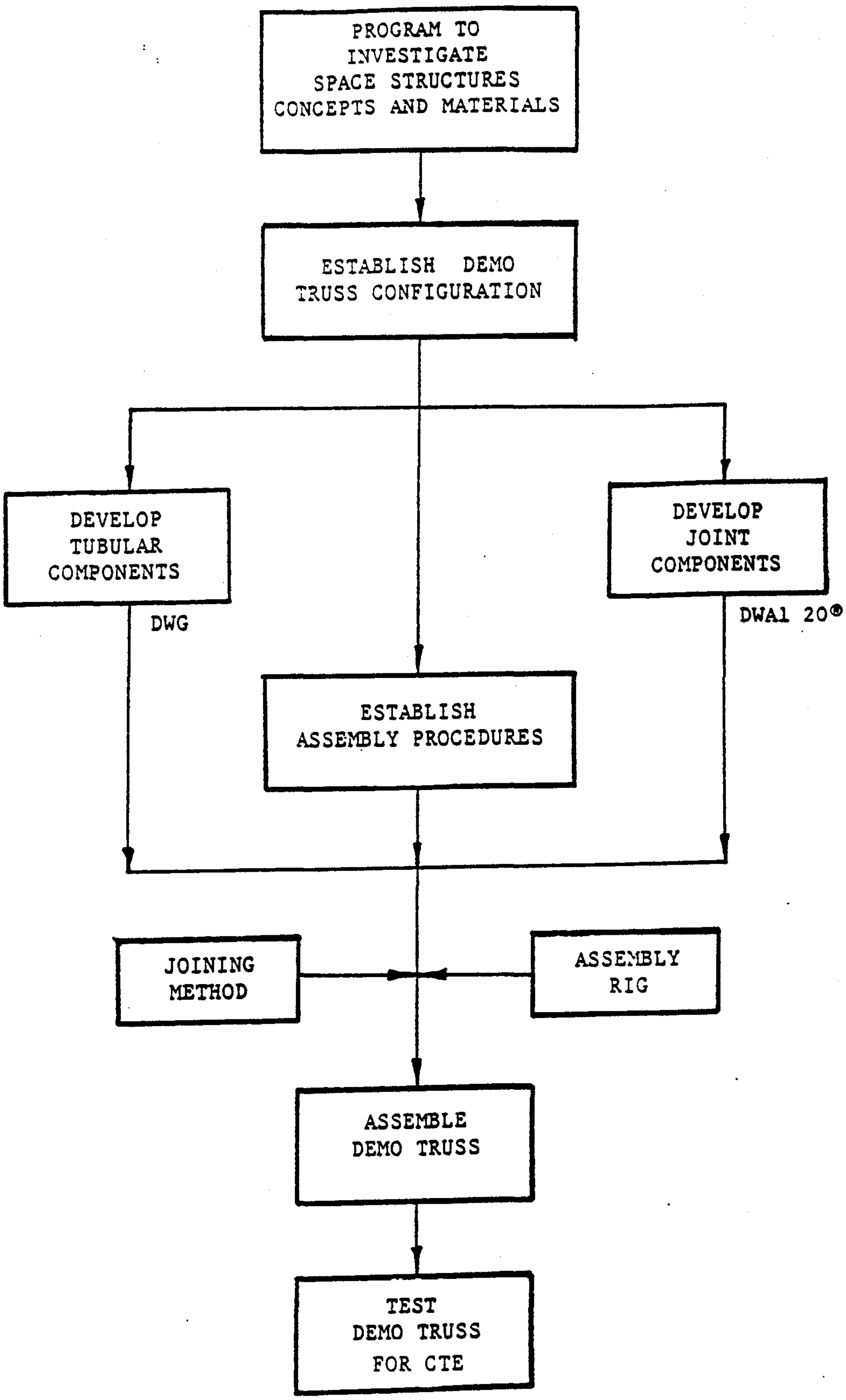


Figure 1. Phase 2 Program Plan

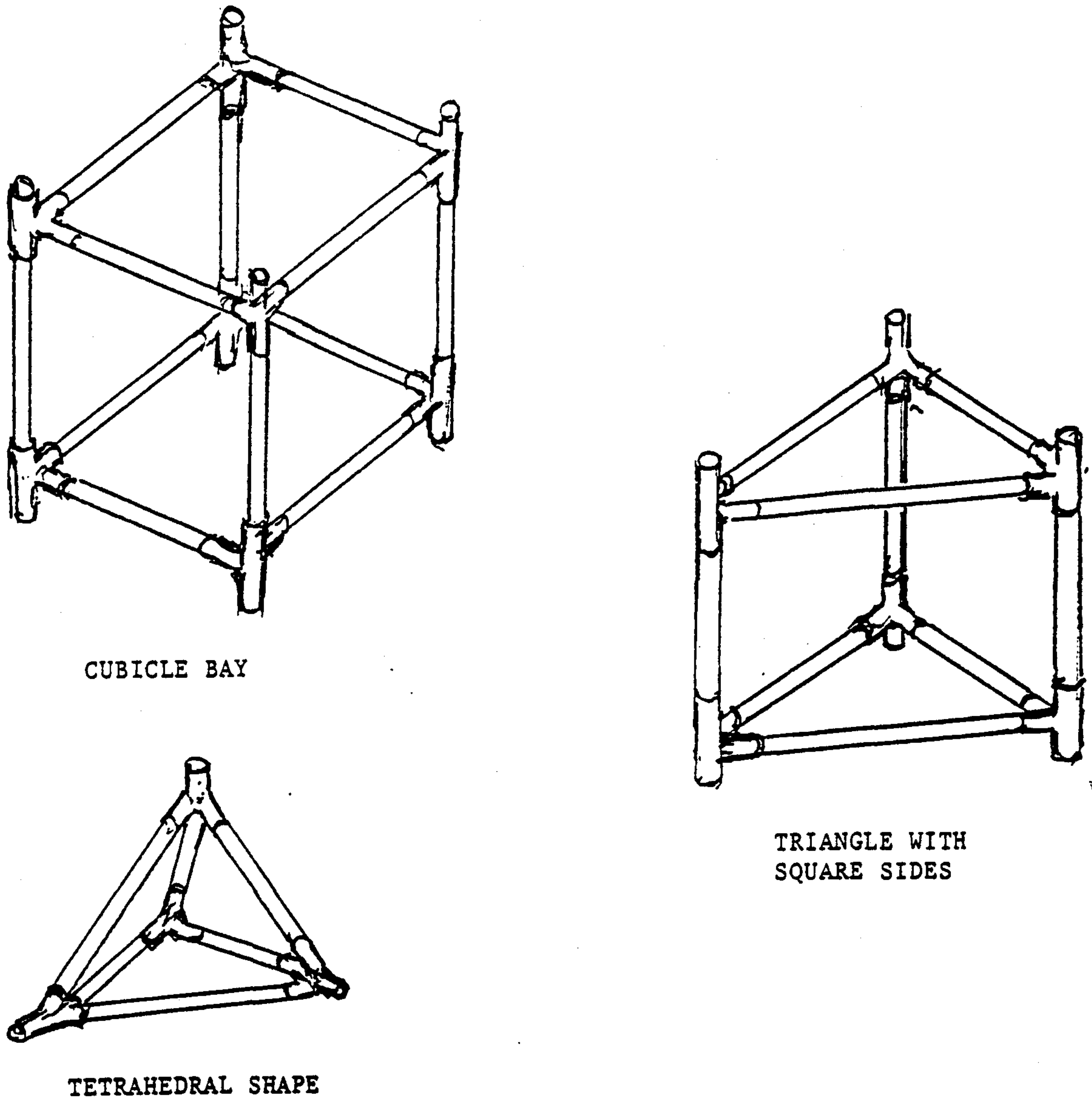


Figure 2. Candidate Truss Assembly Configurations

installation, and it can be tested readily. The selected truss is illustrated in more detail in Figure 3, showing overall dimensions, diagonal stiffeners, and assembly sleeves installed on the diagonals. Nominal diameter was specified at 1½ inches for the tubes, the sleeves and the end fitting appendages.

2.2 TUBULAR COMPONENT DEVELOPMENT

Development tasks to produce the required graphite aluminum tubes included:

a. integral end collar fabrication.
b. scaling up from 1-inch diameter tubes to 1½-inch diameter tubes.
c. scaling up to 4 feet and 5 feet tube lengths.
d. crossply fabrication of the required size tubes.

Fabrication of tubes with integral end collars proved to be impractical for this program since the tube ends would be inserted into end fittings and sleeves, then subsequently bonded in place. While fabricating DWG tubes with integral DWAl 20® end collars is not sufficiently feasible for application at this time, it has merit for protecting graphite-aluminum tube ends during packing, handling, and transport, as well as providing an option of joining; i.e., welding in the future.

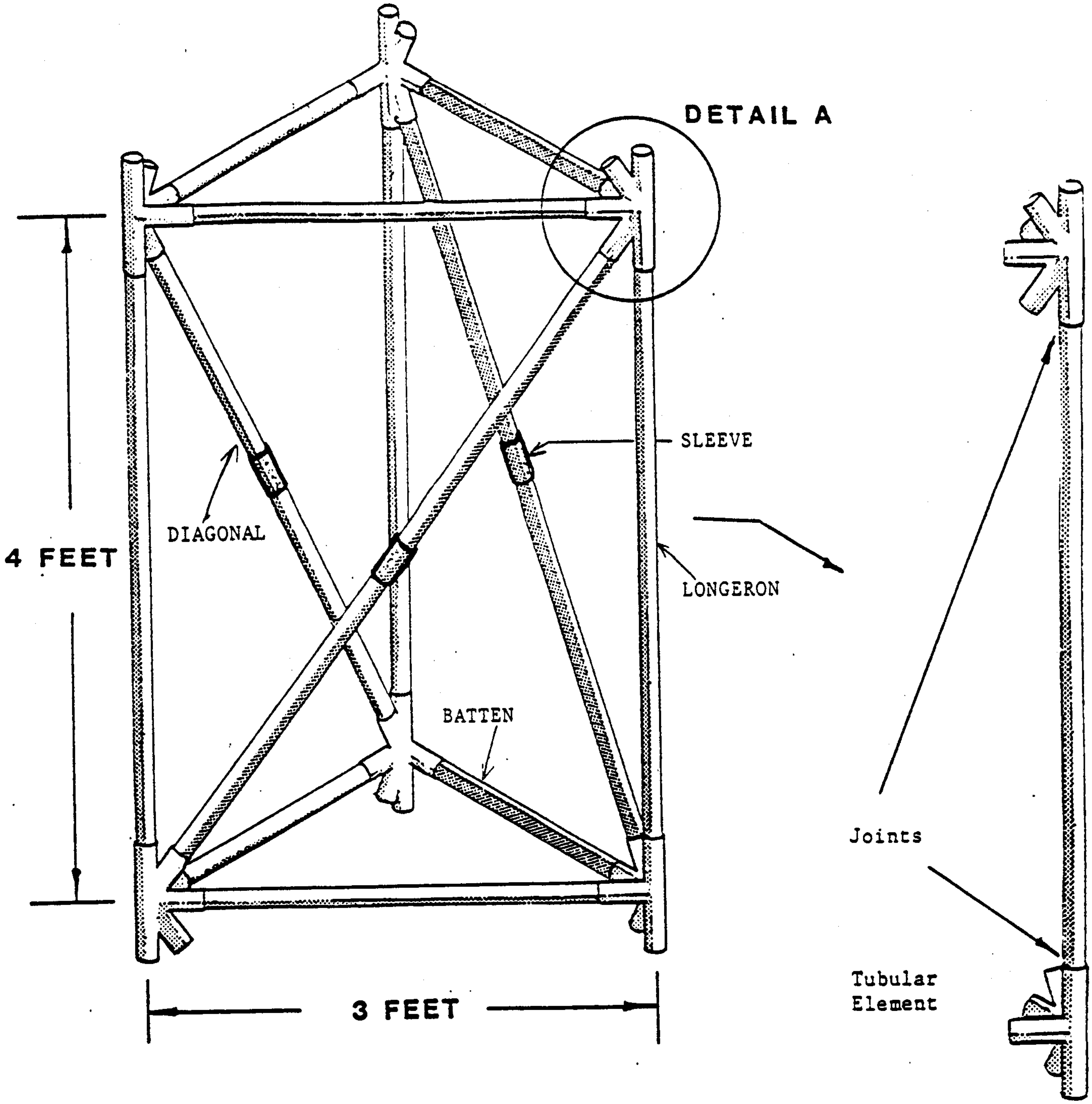
Mechanical and thermal properties of the DWG tubes were first established by testing flat panel material constructed of aluminum foil and graphite fibers with ply orientation varied over the range of interest. These DWG properties are summarized in Table 1 for the seven panels fabricated, each employing 8 layers and varying fiber crossply angle.

To illustrate consistency of consolidation as well as to reveal any anomalies in the fabrication of each panel, metallography was produced and is presented in Figures 4 and 5.

Having established the structural integrity of the applicable DWG tube material of construction, the associated thermal properties were evaluated. Small samples were extracted from each of the DWG panels. Corresponding thermal expansion tests were conducted at Harrop Industries, Incorporated, Columbus, Ohio. The test samples are shown in Figure 6 with dimensions indicated. Test results are presented in Table 2, illustrating the expected variation of CTE with crossply angle in the composite. The raw test data is further included in Appendix A.

After determining composite design conditions required for tubular truss members, DWG tubing was manufactured to the specified dimensions. The type of tooling used is illustrated in Figure 7, whereby the tube material is placed on the mandrel which is then positioned inside the pressure reactor. Parameters are set to generate conditions that consolidate the tube unit which is removed subsequently, cleaned and trimmed.

A number of completed DWG tubes are illustrated in Figure 8. These tubes incorporated approximately 45v/o P100/6061, 4 layers, ±12° crossply angle,



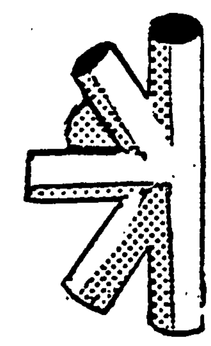
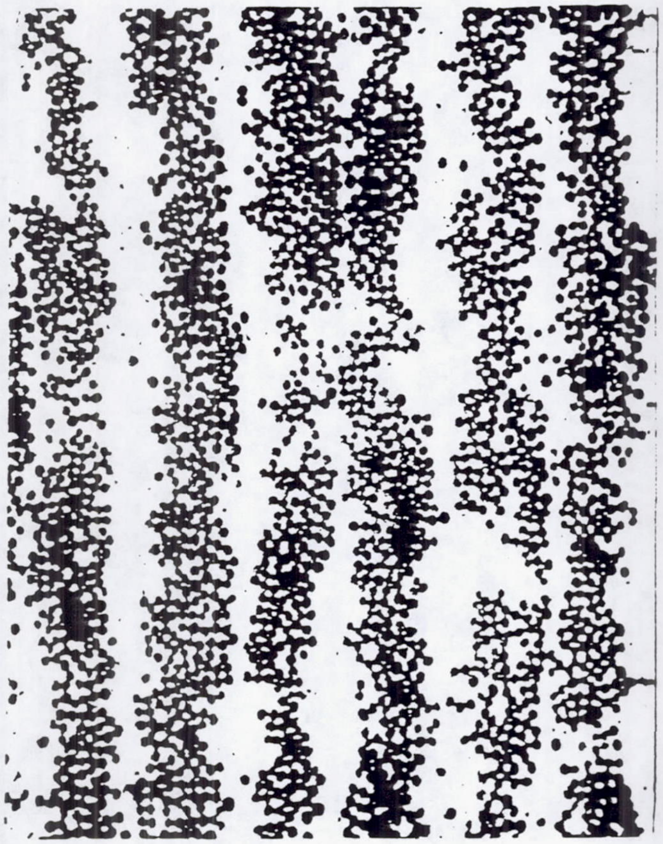


Figure 3. Final Truss Assembly with Component Definition

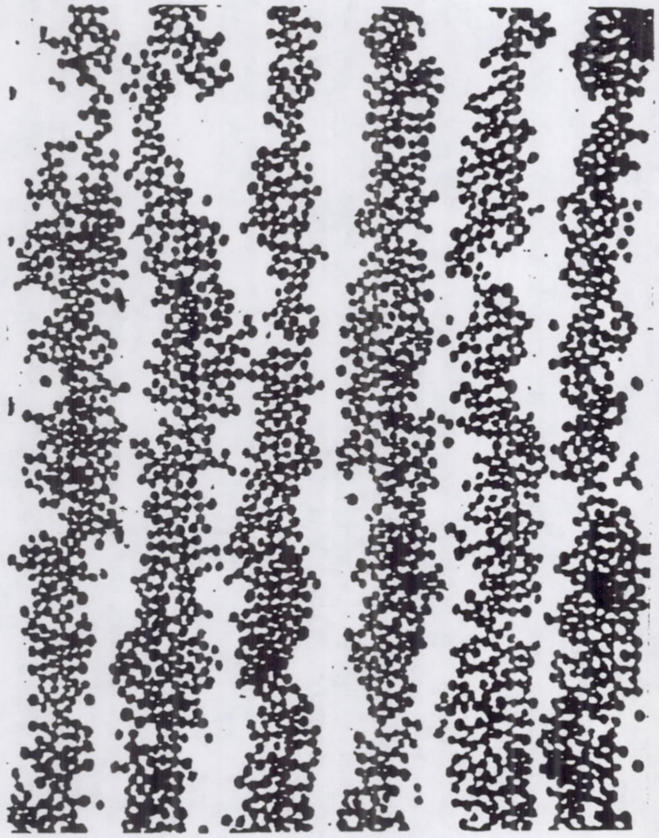
TABLE 1. Tensile Test Results of 8-layer Crossply DWG P100 Gr/6061 Al

PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	TEST DIRECTION	E, msi	UTS, ksi	ϵ_f, %	REMARKS*
D-1472	17002	10°	49.7	0°	44.20	85.4	0.211	
	17003				42.34	77.0	0.196	
	17004				40.35	66.5	0.180	
	17005				41.40	68.6	0.174	
	17192			90°	3.49	5.30	0.297	
	17193				3.76	5.49	0.455	
	17194				3.74	5.38	0.384	
	17195				3.84	4.96	0.224	
D-1518	17356	5°	45.1	0°	60.84	>64.30	>0.107	Glue Failure
	17357				57.05	>45.10	>0.081	Glue Failure
	17358				59.87	>79.87	>0.147	Glue Failure
	17359				56.93	>67.50	>0.122	Glue Failure
	17370			90°	3.56	4.82	0.209	
	17371				4.89	5.80	0.231	
D-1519	17352	15°	48.8	0°	46.68	63.91	0.149	
	17353				45.48	72.44	0.172	
	17354				50.87	>81.08	>0.185	Glue Failure
	17355				51.31	>60.06	>0.128	Glue Failure
	17376			90°	4.20	7.65	0.486	
	17377				4.77	7.93	0.385	
D-1520	17348	10°	41.4	0°	51.57	76.76	0.161	
	17349				45.70	53.26	0.129	
	17350				52.40	80.39	0.189	
	17351				48.15	75.24	0.161	
	17372			90°	4.88	8.60	0.322	
	17373				4.53	7.00	0.210	
D-1521	17360	15°	42.0	0°	44.76	71.76	0.187	
	17361				39.76	67.56	0.187	
	17362				44.87	>66.40	>0.171	Glue Failure
	17363				45.09	72.27	0.178	
	17374			90°	5.16	9.64	0.390	
	17375				5.70	9.54	0.447	
D-1522	17342	20°	41.1	0°	36.48	66.63	0.230	
	17343				33.72	57.45	0.209	
	17344				37.51	53.18	0.169	
	17345				36.66	>55.97	>0.195	Glue Failure
	17346			90°	5.18	10.48	0.572	
	17347				5.34	10.70	0.483	
D-1523	17364	25°	47.3	0°	31.60	65.15	0.356	
	17365				30.08	63.28	0.324	
	17366				29.40	52.50	0.273	
	17367				30.31	51.12	0.268	
	17378			90°	4.85	10.02	0.529	
	17379				4.89	10.35	0.478	

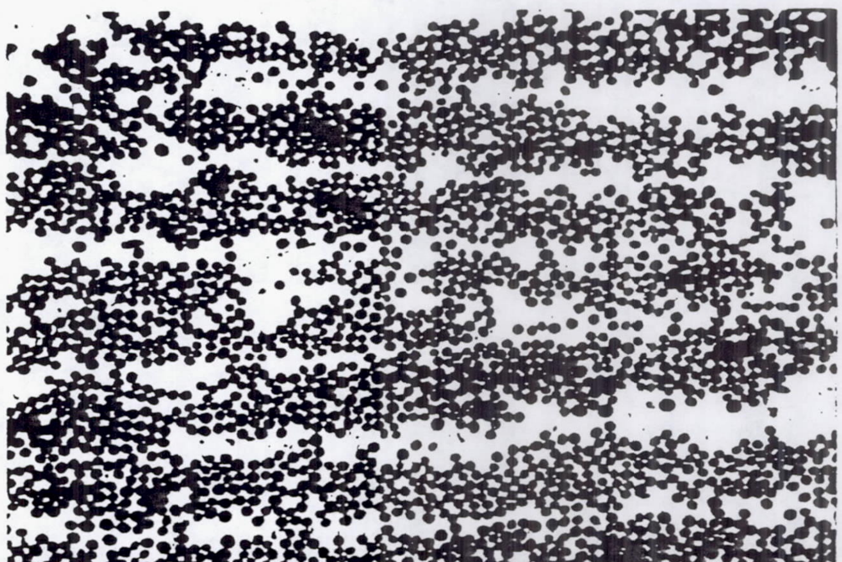
GLUE FAILURE = Adhesive Bonded Tabs for Pin-load Gripping Failed in Adhesive Joint (Epoxy)
E = Young's Modulus
UTS = Ultimate Tensile Strength
ϵ_f = Strain at Fracture



D-1521 ±15°

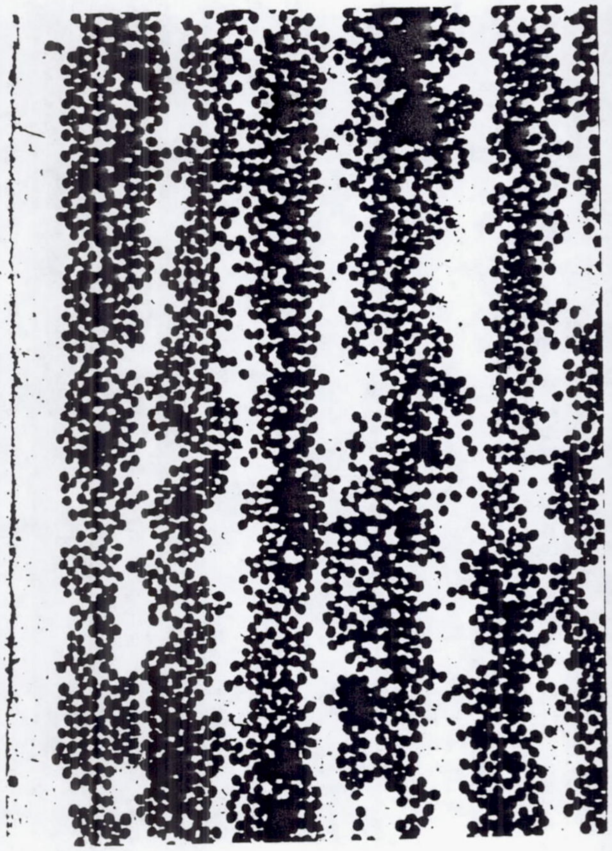


D-1522 ±20°

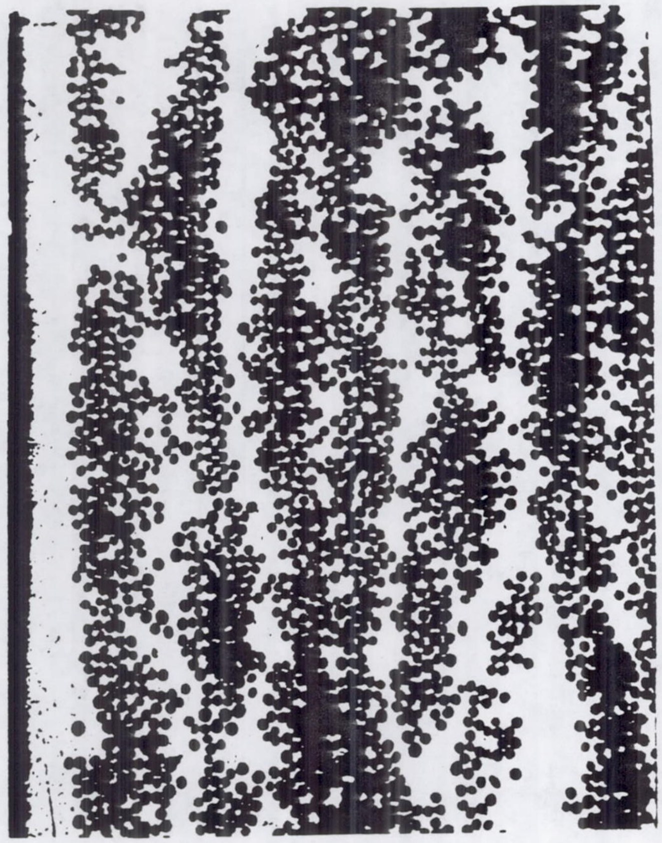


D-1523 ±25°

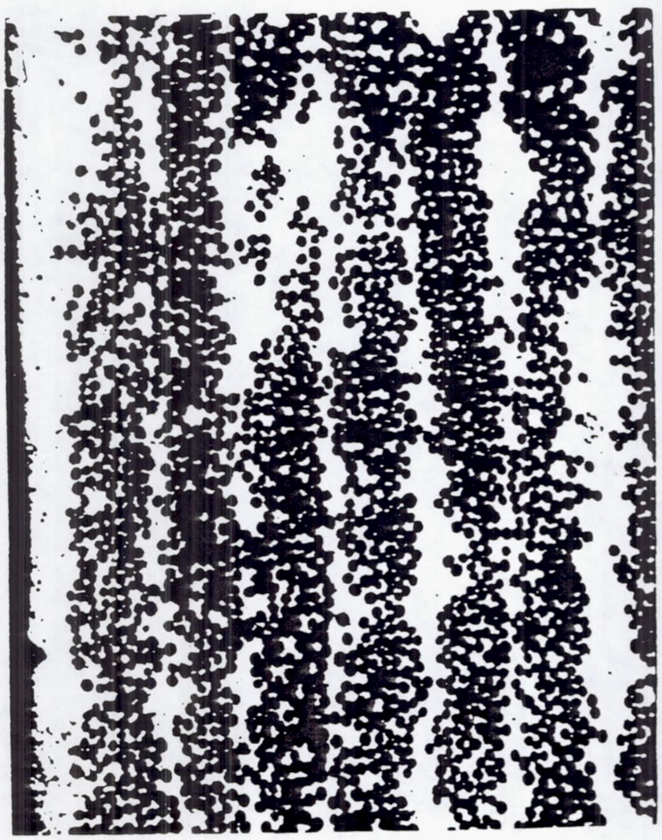
FIGURE 4. Metallography Observed of the 8-layer DWG Panels Reported in Table 1, P100 Graphite/6061 Aluminum. 150X Magnification



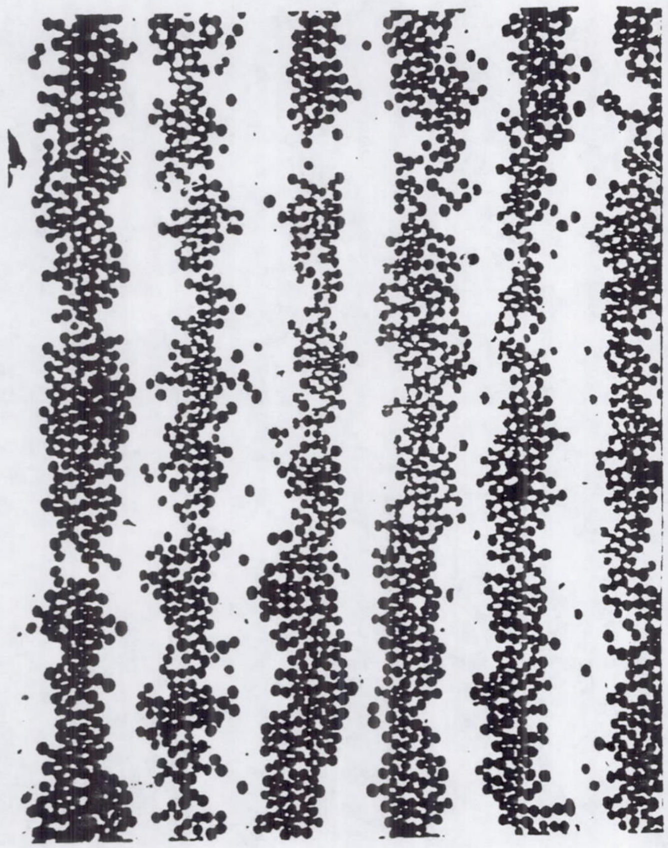
D-1472 ±10°



D-1518 ±5°



D-1519 ±15°



D-1520 ±10°

Figure 5. Metallography Observed of the 8-layer DWG Panels Reported in Table 1, P100 Graphite/6061 Aluminum. 150X Magnification

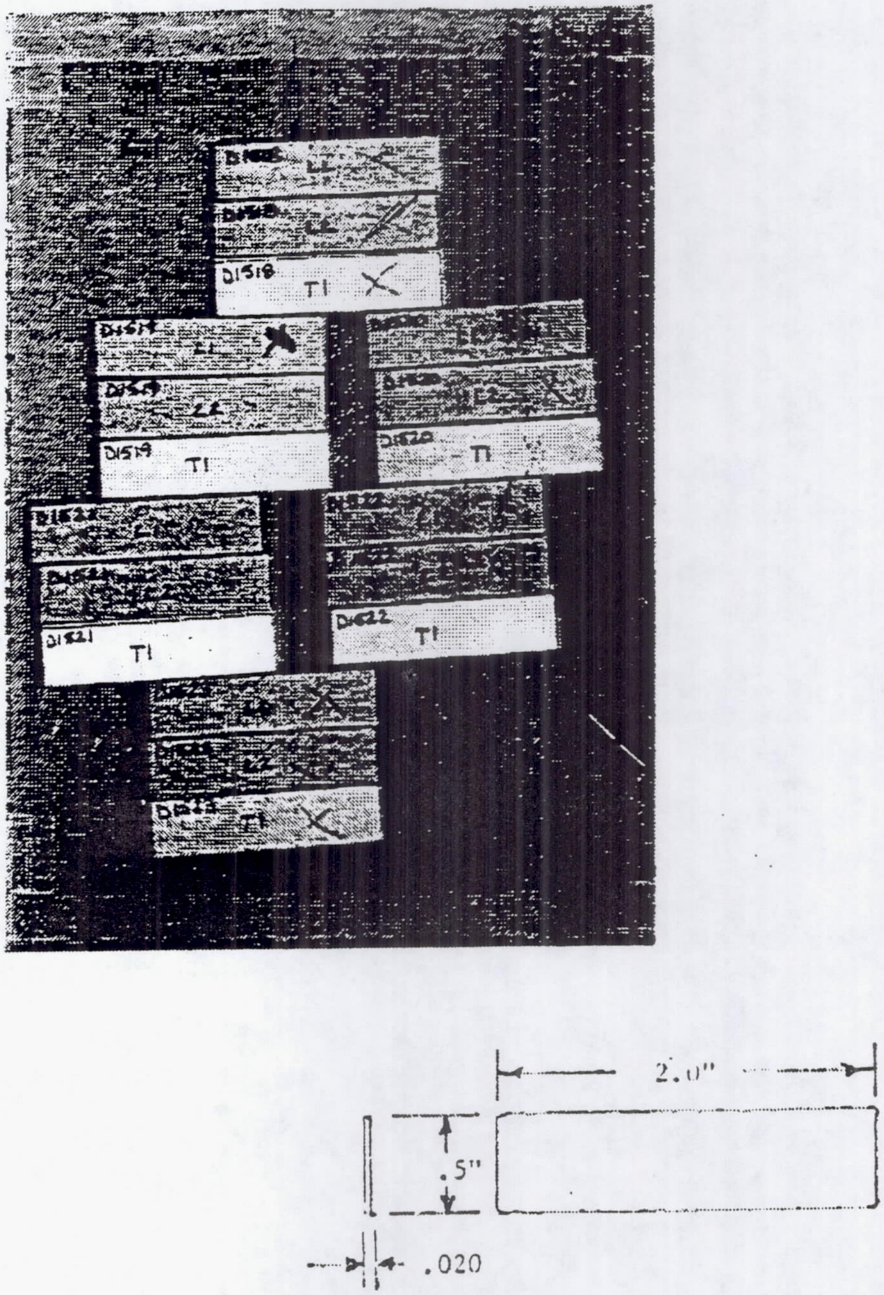
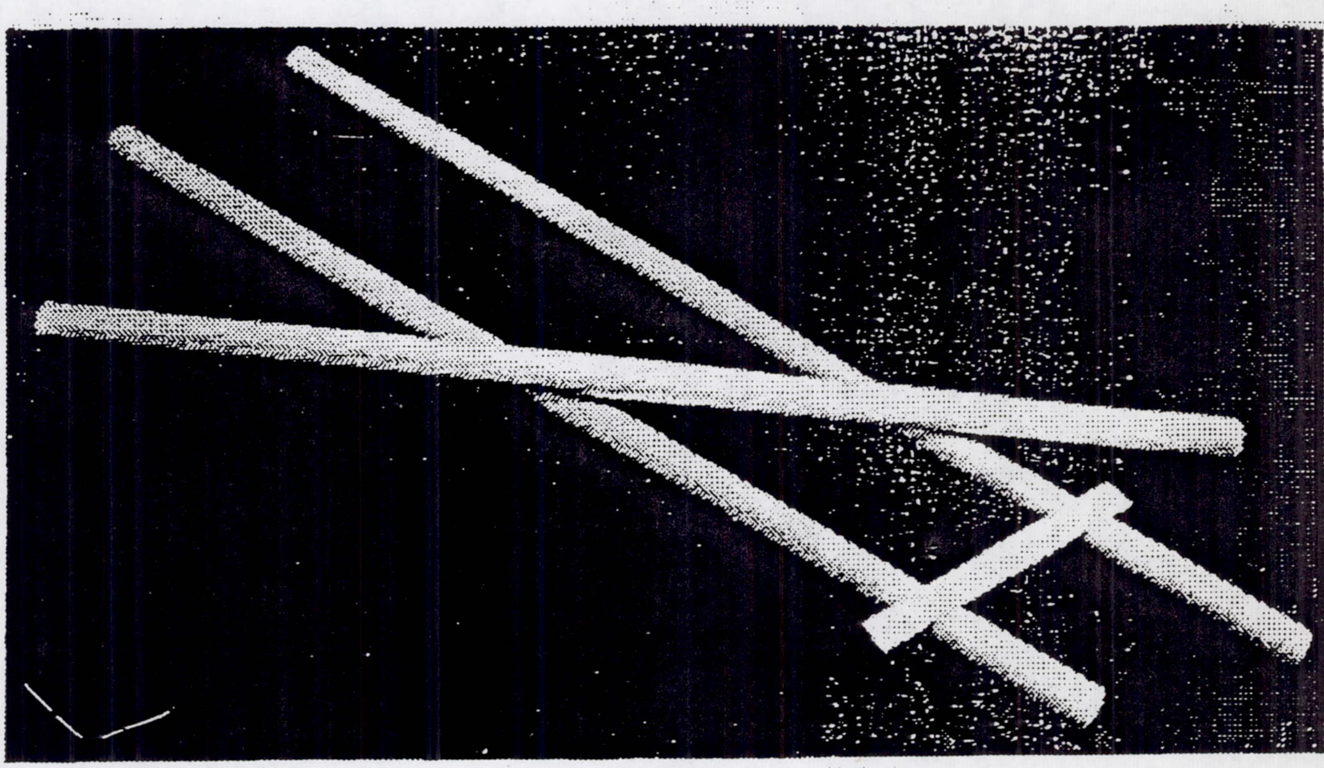


Figure 6. Panel Samples for CTE Tests

Table 2. Thermal Expansion (CTE) Measurements of 8-Layer Crossply DWG P100 Gr/6061 Al.

PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1518	17356	±5°	45.1	.694
	17357			.749
	17358			
	17359			
	17370			
	17371			
D-1519	17352	±15°	48.8	-.1378
	17353			-.0895
	17354			
	17355			
	17376			
	17377			
D-1520	17348	±10°	41.4	.3651
	17349			.555
	17350			
	17351			
	17372			
	17373			
D-1521	17360	±15°	42.0	
	17361			.0806
	17362			.0358
	17363			
	17374			
	17375			
D-1522	17342	±20°	41.1	-.297
	17343			
	17344			-.1145
	17345			
	17346			
	17347			
D-1523	17364	±25°	47.3	
	17365			-.8769
	17366			
	17367			-.6836
	17378			
	17379			



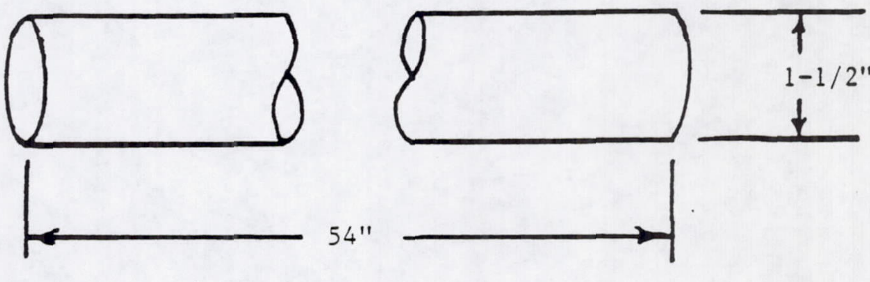


Figure 8. Successfully Fabricated Tubes, 4 ply, P100/6061 Aluminum, Crossply Varied.

with wall thickness .025 inches. The crossply angle was established in consonance with the estimated end fitting CTE and the truss dimensions.

2.3 END FITTING DEVELOPMENT

Thermal stability of the MMC space truss assembly is facilitated by providing minimum CTE in all component parts. Accordingly, the end fittings must be constructed of low CTE material. Consequently, the total truss - DWG tubes combined with DWAl 20® end fittings - will exhibit essentially zero CTE, maximizing the probability of thermal stability in the truss assembly.

The established demonstration truss configuration dictates multi-appendaged end fittings. For MMC, the most practical approach to producing this complex shape is to forge the basic unit to near net dimensions externally, then machine the inside contours to the dimensions required for mating with the DWG tubes.

2.3.1. End Fitting Material of Construction

The selected DWAl 20® MMC material system was 30v/o B_4C/6061. This system is representative of those with which DWA has reached a significant level of experience, especially the matrix aluminum alloy 6061. The selection of 30v/o B_4C was based on structural considerations and recent experience forging similar end fittings. With the relatively high reinforcement level of 30v/o, using B_4C could represent a reasonable weight saving particularly when reflected throughout a large size space station. In addition, welding is more compatible with MMC materials reinforced with B_4C than with competing ceramic reinforcements, and higher propensity for minimizing CTE in the resulting composite is suspected (but not fully investigated as yet). The DWA bank of thermal expansion data (Figure 9) indicated that the CTE of 30v/o B_4C/6061 ranges between 7 and 7.5 PPM/°F (μ-in/in/°F). As shown in Figure 10, Cribb's estimate falls within these bounds, for a practical value of 7.2 PPM/°F for CTE in the truss end fittings. The previously discussed selection of ±12° for the tube component was derived from this value. The corresponding analysis follows.

For end fittings constructed from particulate reinforced DWAl 20®, the reinforcement volume percent must be sufficiently high to provide a favorably low CTE (as illustrated in Figures 9 and 10). Accordingly, the tube components must be so fabricated that the CTE is tailored to a low enough value to render near-zero net CTE in the assembly. The required combination is calculated using the rule-of-mixtures as follows:

$$\alpha_C = (L/O)_T(\alpha_T) + [1 - (L/O)_T](\alpha_E) \quad (1)$$

Where: α = Coefficient of Thermal Expansion

L/O = Length Percent $\frac{\text{LENGTH OF TUBE}}{\text{TUBE + END FITTINGS}}$

SUBSCRIPTS: T = Tube

E = End Fitting

C = Combination

α_C 0

$-(L/O)_T \alpha_T = [1-(L/O)$

$\alpha_T = \frac{[1-(L/O)_T]\alpha}{(L/O)_T}$

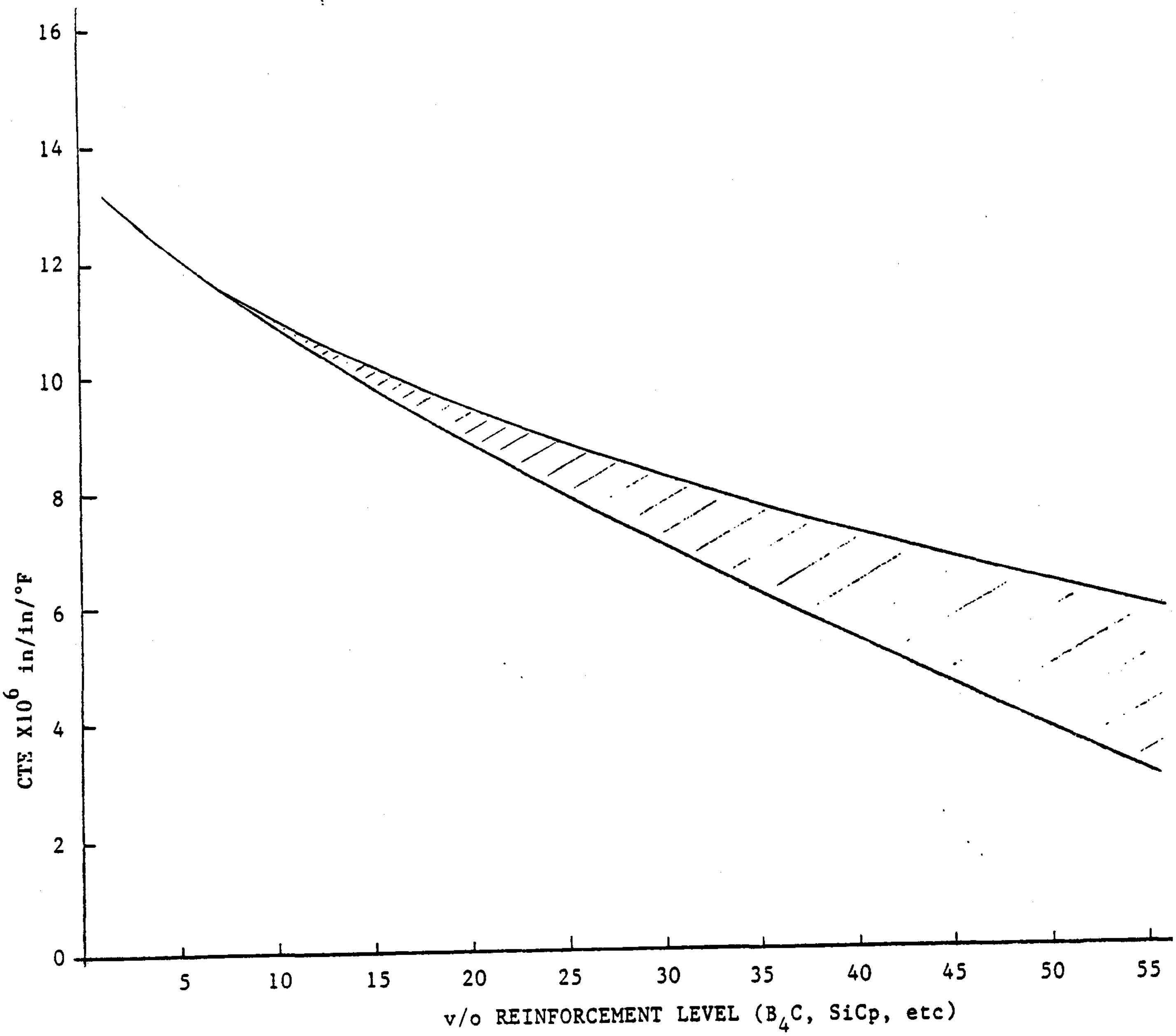


FIGURE 9. Decrease in Thermal Expansion of DWAl 20® with Increase in Reinforcement Loading.

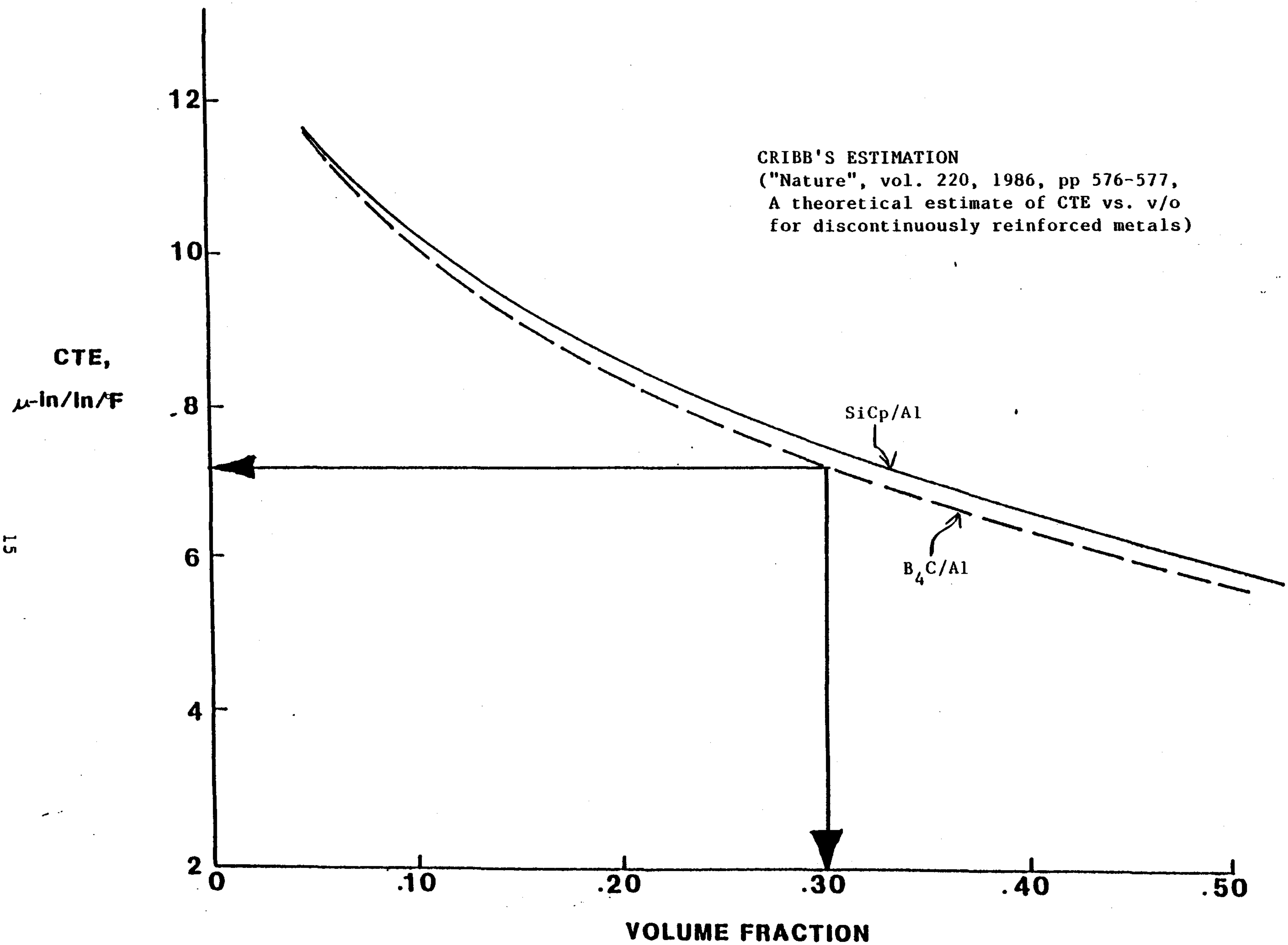


Figure 10. Variation of CTE with Ceramic Particulate Reinforcement Volume Percent in DWAl 20® End Fittings

For $\alpha_C = 0$,

$$\alpha_T = \frac{-[1-(L/O)_T]\alpha_E}{(L/O)_T} \quad \text{———————} \quad (2)$$

As an example of the relationship between component CTE values and truss dimensions, for 0-CTE in the assembly, assume that an assembly consists of a 3-foot long tube with two identical end fittings. Further assume in the example that $\alpha_E = 6$ (for the two equivalent 3-inch end fittings). Then, from equation 2, for a 3-foot long tubular element, $\alpha_T = -1$, as read on Figure 11. Similarly, Figure 12 illustrates the relationship for a 5-foot long tubular element. From the above presentations, the general influence of tube length on the assembly CTE is illustrated in Figure 13 for the examples of $\alpha_E = 3$ and 6, and end fitting effective length of 3 inches. Shown is the decreasing requirement for utilizing negative CTE tubes as the tubular strut length increases. Further illustrated is the desirability for lower end fitting CTE, for example, directly proportional to the requirement for negative tube CTE. The lower the end fitting CTE (α_e), the less the demand for negative tube CTE (α_T). For reference, the CTE value of 7.2 (30v/o B_4C/6061) is indicated on the above example figures.

2.3.2. End Fitting Fabrication

Development of the selected end fitting commenced with design of the multi-appendaged unit shown in Figure 14. Key dimensions are presented in Figures 15 and 16 in consonance with tubular components and the established truss configuration.

Since the end fittings were forged units it was important to establish at an early stage the preform dimensions and configuration to facilitate timely preform stock extrusion. DWA was fortunate to have experienced recent development of a similar but smaller end fitting. Wooden models of the two units are compared in Figure 17. As was done in the previous activity with the smaller unit, the larger (NASA) end fitting model was immersed in a beaker of water to provide an initial estimate of the required preform volume (41 cubic inches). Combining previous experience with the plan view configuration depicted previously in Figure 15, and considering the volumetric measurement of the end fitting model, it was decided to extrude a round bar with 3½ inch diameter from an eight-inch diameter billet. Subsequent to extrusion, the bar was cut to lengths to provide forging preforms.

2.3.2.1 Forging Die Set Development. The die set required to forge the rigid end fittings was fabricated as described in the series of sketches which follow. The punch element was cut out of a solid piece of H13 tool steel by EDM. The outer remaining shell formed the die sleeve which was bolted to the base plate. The contours in the base plate and punch face were machined by conventional methods. The sketches describing the die set are summarized in Figures 18 through 22.

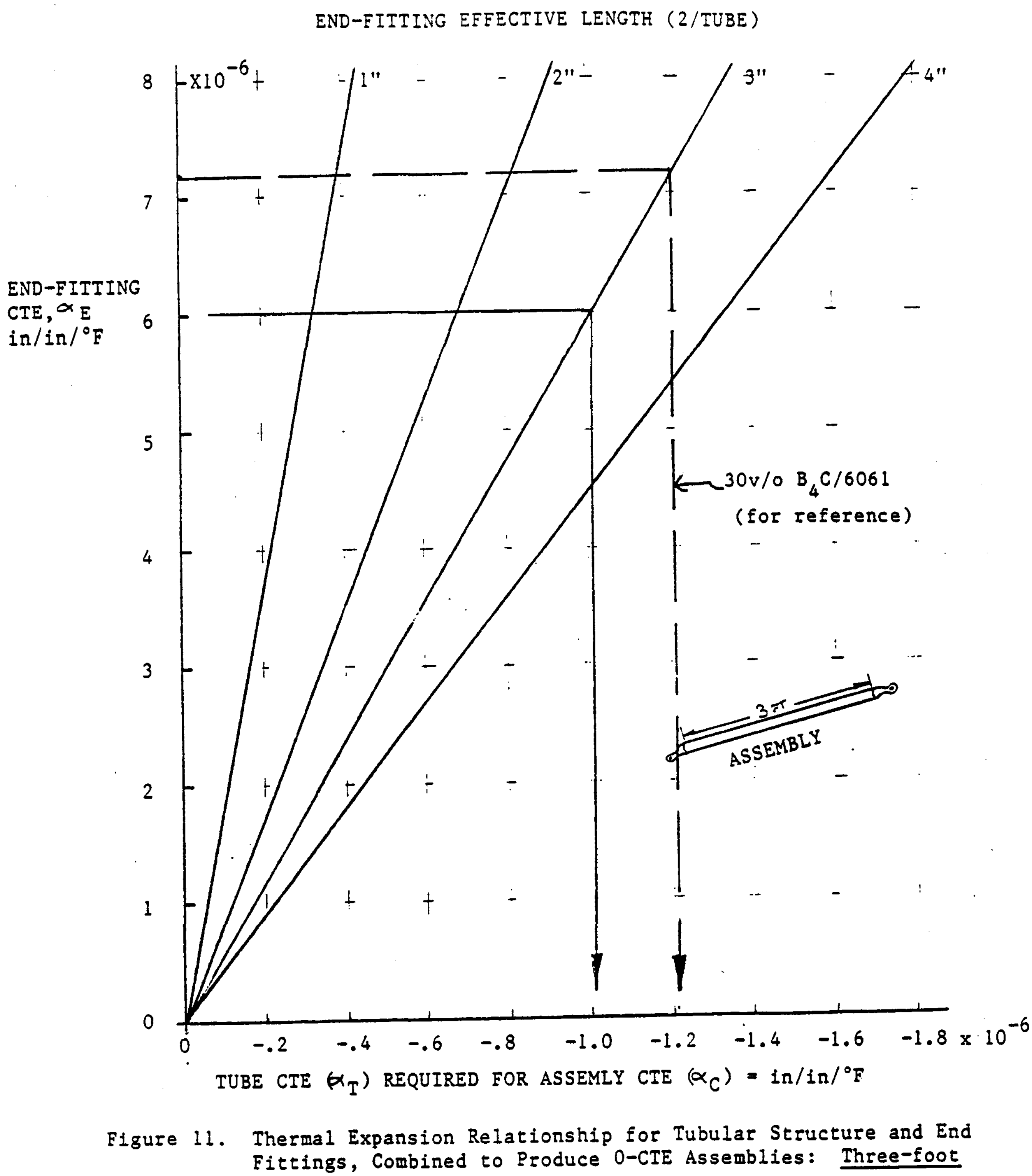


Figure 11. Thermal Expansion Relationship for Tubular Structure and End Fittings, Combined to Produce 0-CTE Assemblies: Three-foot Assembly.

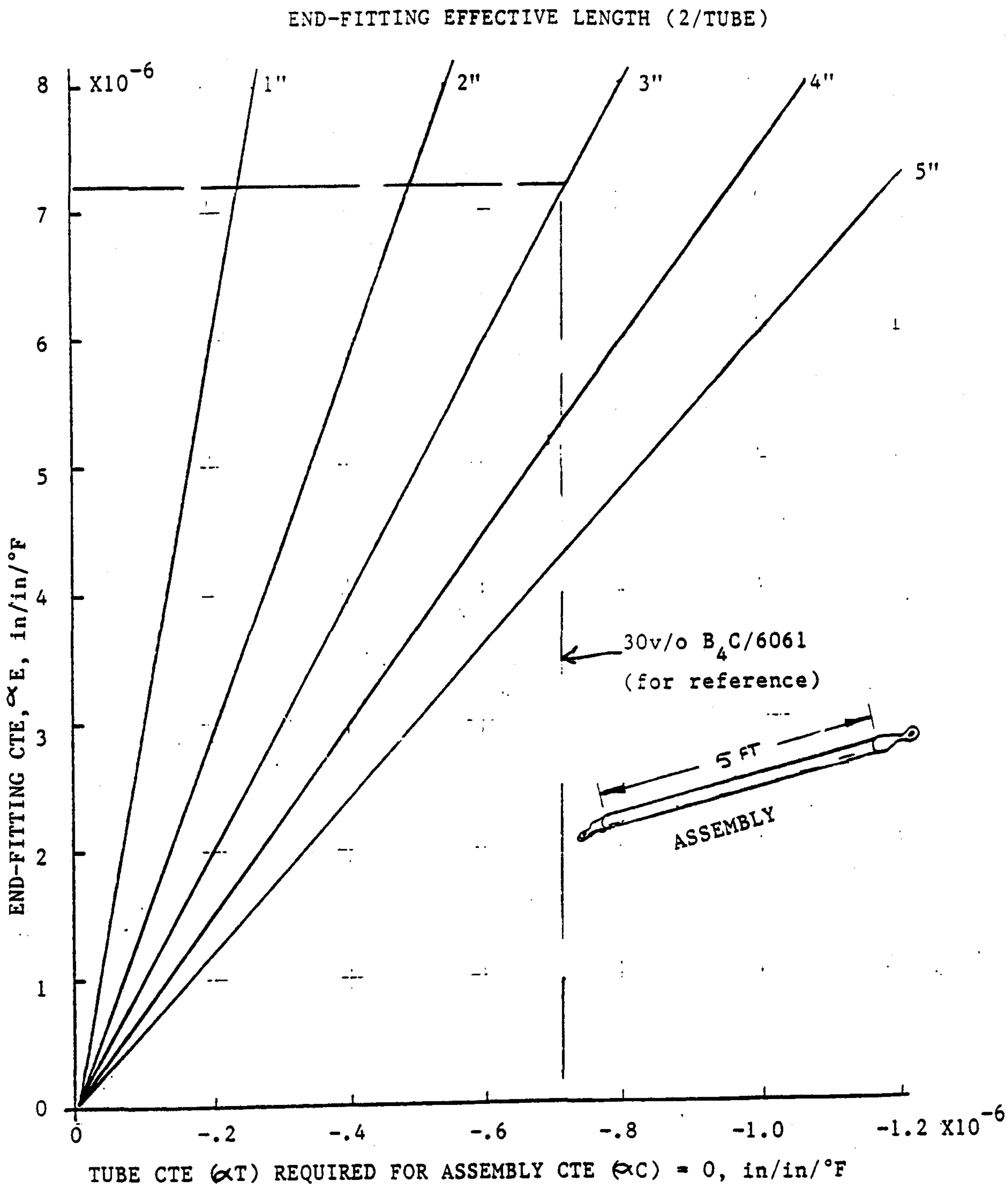


Figure 12. Thermal Expansion Relationship for Tubular Structure and End Fittings, Combined to Produce 0-CTE Assemblies: Five-Foot Assembly.

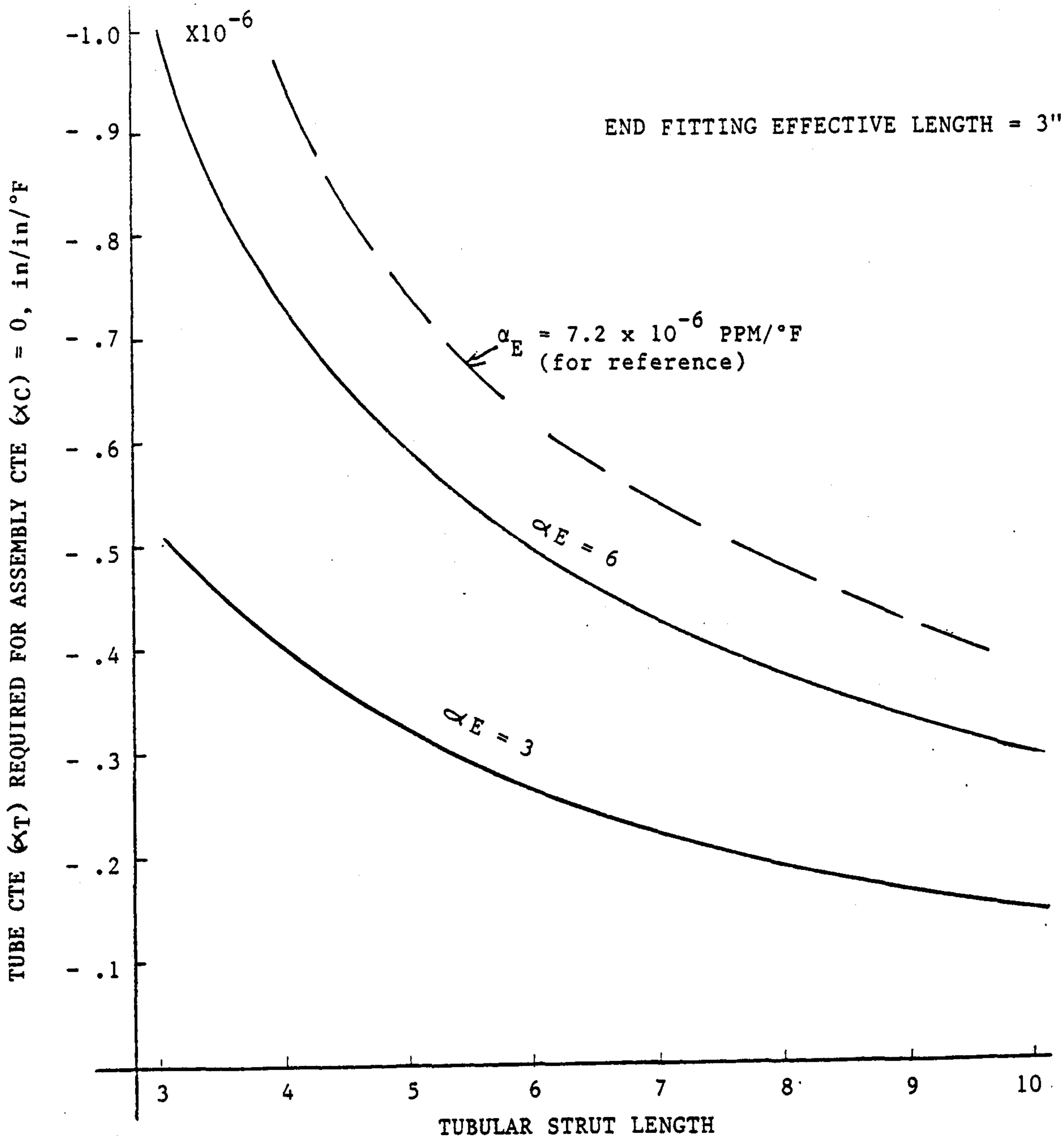


Figure 13. Influence of Tube Length and End Fitting CTE (αE) on Tube CTE (αT) Negative Requirement.

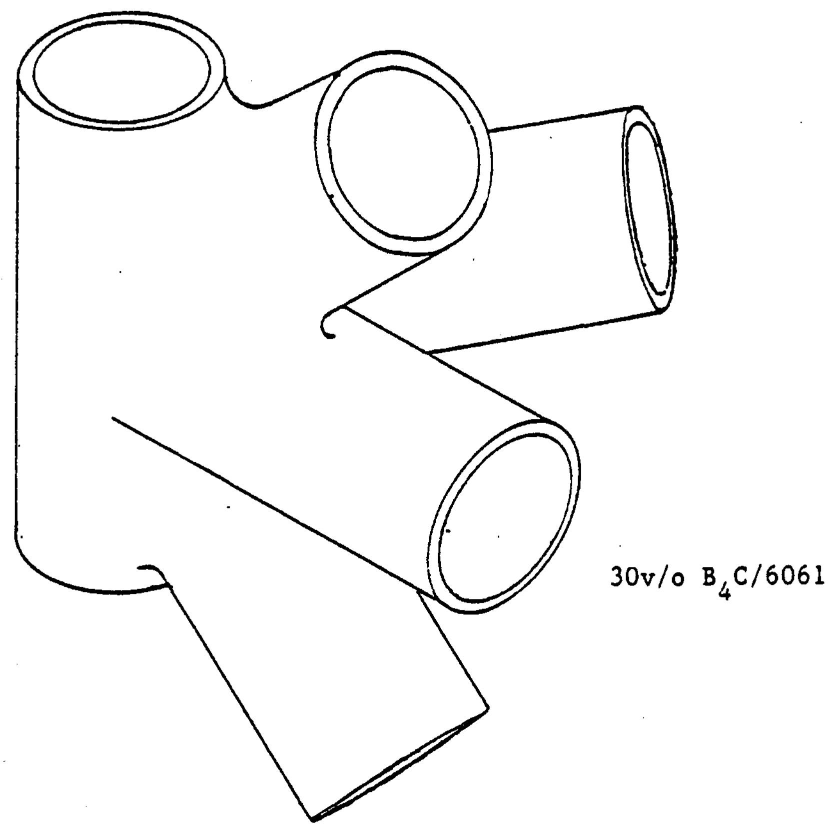


FIGURE 14. Rigid, Multi-appendaged, DWAl 20® End Fitting Configuration

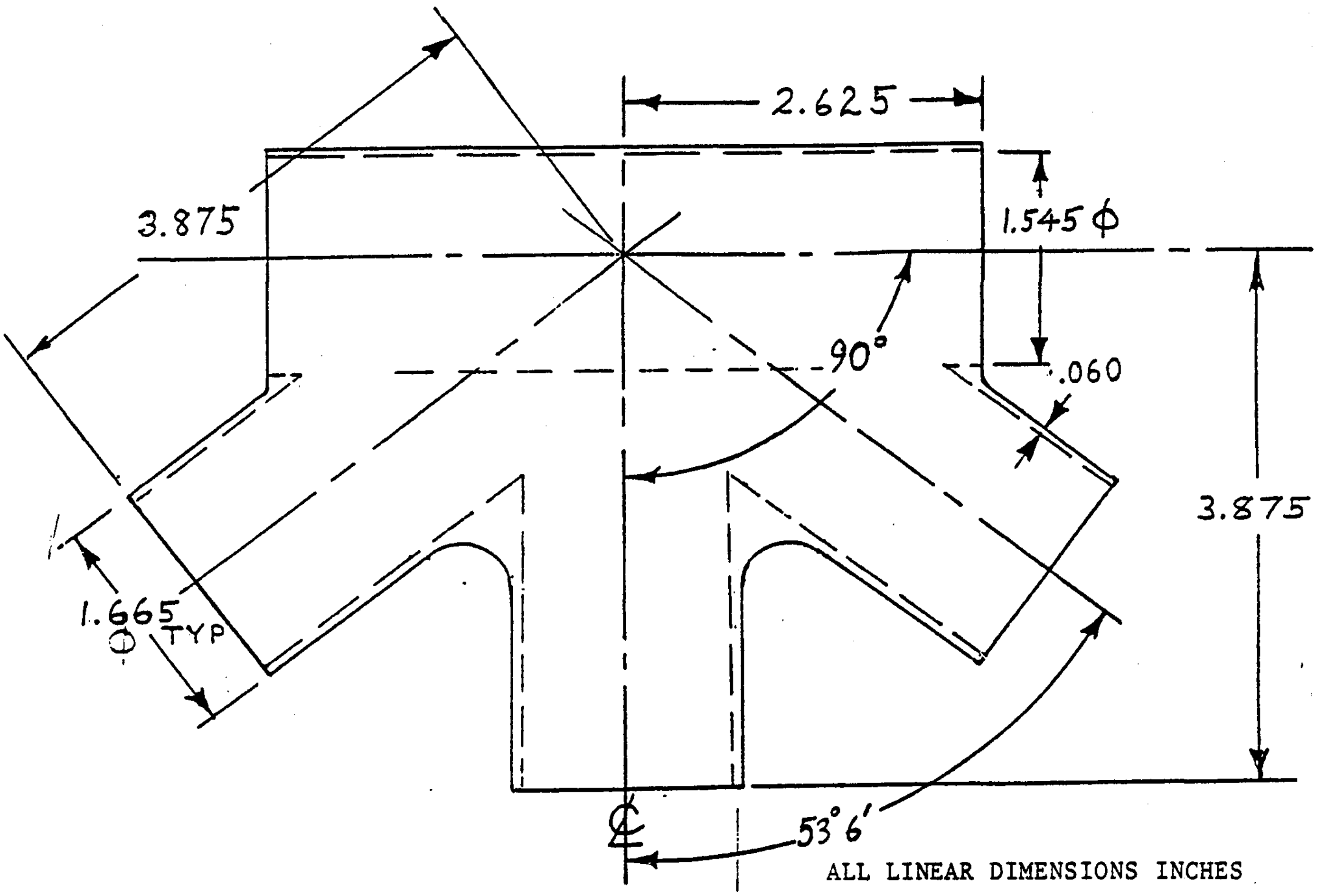
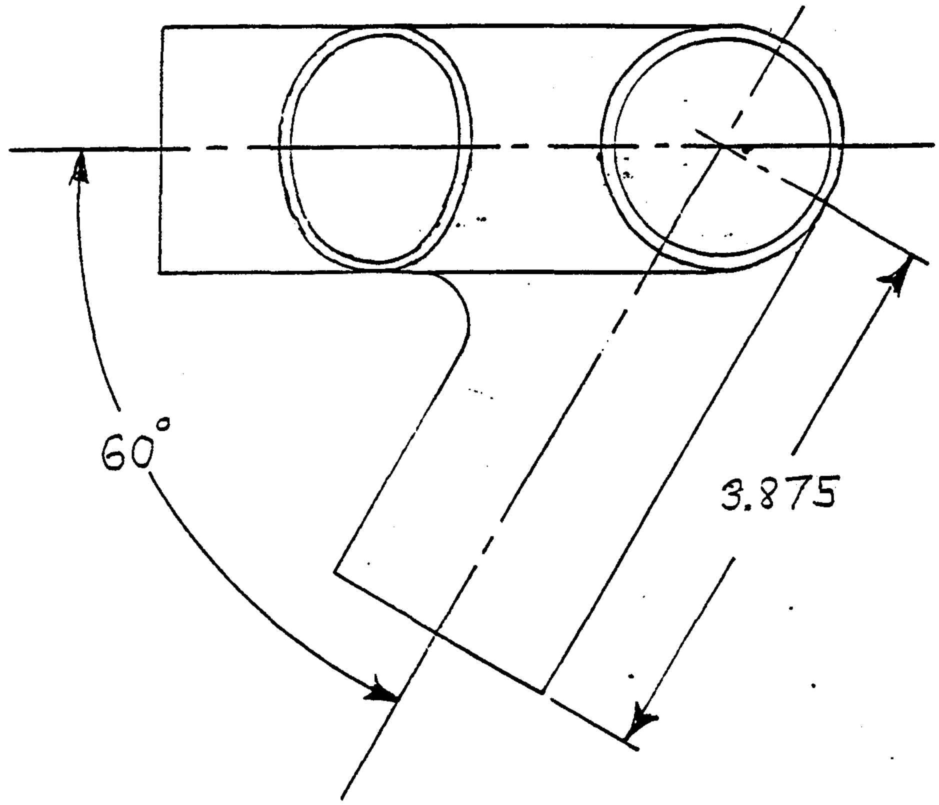
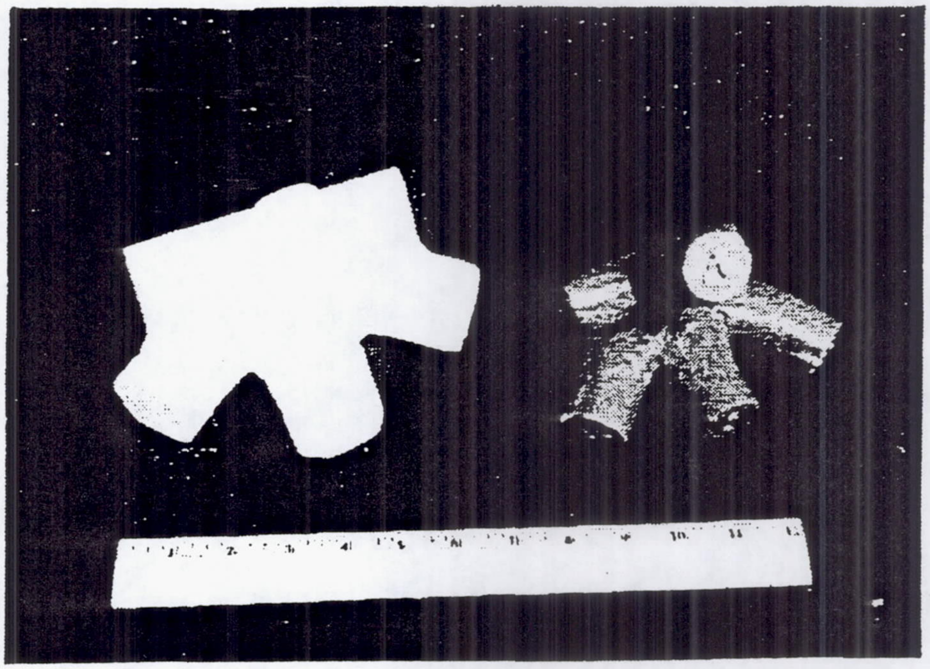


FIGURE 15. Key Dimensions of Rigid End Fitting, Plan View.

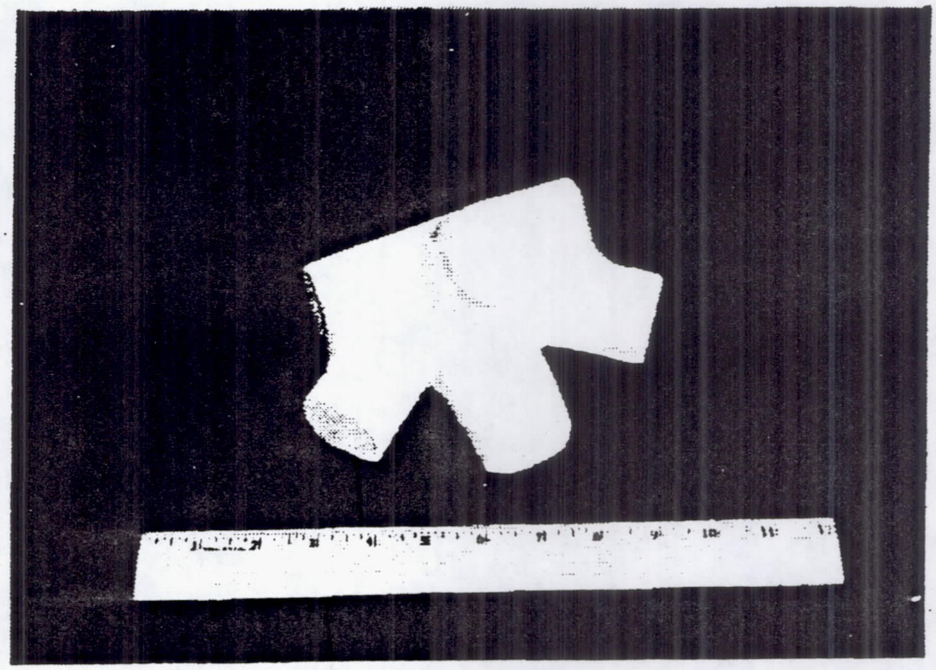


ALL LINEAR DIMENSIONS INCHES

FIGURE 16. Key Dimensions of Rigid End Fitting, Side View



A. NASA (left) and the Previous, Smaller, End Fitting Model.



B. Model of NASA End Fitting.

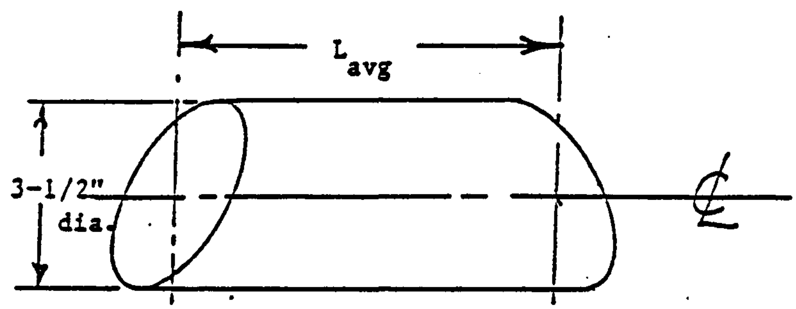
Figure 17. Wooden Models of End Fitting used for Immersion to Provide Initial Estimate of Forging Preform Volume.

Figure 18 illustrates the simple general arrangement of the die set: a punch, a sleeve, and a base plate. Figure 19 illustrates the forging die base plate side view, and top view through the sleeve showing the contour of the part as viewed through the punch recess. Illustrated in Figure 20 is a side view of the forging punch element. Dimensions are approximate and depended on EDM. Figure 21 shows the punch recess with approximate dimensions which also depended on EDM wire cut size. As illustrated in Figure 22, end fitting contours in the base plate were designed to overfill the extensions of all appendages, included to insure complete fill of MMC material in the end fitting extremities after final machining.

Standard milling tools were employed to machine the end fitting contours into the punch and base plate. These contours provide for the shape of the forged end fitting illustrated in Figure 23 indicating the portions formed in the base plate and punch, respectively.

The completed forging die punch element is shown in Figure 24, including flash relief slots, and further showing the deeper contour needed to form one of the battens (Figure 23). The base plate is illustrated in Figure 25, including attachment holes and the contour designed to mate precisely with the contour in the punch. The forging die sleeve element is shown in Figure 26. The cavity in the sleeve was cut by EDM wire to provide precise access by the punch element. The width of the EDM wire provided the exact clearance for the punch during the forging operation. Two views of the die set assembly are pictured in Figure 27.

2.3.2.2 Preform Development. The preform shape, from previous experience, was found to be trapezoidal for most-efficient forging, facilitating tool loading and subsequent initiation of metal flow. The preform stock was scheduled for extrusion. Diameter of the preforms was estimated to be 3½ inches based on practical extrusion die considerations, expected yield from a DWA standard 8-inch diameter billet, and previous experience with similar but smaller preforms. The following analysis provided guidance prior to cutting the initial preform:



The average length and weight were estimated as follows:

ρ = density of MMC material, 30v/o B_4C/6061

$$\rho = (.3)(\rho_{B4C}) + (.7)(\rho_{6061\ Al})$$

$$= (.3)(2.54) + (.7)(2.715) = \underline{2.6625 g/cc}$$

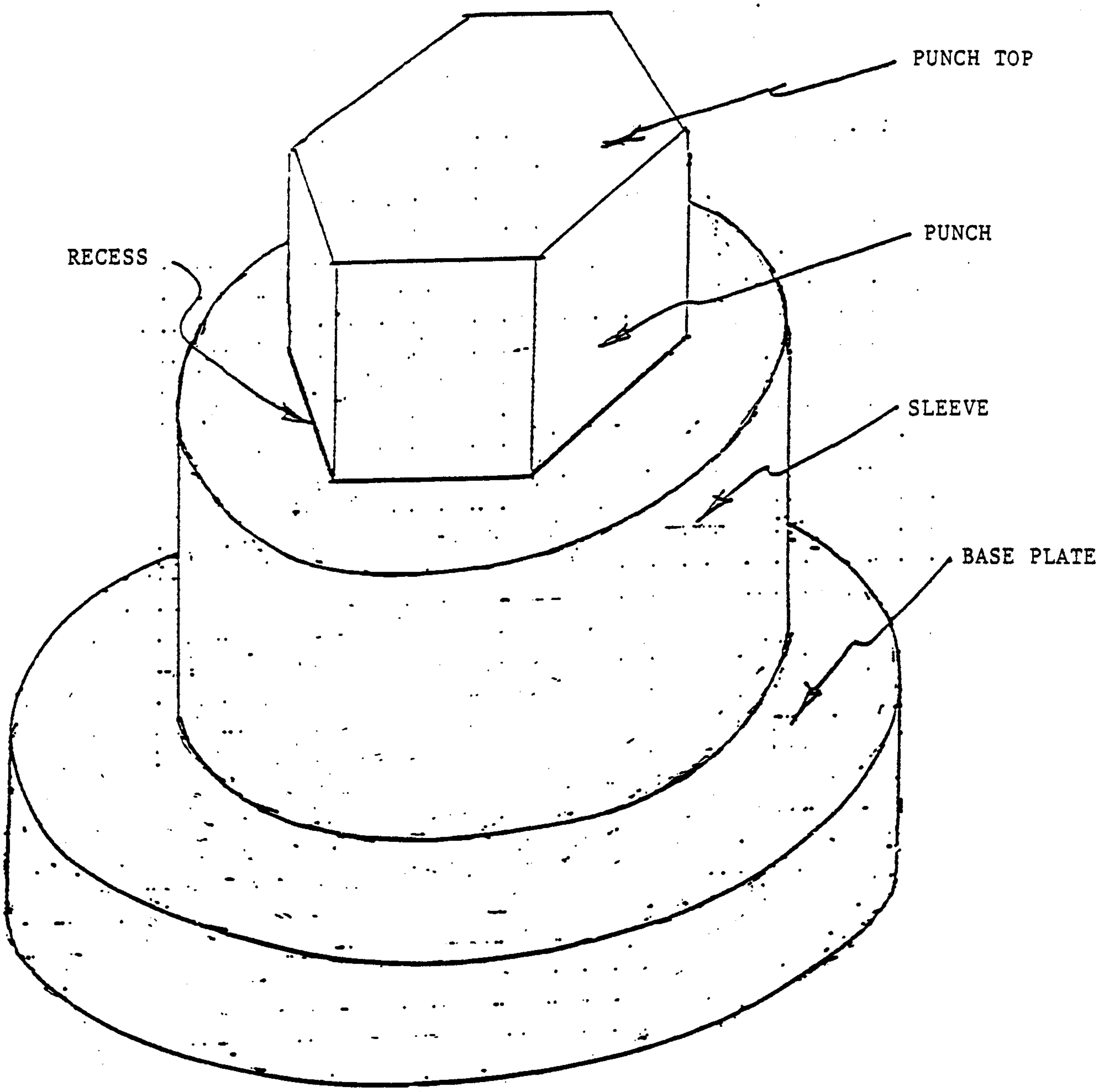


Figure 18. General Arrangement of Forging Die Set for Rigid End Fittings

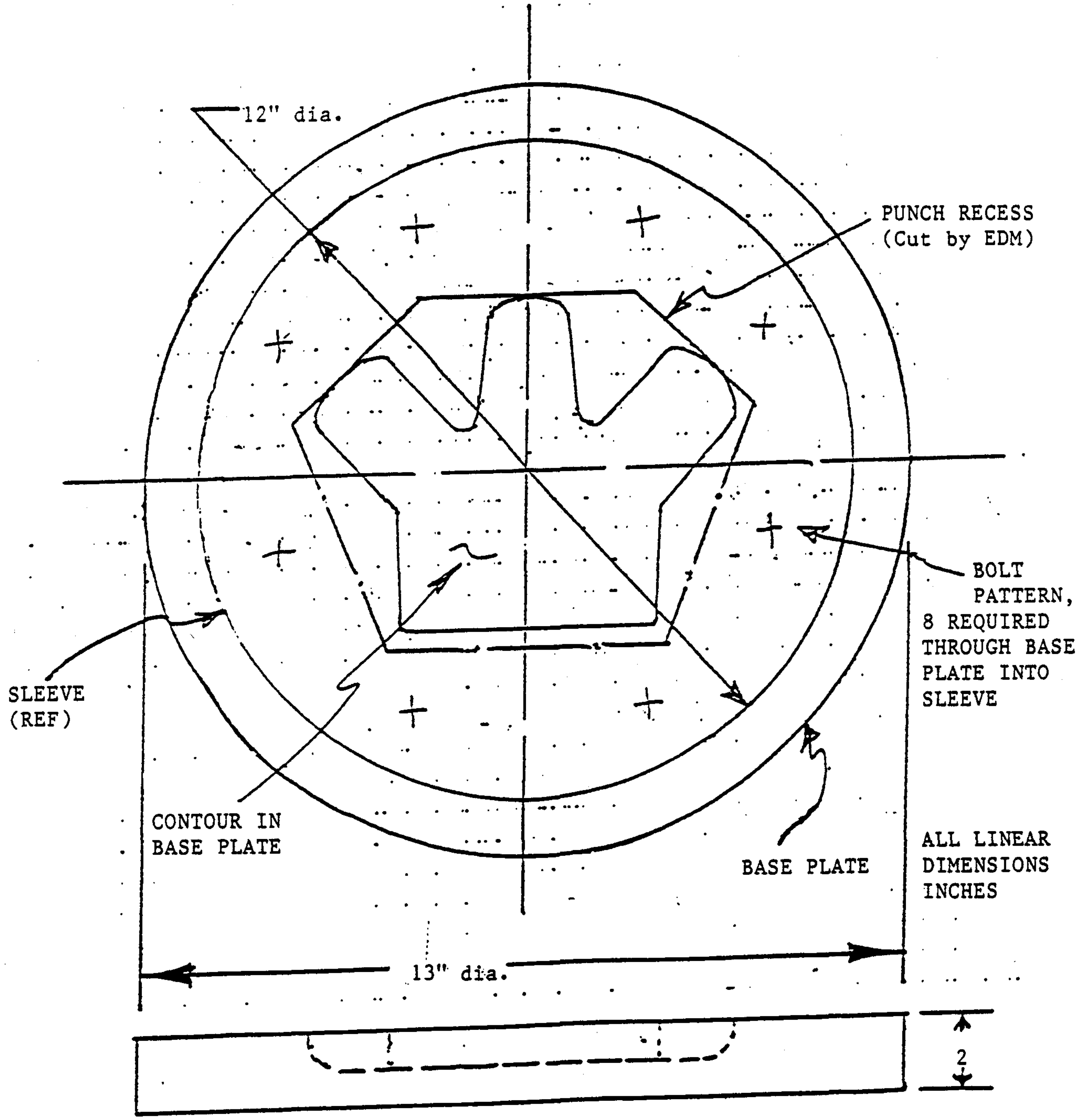


Figure 19. Forging Die Base Plate Including Top View Through Sleeve into Contour.

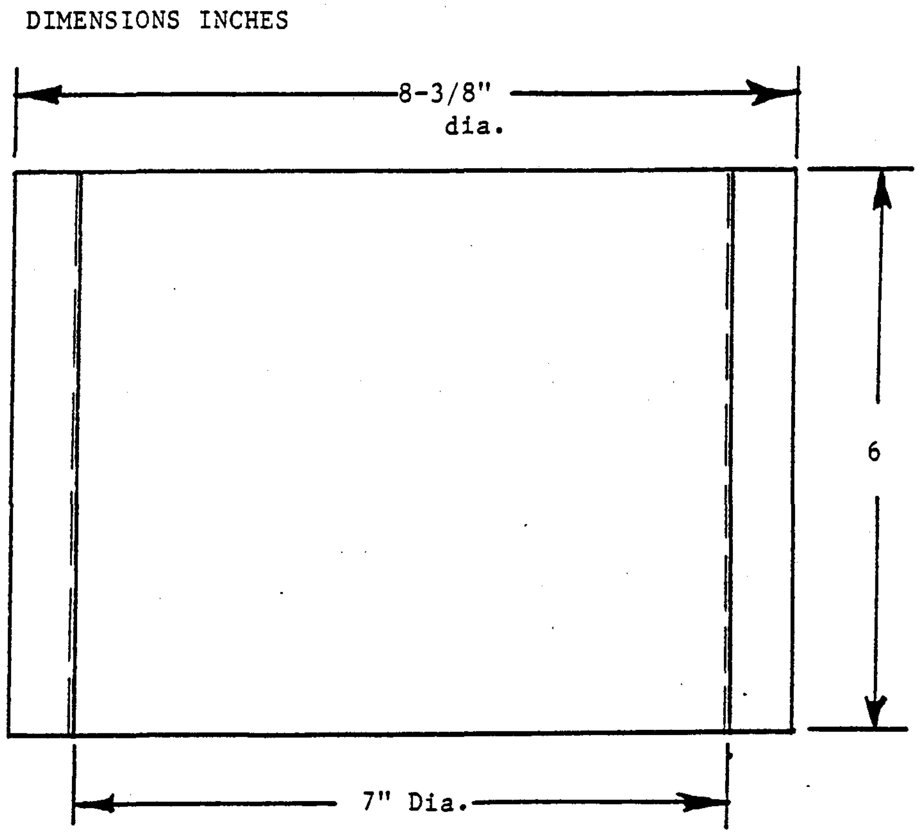


Figure 20. Forging Punch Element, Approximate Dimensions, Front View

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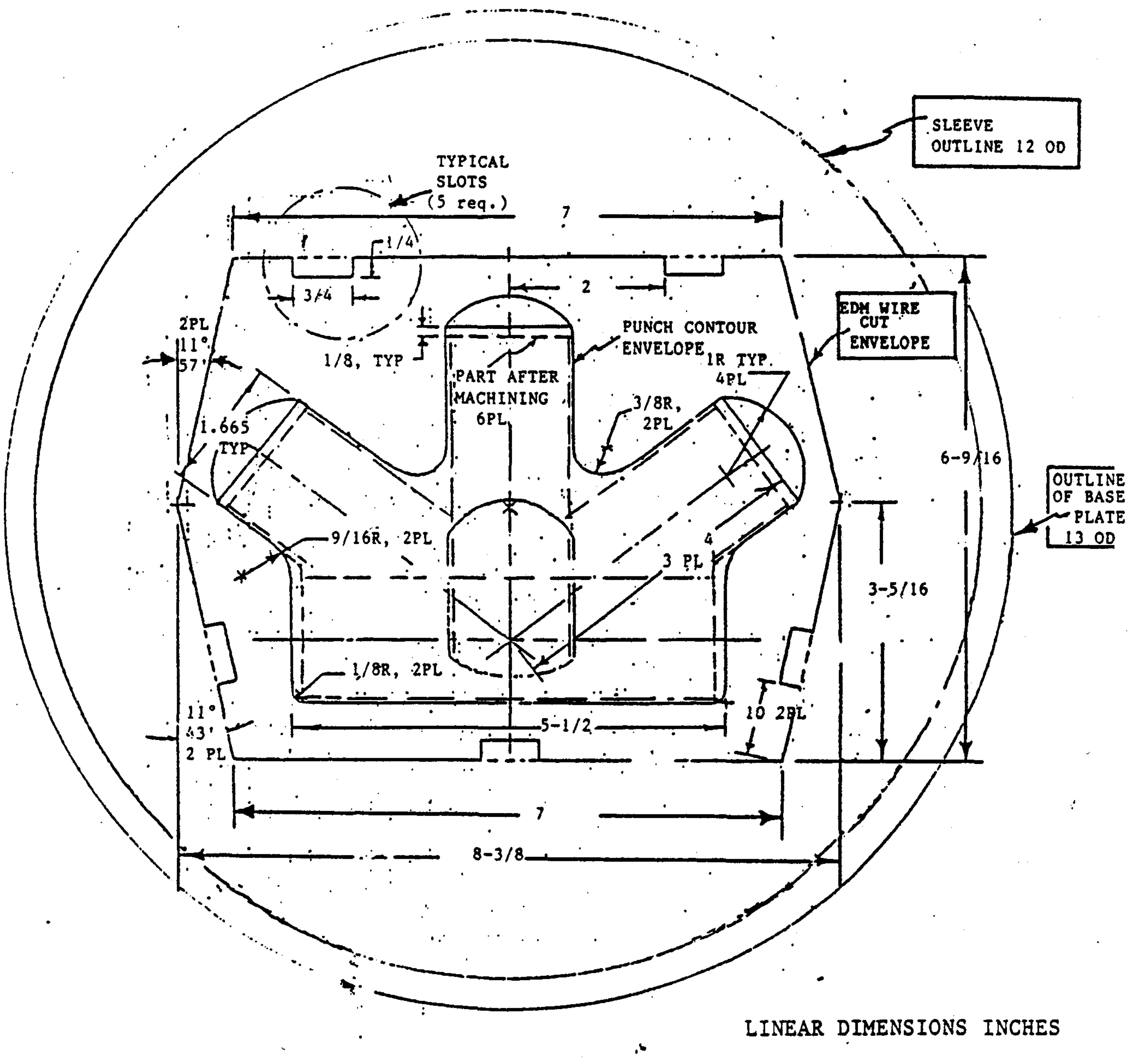

Figure 21. Punch Recess, Cut by EDM Wire, from 12-inch Diameter Round Bar H13 Steel, 6-inch Length. Punch and Die Sleeve thereby Cut Simultaneously.

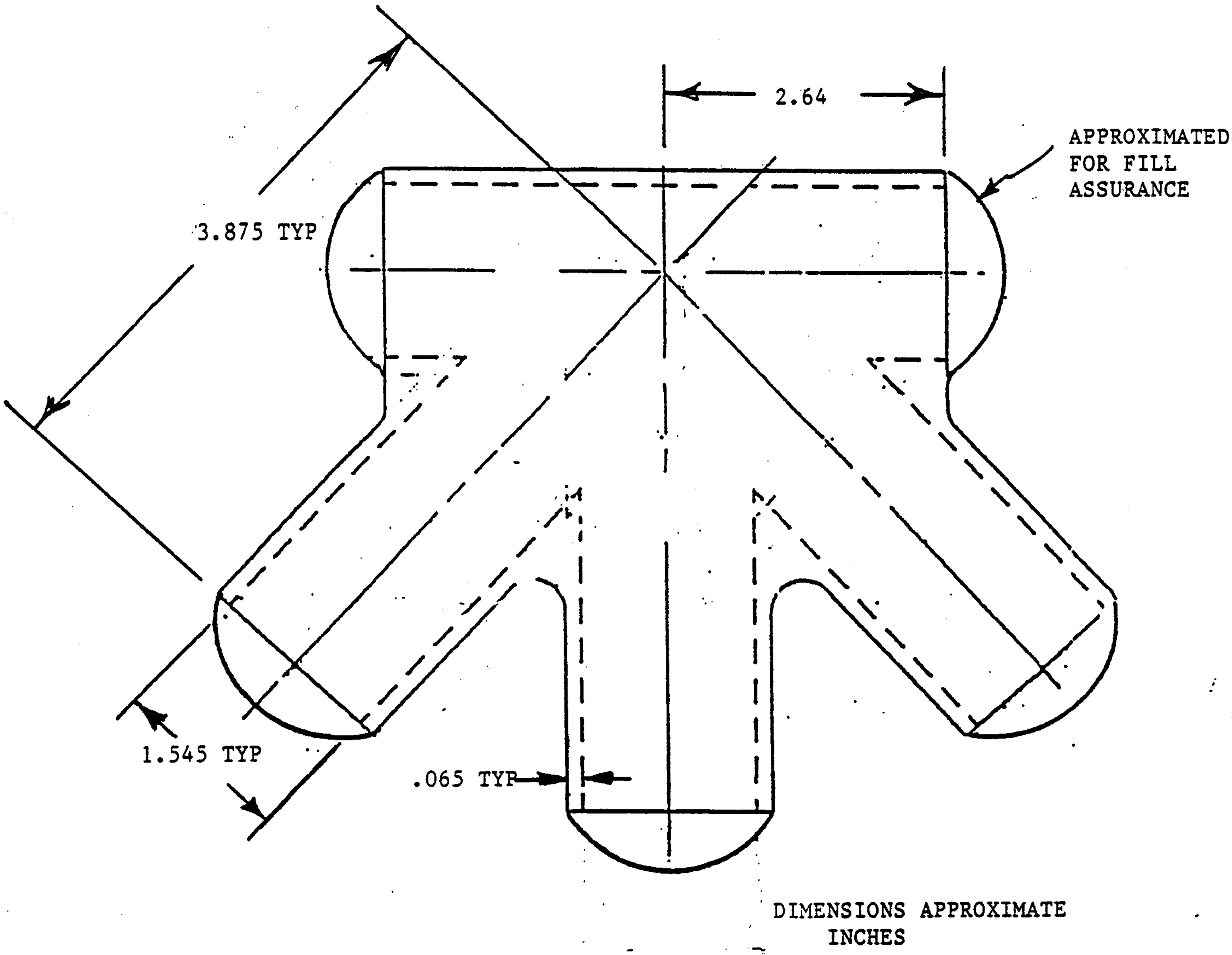

Figure 22. View of End Fitting Contours in Base Plate

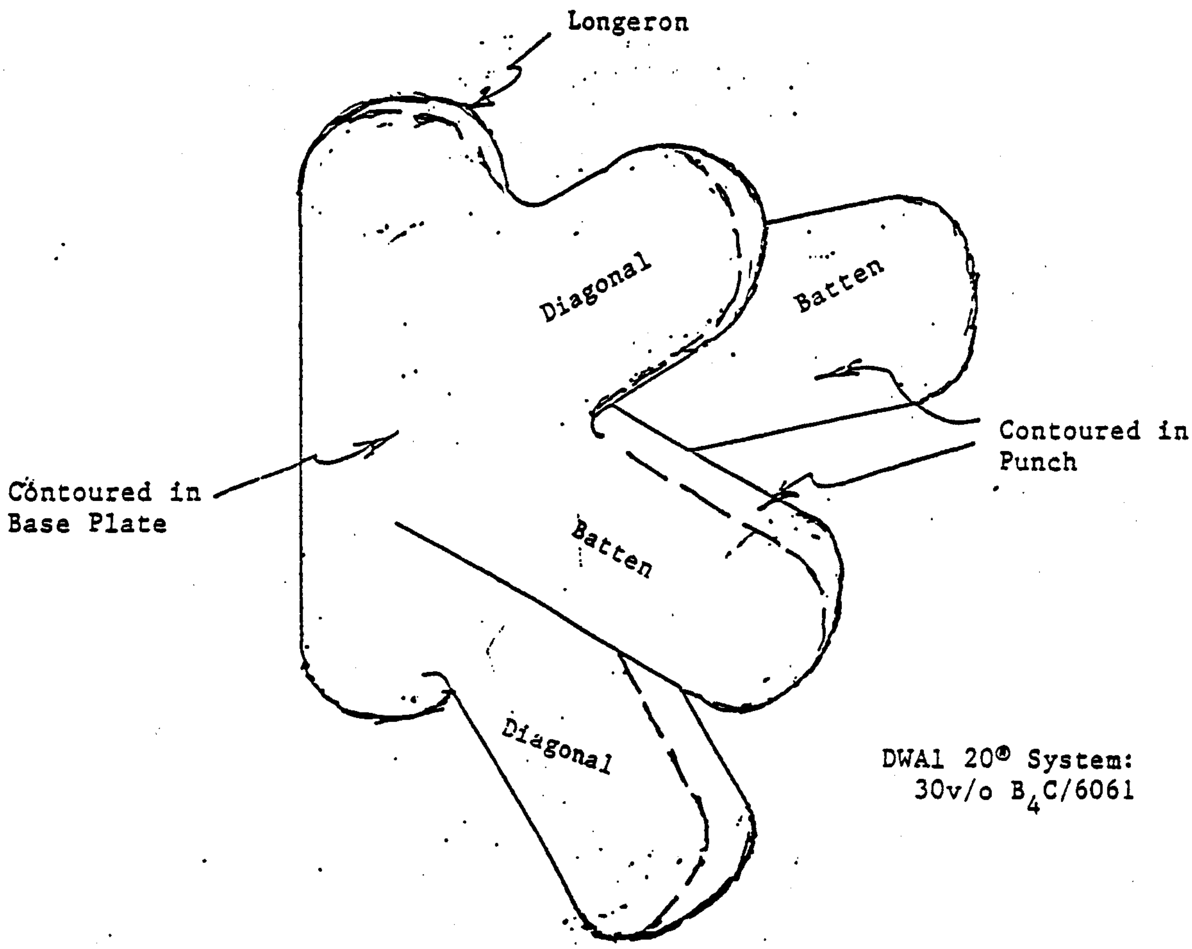

Figure 23. Rigid, Multi-appendaged, DWAl 20 End Fitting Configuration, Forged, Before Machining.

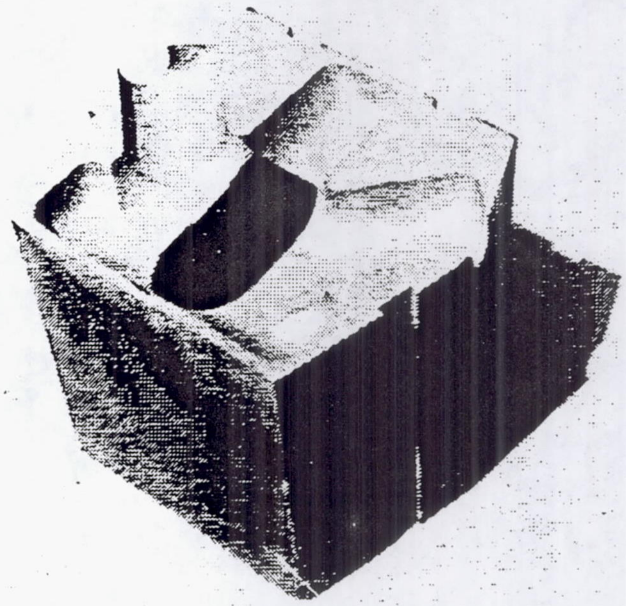

Figure 24. Forging Die Punch Element

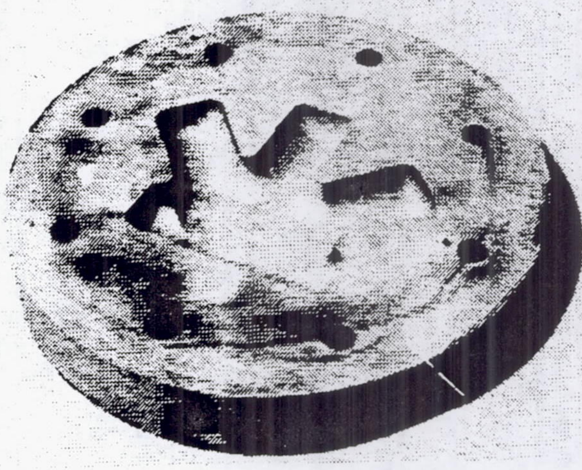

Figure 25. Forging Die Base Plate Element.

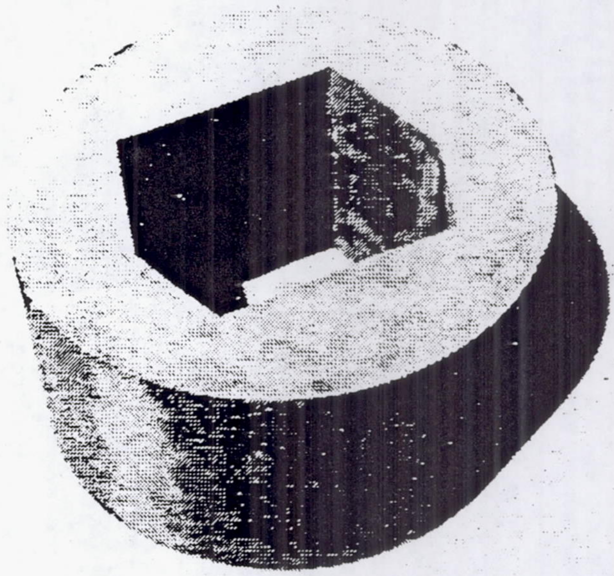

Figure 26. Forging Die Sleeve Element.

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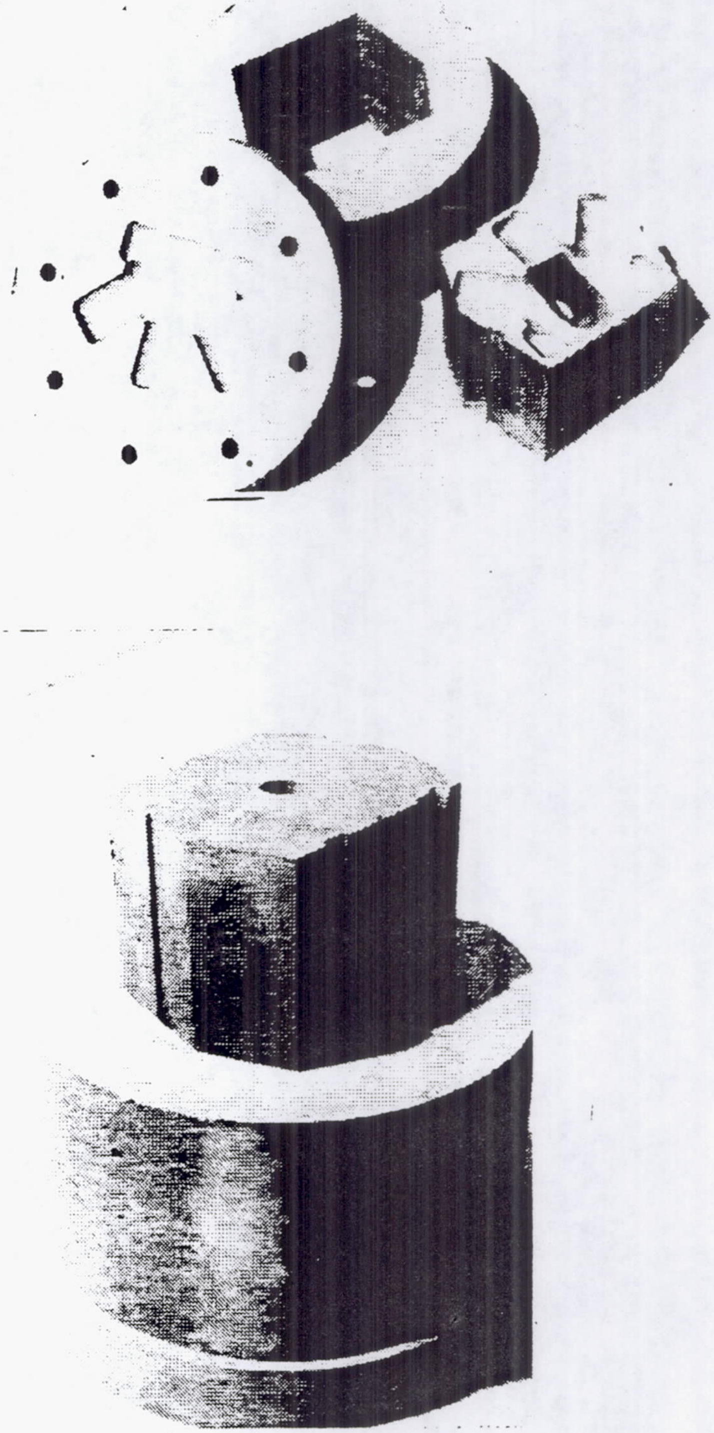


Figure 27. Forging Die Set Components, Disassembled and Assembled, Respectively.

First estimate for preform weight, W:

$W = \rho V$ Where: W = weight
V = volume
ρ = density

Volume was measured by immersing a wooden model of the desired end fitting:

$V = 41$ cu.in. $= \underline{671.87 \text{ cc}}$

Preform weight was then calculated:

$$W = \rho V = (2.6625)(671.87)$$

$$= \underline{1{,}789 \text{ grams}}$$

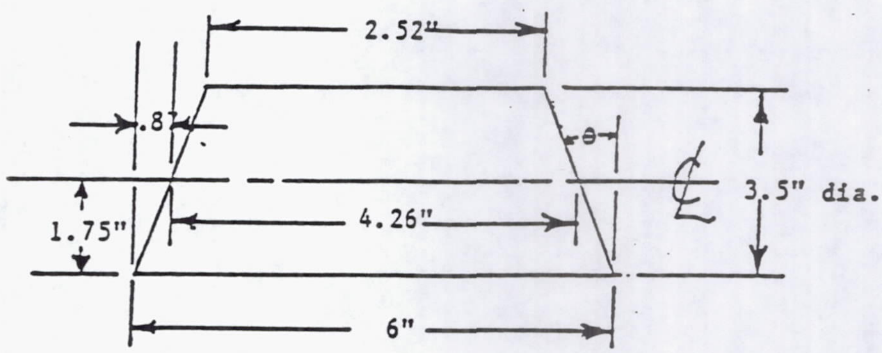
Average preform length, L_{avg}, was next calculated:

$$V = \frac{\pi D^2}{4} (L_{avg})$$ Where: D = preform diameter

from which,

$$L_{avg} = \frac{(4)(41)}{\pi(3.5)^2} = \underline{4.26} \ \underline{\text{inches}}$$

From the previous experience with a similar preform requirement, and in consonance with the measured end fitting contour in the die set base plate, the preform cutting plan was established as follows.



Observing the above preform longitudinal section, the end angle was calculated to be:

$$\theta = \tan^{-1} \frac{.87}{1.75} = \underline{0.4971}$$

from which,

$$\theta = 26° \ 26'$$

Preforms were cut initially to the dimensions calculated above, with adjustments planned as required, as the forged units are evaluated.

A typical forging preform is shown in Figure 28, based on the foregoing analysis.

2.3.2.3 Forging Operations. The punch element of the end fitting forging die set was shortened to provide for measured flash, necessary to assure homogeneous densification and structural integrity in each forged unit. In eleven attempts, nine end fittings were forged successfully; one typical unit is shown in Figure 29.

Summarizing the forging procedures:

a. The preform and all elements of the forging die set are cleaned and sand-blasted;

b. Stop-off agent is applied to all wetting surfaces;

c. The loaded die set is positioned between platens of a suitable press;

d. Instrumentation and insulation are installed, and heatup power is applied;

e. When the appropriate forging temperature is reached, forge pressure is applied.

A group picture of seven (and nine, two gun-drilled) of the forged units, with flash removed, is presented in Figure 30. These forgings are ready for the subsequent operations of machining, heat treat, and assembly installation.

2.3.2.4 Machining. A number of optional approaches were considered for most efficient machining of the end fittings; viz., gun-drilling plus machining, machining totally, and EDM (electric discharged machine). The EDM method was rejected on the basis of cost and excessive time.

In a further effort to conserve time and money, gun-drilling was evaluated as an initial step in the machining process. Two forged units were gun-drilled at Thompson Gun-Drilling Company, Van Nuys, CA. These two units are shown in Figure 31 with one not yet drilled and with both units drilled, respectively.

The gun-drilling exercise confirmed that CNC machining of the holes was more cost-effective because;

a. gun-drilling required set-up time and cost that has to be repeated for subsequent machining to tolerance;

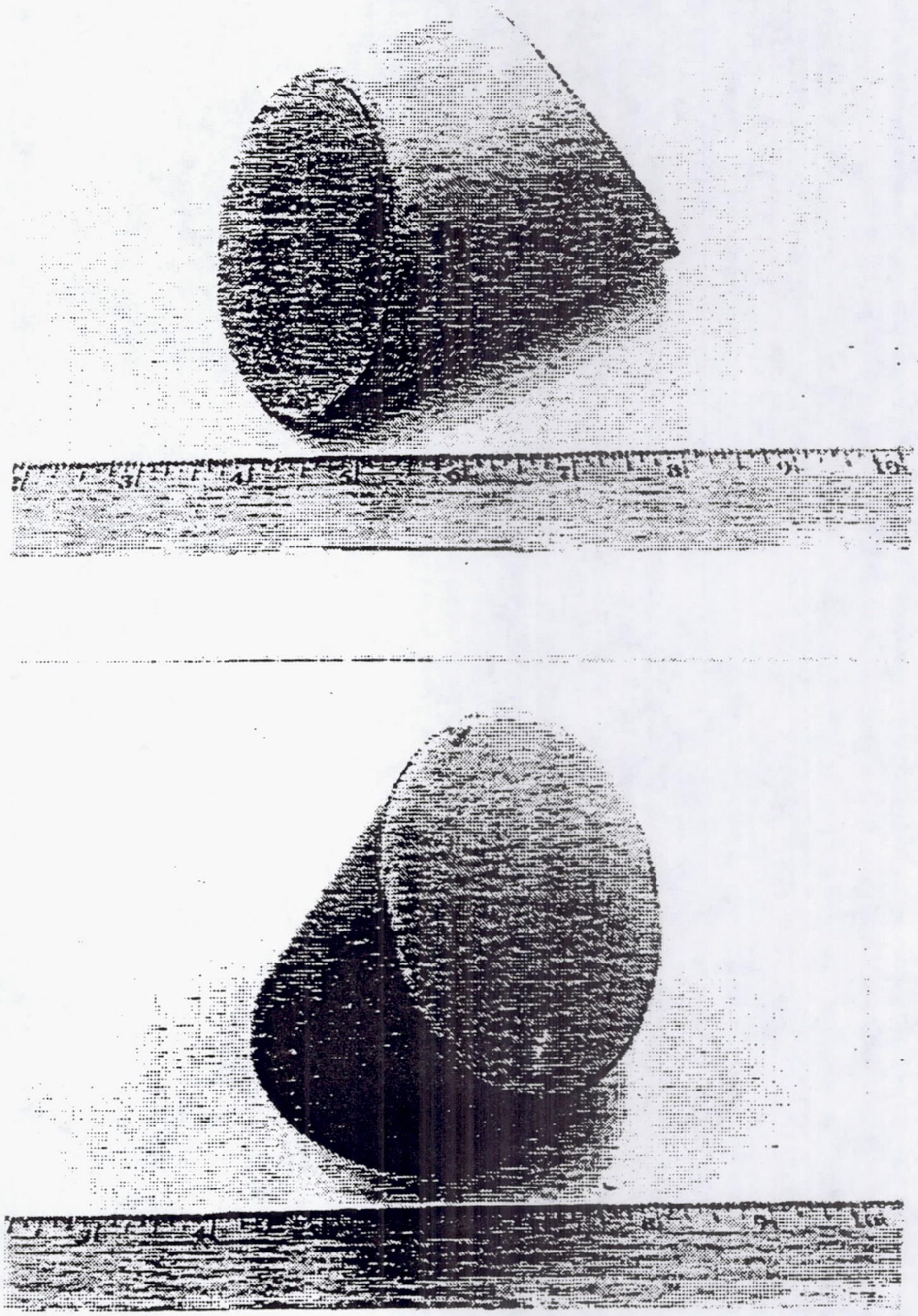


Figure 28. Selected Trapezoidal Preform Shape

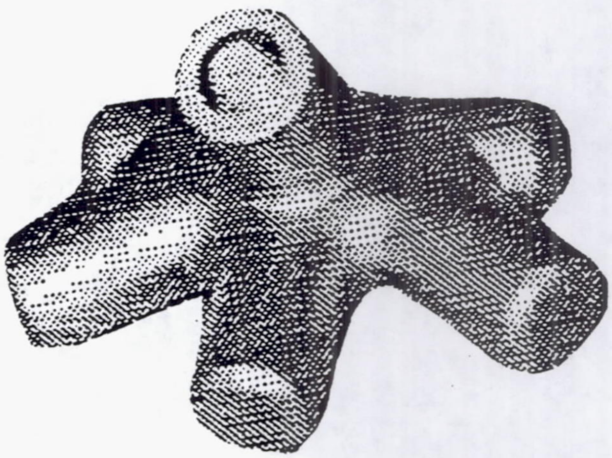
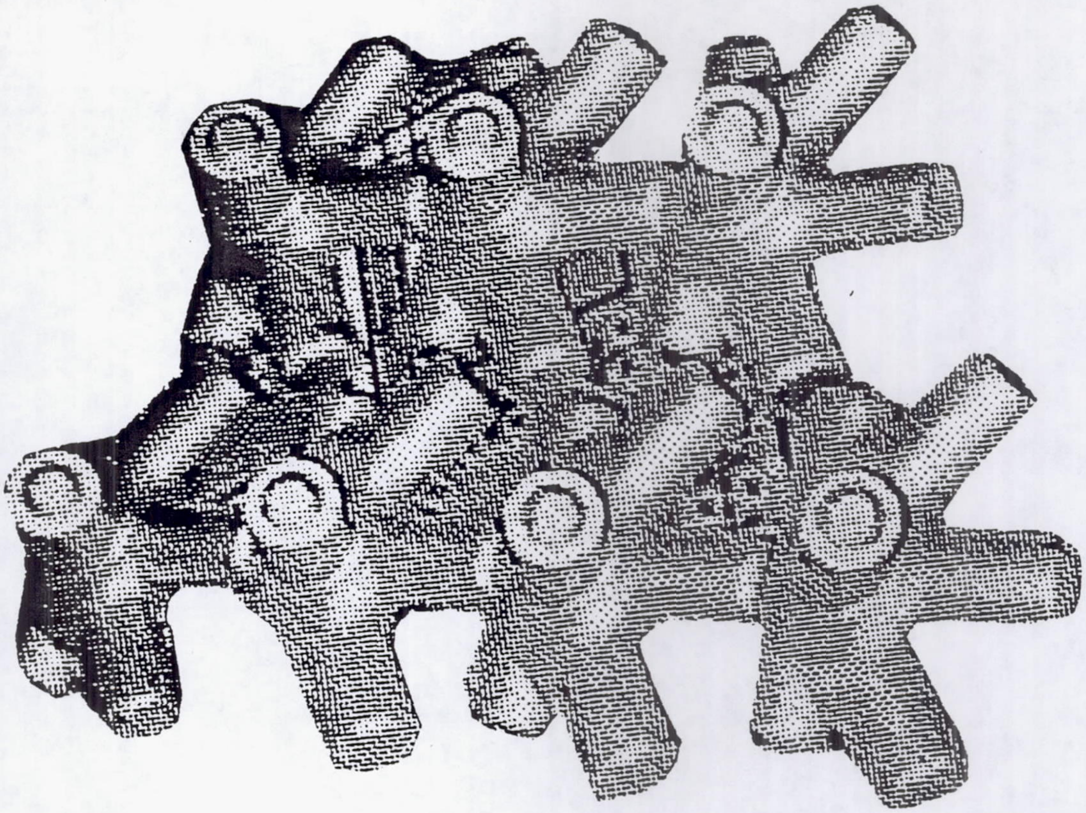


Figure 29. Typical Forging of a DWAl 20® End Fitting



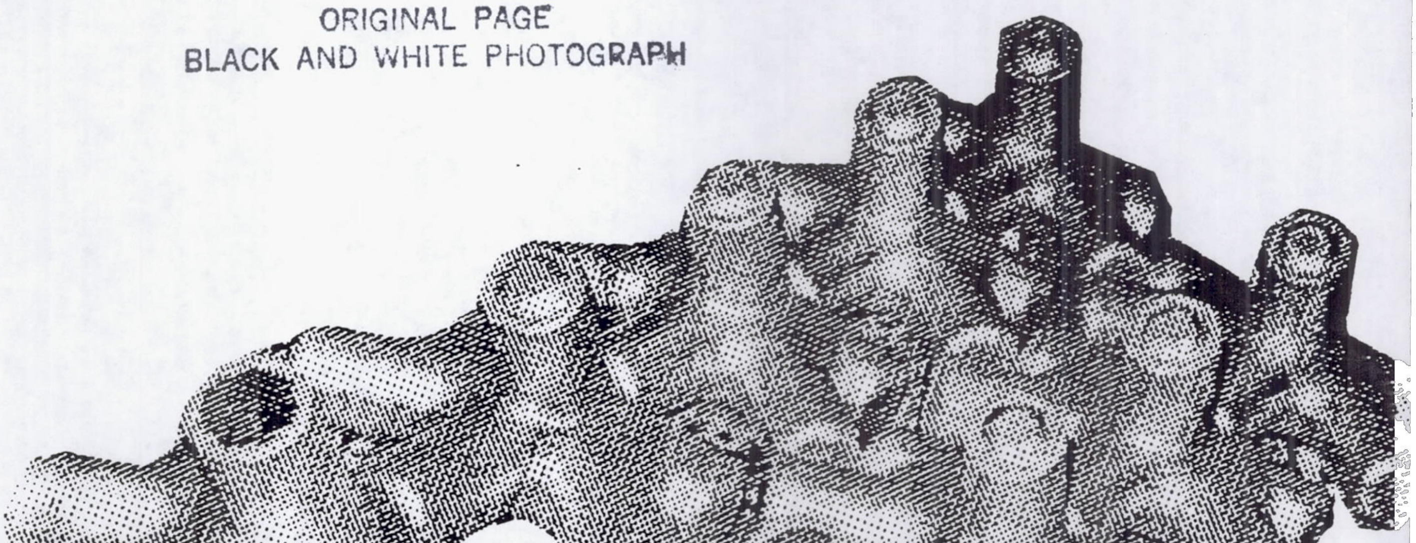


Figure 30. Nine End Fittings, Seven Forgings (Top) and All Nine Grouped, Including Two Gun-drilled.

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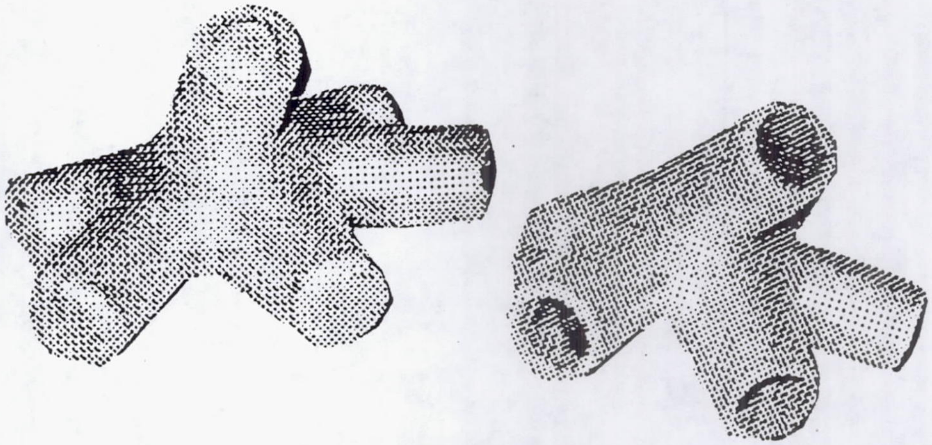
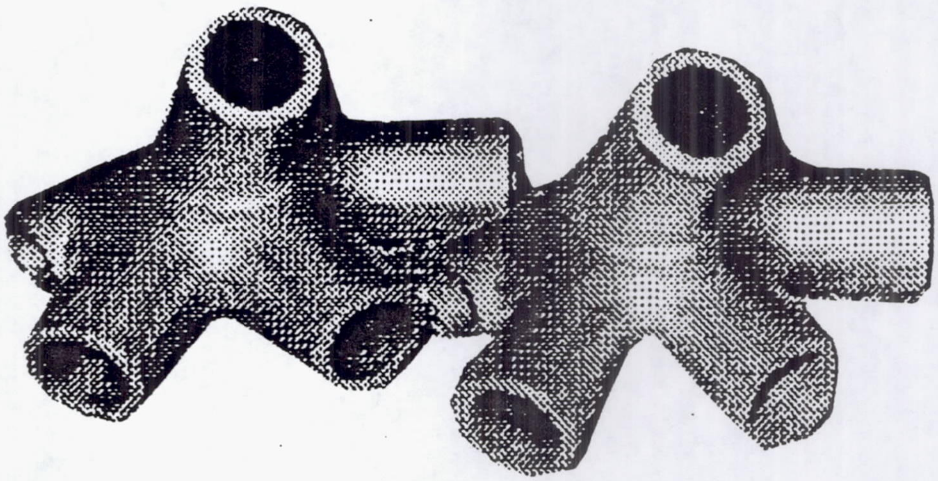


A. Before and After Gun Drilling



B. Two Gun-Drilled End Fittings.

Figure 31. Forged, Gun-drilled DWAl 20® End Fittings

b. excessive tool wear in gun-drilling;
c. pressure of gun-drilling put walls in tension with attendant damage potential.

Accordingly, special diamond milling tools were acquired, and all machining was programmed on the ACROMAX CNC 4-axis milling machine at RIMO Manufacturing Company, Canoga Park, CA. This machine, with an end fitting forging in place, is pictured in several views in Figures 32 and 33.

In Figure 34 is illustrated seven of the nine end fittings machined completely, ready for heat treatment and installation in the deliverable truss bay assembly. Of the two remaining end fittings, one was damaged in machining too severely to repair. The other was weld-repaired and shipped to NASA as a visual demo.

2.3.2.5 Heat Treatment. During the course of the MMC DWAl 20® development, heat treat parameters have evolved to which the MMC best responds as a function of the particular aluminum alloy employed and a number of other factors. The proper set of parameters was selected for the end fitting material of construction, 30v/o $B_4C/6061$, and applied in a heat treat operation which included quench in glycol solution, thus inhibiting dimensional distortion.

2.4 ASSEMBLY OPERATIONS

Primary considerations involved in the truss assembly operations were:

a. Joining methodology;
b. Precision assembly procedures.

2.4.1 Joining Methods

Joining criteria of primary concern for this program were:

a. producibility;
b. quality control inspection;
c. effect of thermal cycling on the bonded regions, as would influence thermal expansion of the truss structure.

By far the joining method applied most extensively to date throughout the aerospace industry involved with space structures is adhesive bonding. Accordingly, this approach to joining DWAl 20® components to the DWG tubes was the pacing method with which the other options were compared; viz., solder-bonding, welding, and mechanical fastening.

2.4.1.1 Adhesive Bonding. The bonding agents Hysol 9390A and Epibond 1210 were identified as most promising for this application. Tests were conducted to confirm the adhesive performance expected securing DWG to DWAl 20®.

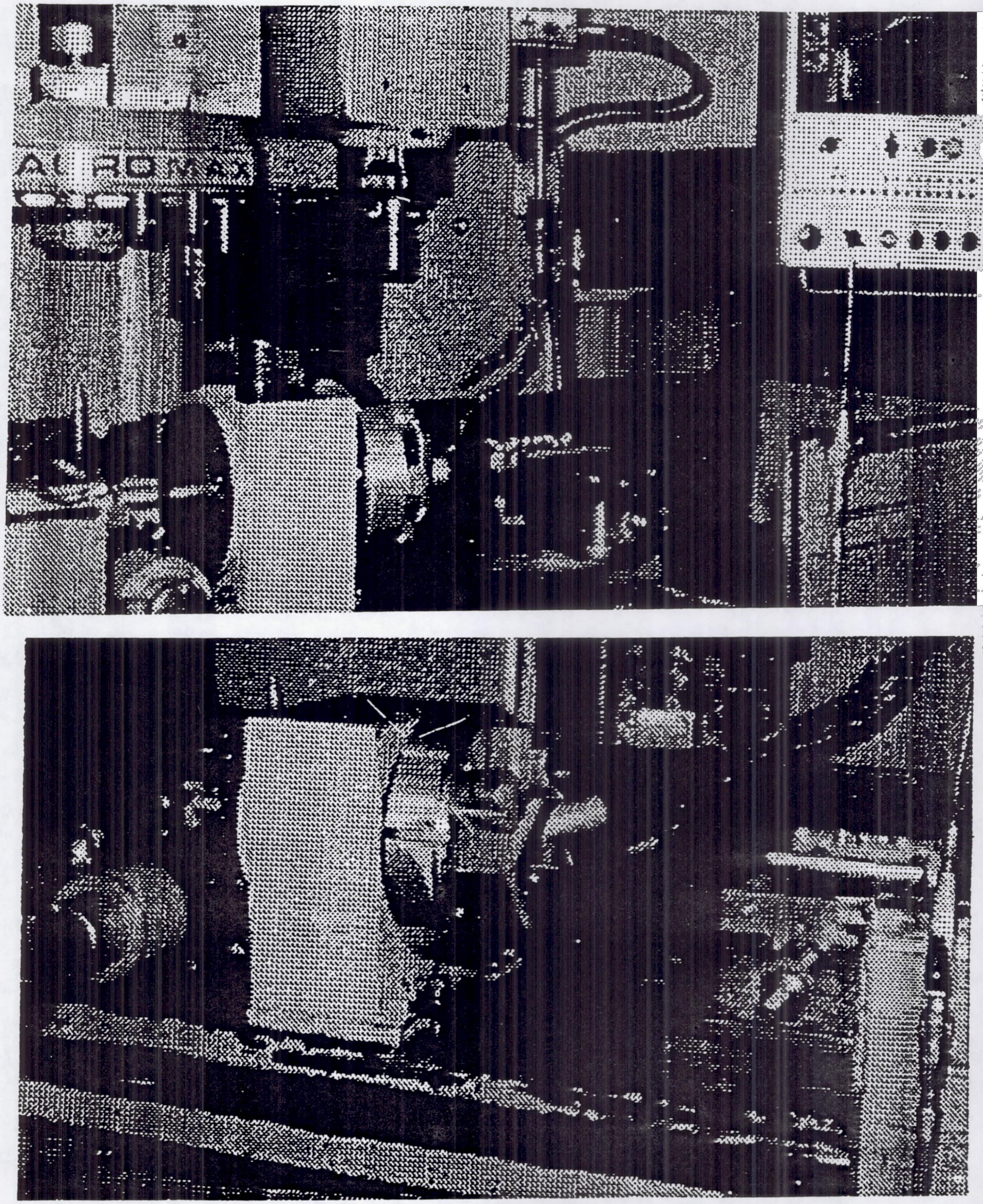
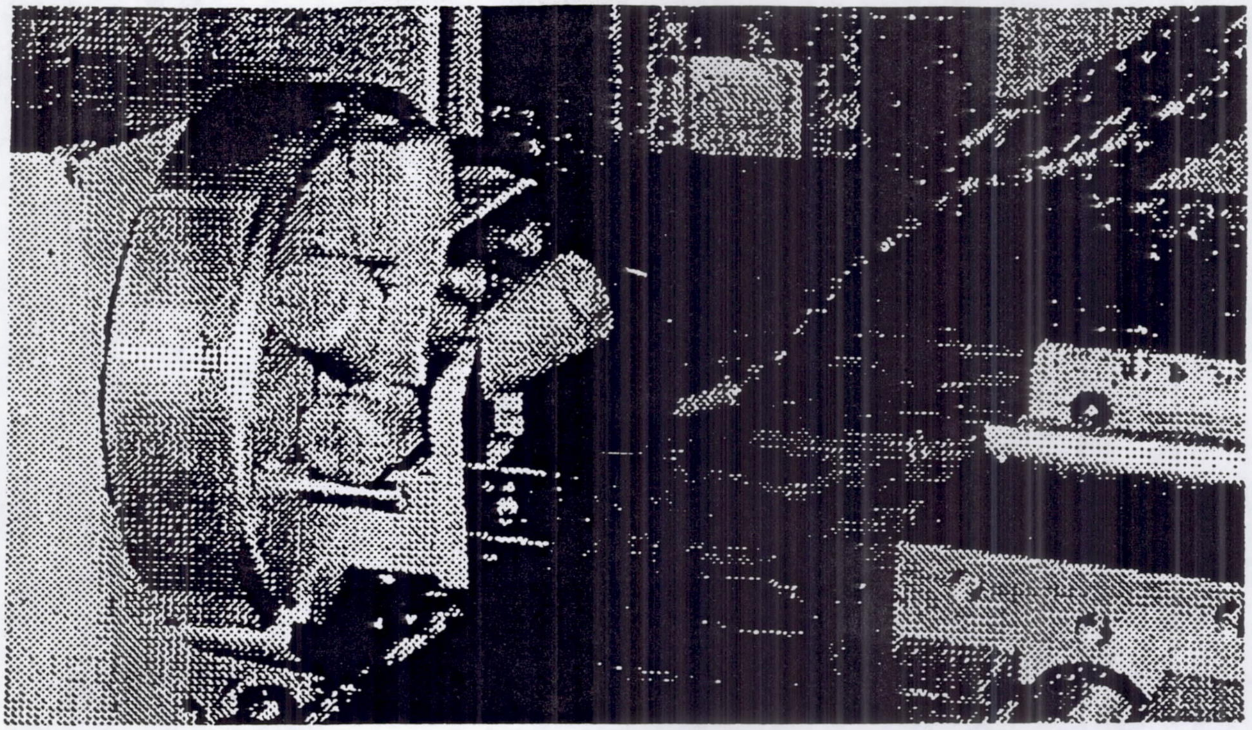


Figure 32. End-fitting Installed in 4-Axis Acromax CNC Machine



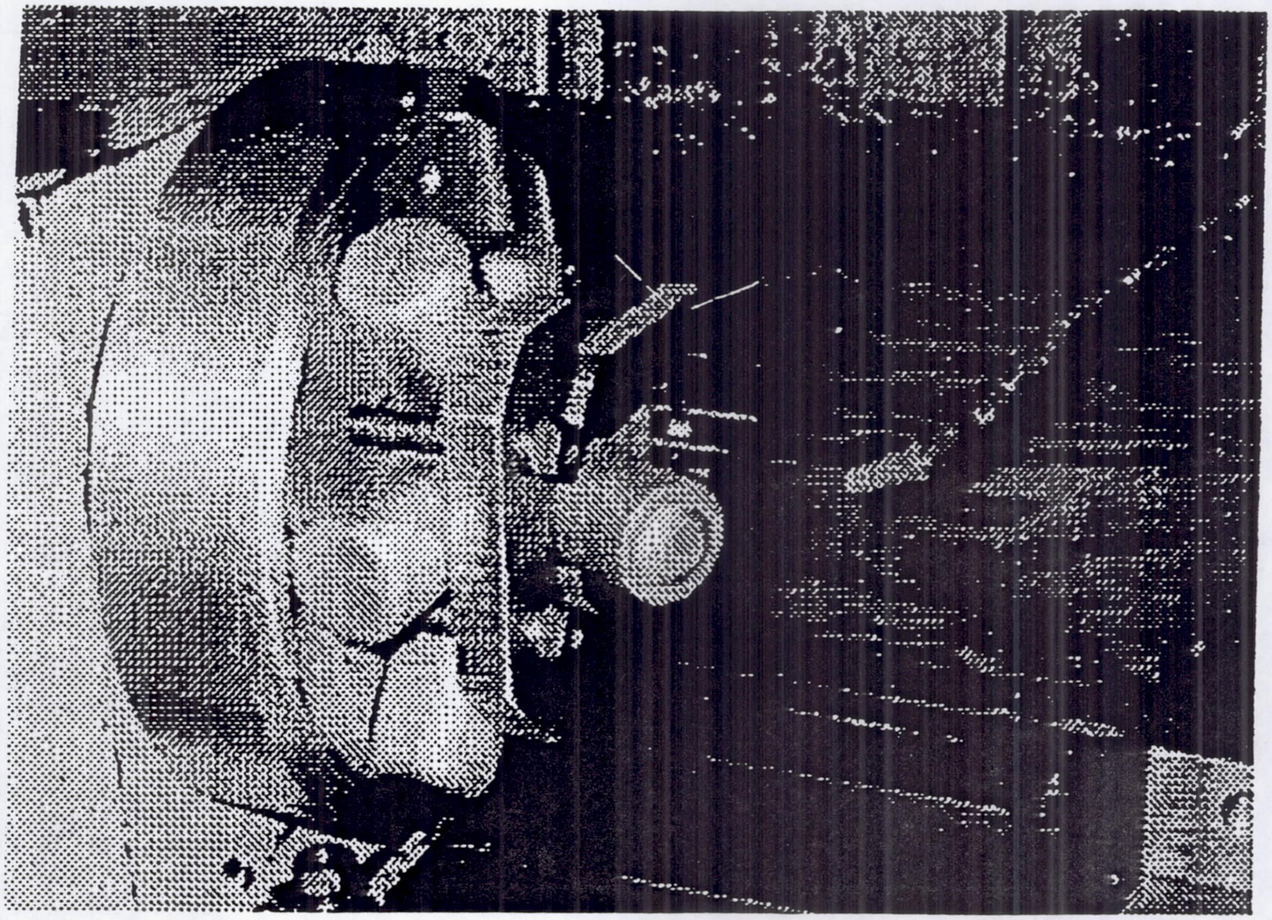


Figure 33. Enlarged Views of Forged End Fitting Installed and Ready for Machining

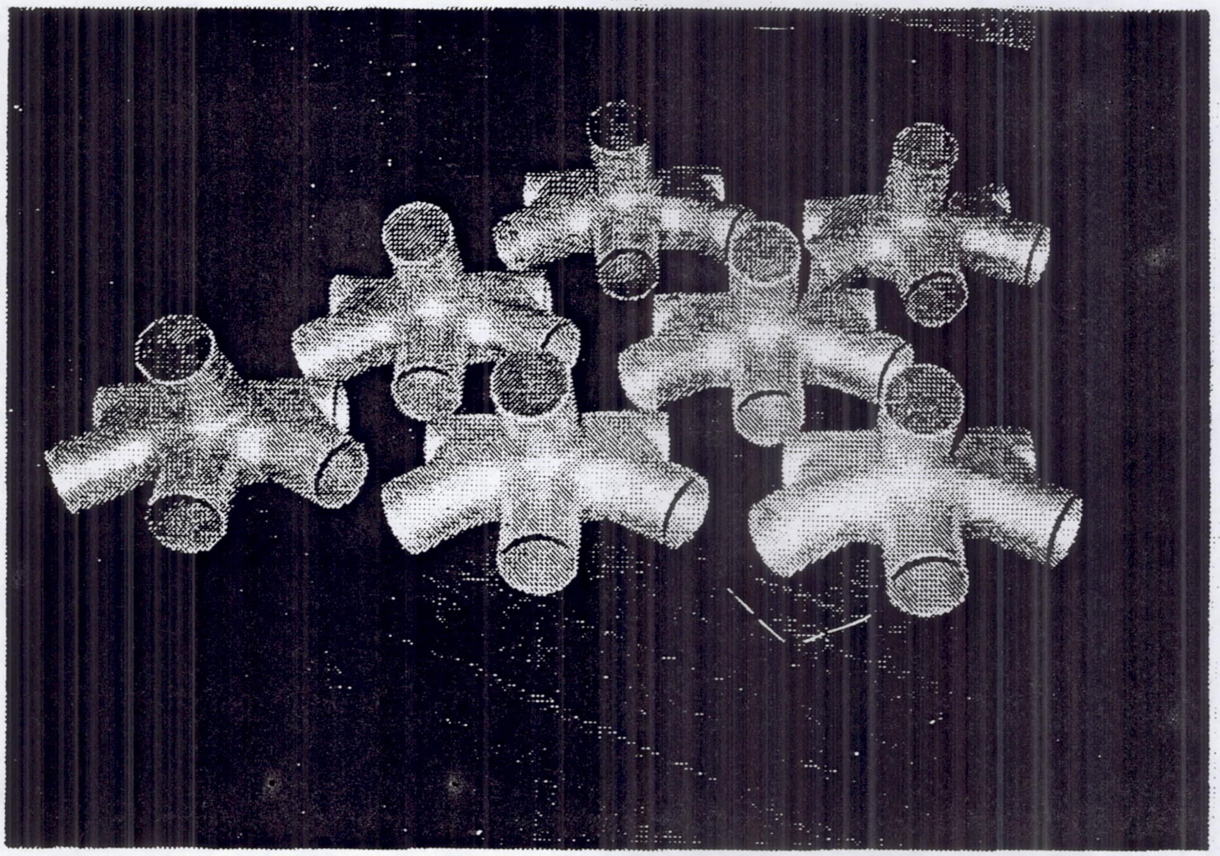


Figure 34. Forged/Machined End Fittings, Ready for Heat Treatment and Assembly Installation.

Flat specimens were prepared by generating lap shear test samples composed of DWAl 20® and graphite-aluminum joined with an epoxy bonding adhesive. The type of epoxy used was Hysol 9309A. The DWAl 20® system was 30v/o B_4C/6061, and the graphite-aluminum was DWG P100/6061, 4 ply, ±10° crossply.

Both MMC components were scrubbed with 600 grit abrasive paper and metal conditioner, then cleaned with conditioner and neutralizer. The specified mixture of the two-part epoxy was applied to the DWAl and DWG, the test unit was assembled (Figure 35), and the recommended curing cycle was used with no application of pressure (24 hours at room temperature).

Tensile tests were conducted on three specimens with the following results:

Unit No.	Shear Strength, ksi
1	3.25
2	5.02
3	4.17

Average shear strength = 4.15 kși, confirming the integrity expected. No additional testing was conducted on adhesive bonding.

2.4.1.2 Solder-Bonding. A specific set of criteria must be met to produce a successful solder-bonded joint, particularly when continuously-reinforced graphite metal is involved:

a. A compatible surface coating must be applied to the surfaces to be bonded;
b. measured spacing must be provided between the surfaces to be bonded, permitting the solder to flow by capillary;
c. rosin is required, the type of which must not be detrimental to the metals involved;
d. thermal expansion and structural integrity of the solder-bonded assembly must be essentially unaffected by the solder formulation and application parameters.

The approach selected by DWA to evaluate the efficacy of the solder-bonded assembly of the subject space truss bay is stated briefly as follows:

a. review previous soldering results for applicability;
b. conduct lap shear tests involving DWG solder-bonded samples;
c. conduct solder-bonding experiments involving DWG tubes inserted into DWAl sleeves.

Review of previous soldering results revealed that nickel plating provided the ideal substrate for subsequent application of tin-silver solder. The solder-bonding study was thus reduced to establishing the plating/soldering technique to best be applied to the assembly of tubular elements.

The solder-bonding study plan is summarized in the flow diagram, Figure 36,

1. In an early trial, the end of a graphite-aluminum tube was ni-plated as was a thin, flat piece of DWAl 20®. The tube end was

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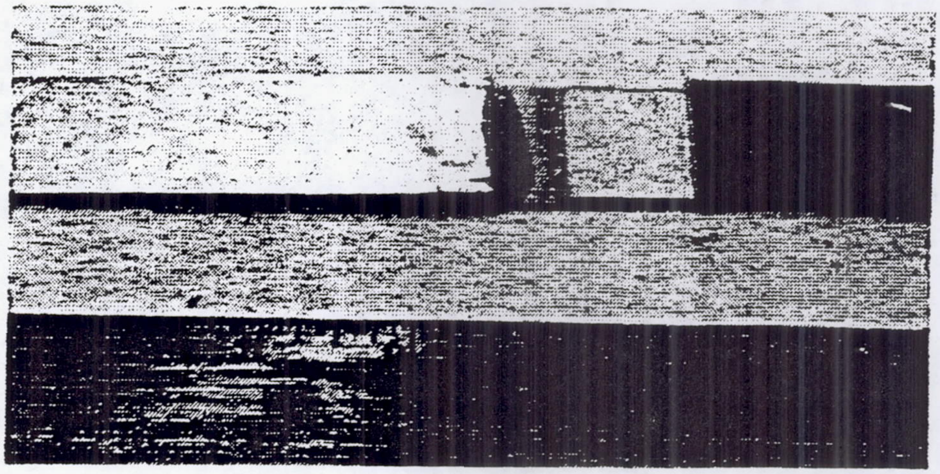
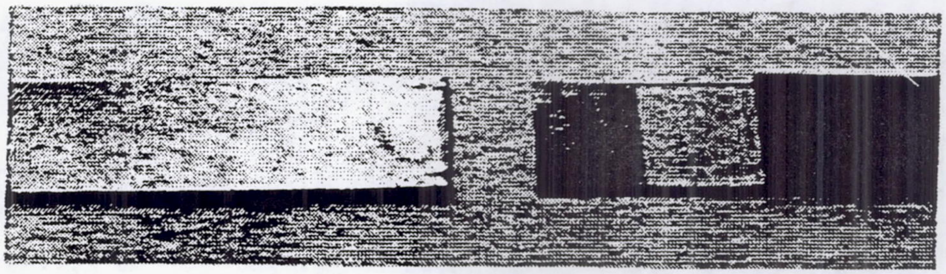
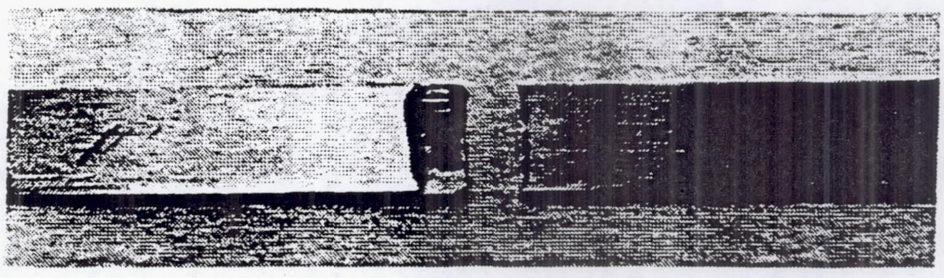


A. Before Shear Test



B(1). After Shear Test



B(2). After Shear Test, Reverse Side

Figure 35. Adhesive Bonding Experiment Sample using Hysol 9309 NA Epoxy

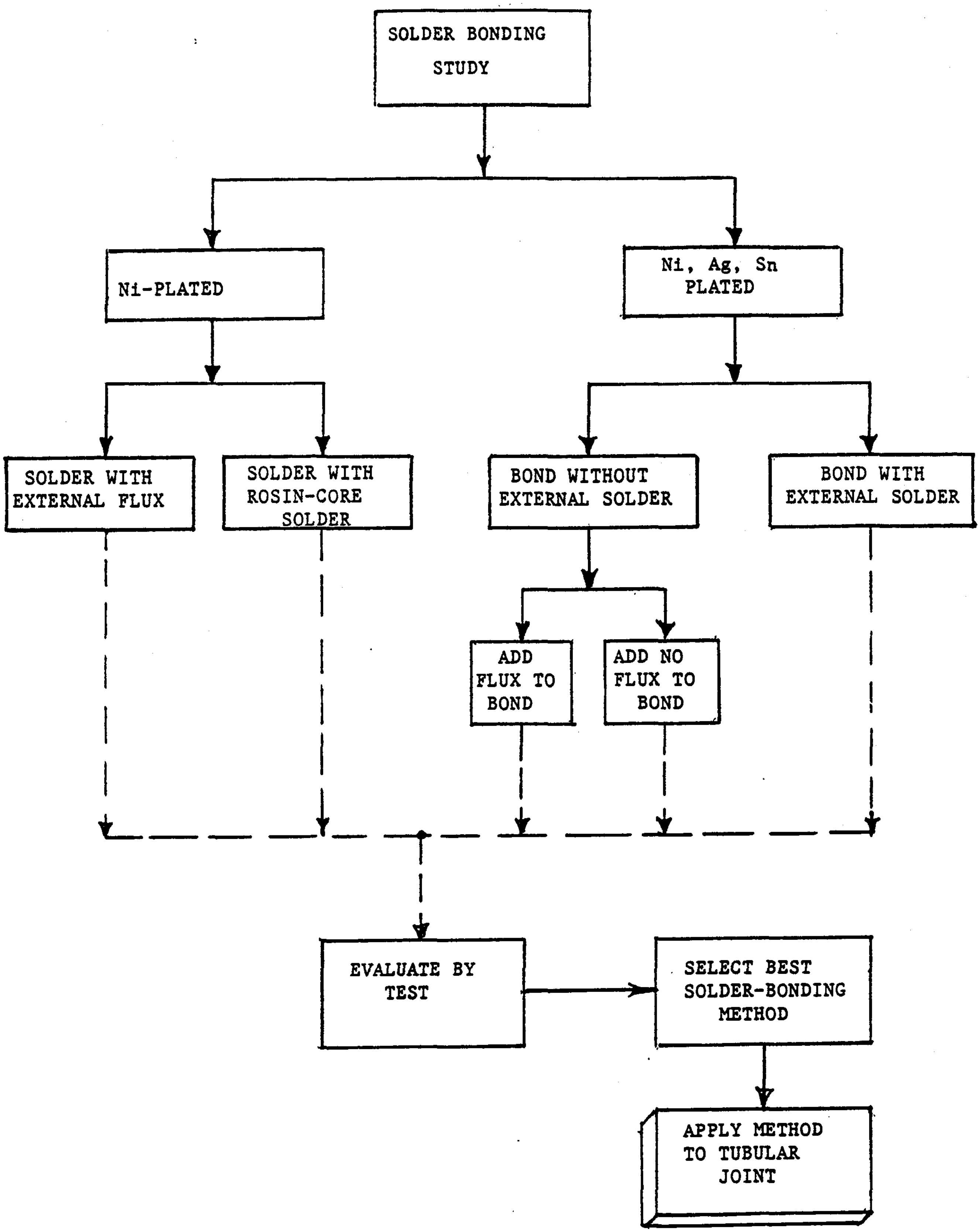


Figure 36. Solder-bonding Study Plan

then butted to the plate, rosin was applied, and the joint was surrounded by solder wire, 95% tin, 5% silver. The assembly was placed in an oven at 500°F for approximately 5 minutes. Solder-bonding appeared to be successful.

2. Simple lap shear test samples were next prepared utilizing thin flat pieces of DWAl and DWG, nickel plated then pressed together under a weight while lying on the oven floor surface. In between the two mating surfaces were placed lengths of solder wire and a liberal coating of rosin. The solder was composed of 95% tin and 5% silver. Samples thus prepared were heated in the oven for approximately 5 mintues at 500°F.

   The single lap shear test samples failed early. Evaluation of test results indicated that failure was due to improper spacing between mating surfaces to be soldered, preventing the necessary capillary action to take place.

3. The next series of experiments involved solder-bonding of tubular parts similar to those involved in fabrication of the program truss structural bay. DWAl 20® sleeves were machined from extruded tube so that the ID was larger than the OD of the DWG tube to be inserted plus the spacing required to accommodate both the plating on the mating surfaces and the coating of solder to be inserted by capillary action when heated. The configuration for solder-bonding the tubular parts was estimated as shown in Figure 37.

   Test units were assembled as shown in Figure 38 (utilizing the plating and spacing illustrated in Figure 37). The end pieces of the test assembly were stainless steel, secured around the DWAl 20® sleeves in the same way that the DWAl tubes were secured to the DWG tube.

   Testing of the solder-bonded, tubular parts was inconclusive due to failure in the joints between the stainless steel fixture tubes and the DWAl tubular test parts. After several trials, it was decided to switch from tensile testing to compressive testing to evaluate the tubular assembly, thus eliminating the need for stainless steel fixture tubes.

   The compressive test setup is illustrated in Figure 39, showing one end of the DWG tube held in plastic so that the test force is applied to the more stable DWAl tube. Testing showed poor solder application; methods need improvement.

4. Finally, the solder-bonding work being conducted on other DWA projects was being observed closely for application to this program. Some of this work involves double-lap shear test specimens to determine the holding strength of solder-bonded parts. One parameter being evaluated is the capillary space provided for solder flow (Figure 40) wherein the space between the test unit and the pull block slot was varied.

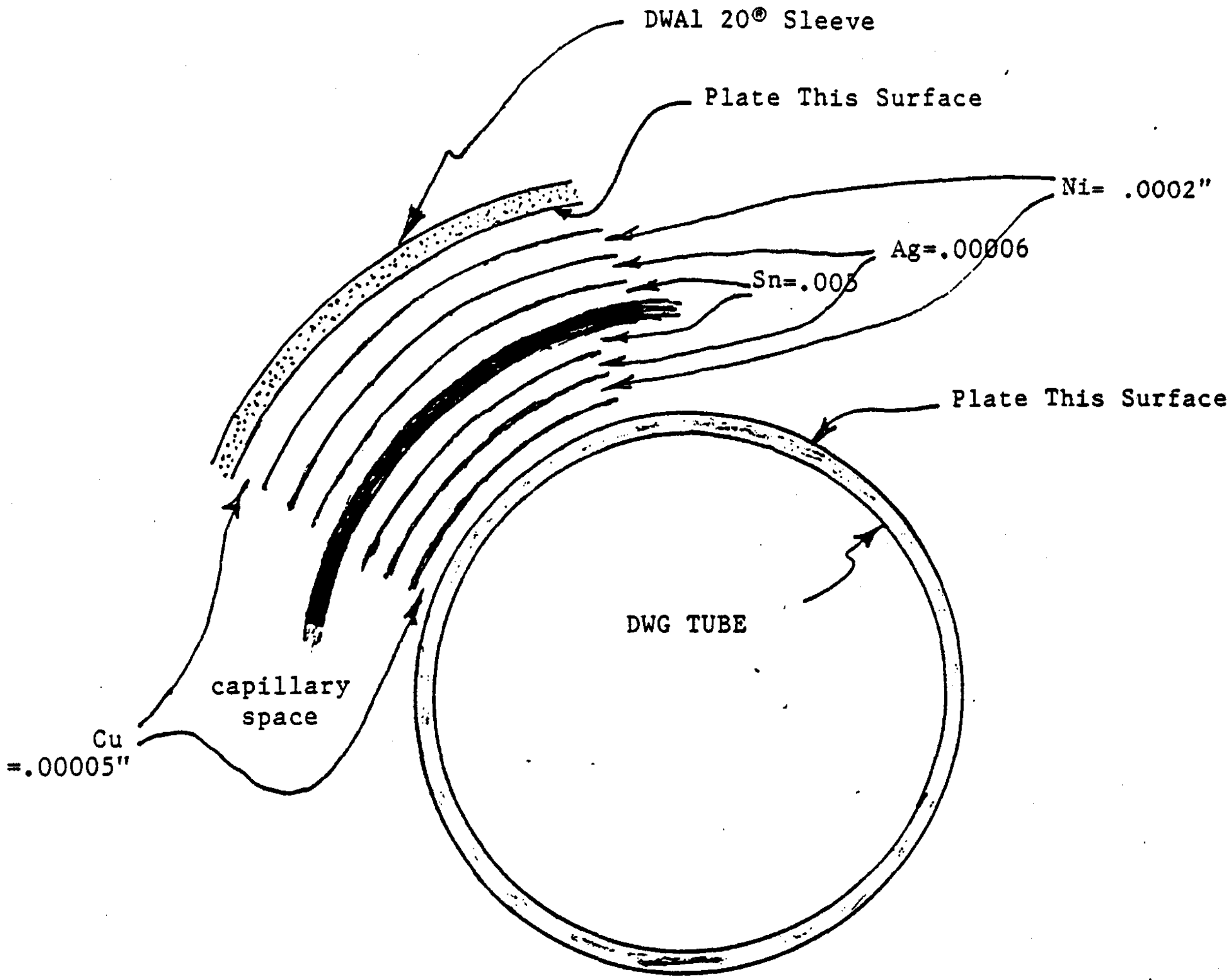


Figure 37. Planned Configuration of Plating for Solder-bonding Tubular Parts

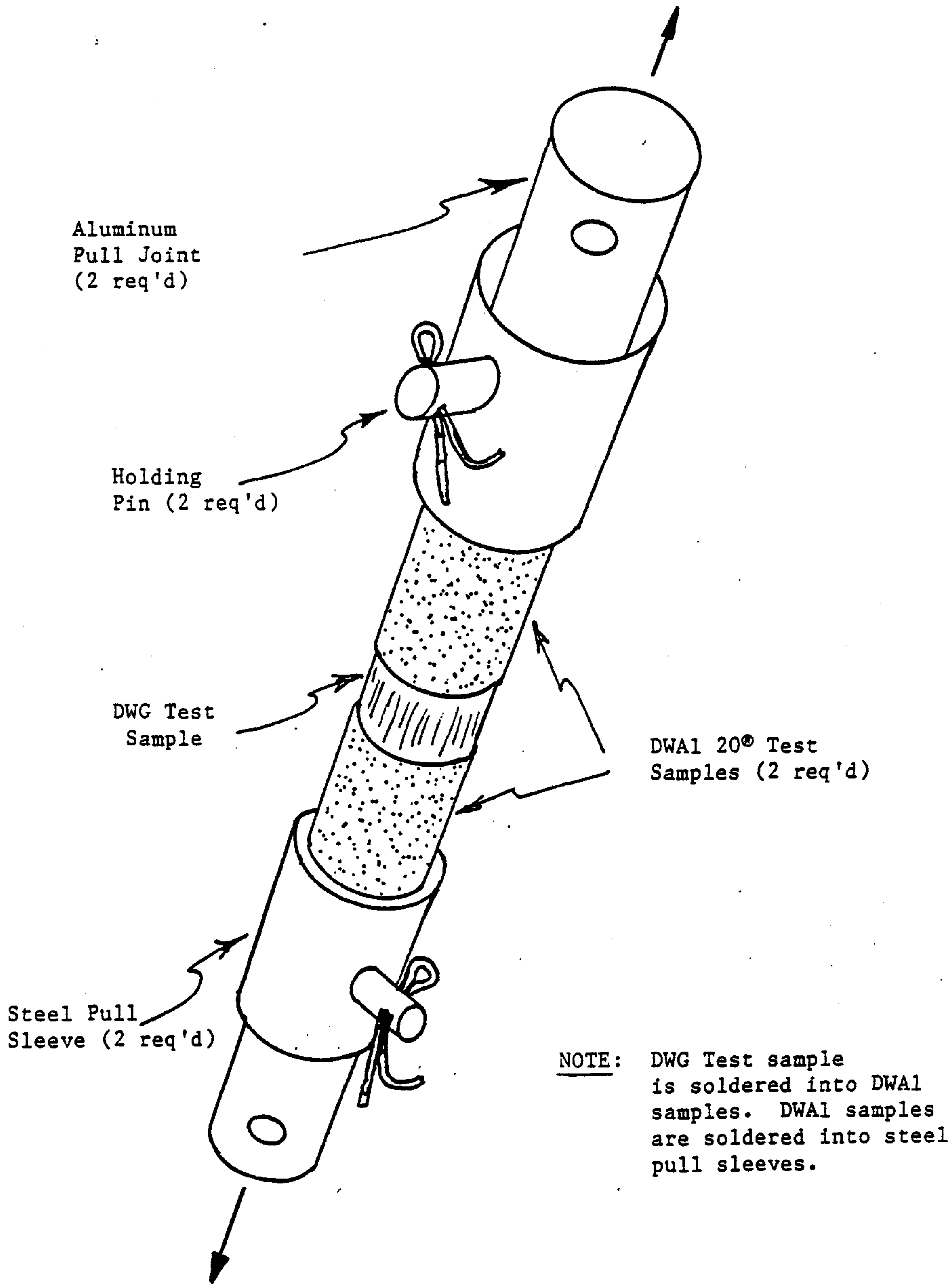


Figure 38. Tensile Test Arrangement for Evaluating Solder-bonded Tubular Parts

NOTE: The DWG tube
is soldered into
the DWAl sleeve.

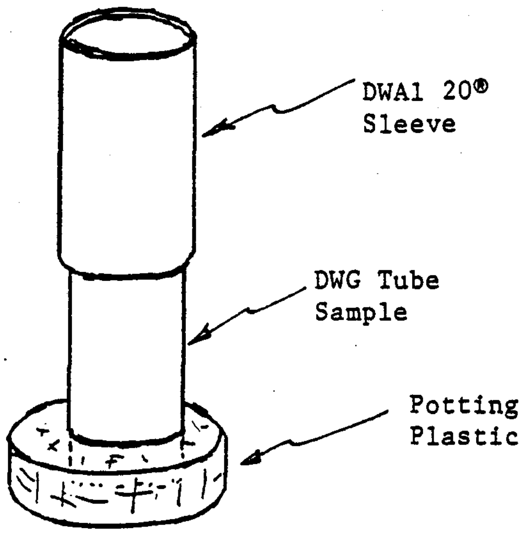


Figure 39. Compression Test Setup for Evaluating Solder-bonded Tubular Parts

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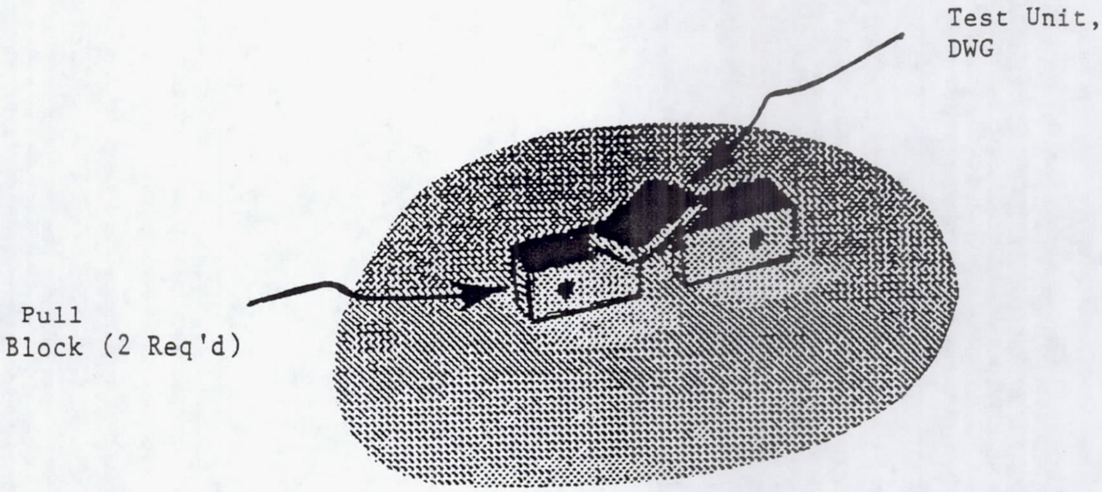
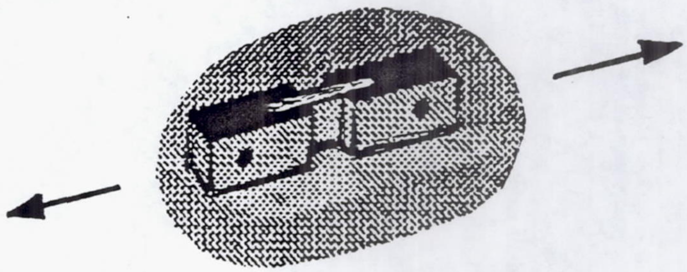


A. TEST PARTS



B. ASSEMBLY, READY FOR TEST

Figure 40. Double-Lap Shear Test Unit Assembly for Solder-bonding Parameter Evaluation.

Another variation tested is the mechanism for applying the solder constituents, including:

a. with and without rosin;
b. plating-on of solder constituents;
c. solder paste application.

5. Finally, a special method of solder application was investigated briefly; viz., solder mat installation, wherein fine solder wire was weaved into a mat, then pressed to about 3 mil thickness in a hydraulic press. A typical mat is pictured in Figure 41.

   Results of solder-mat application were promising but inconclusive. More development is required.

2.4.1.3 Welding. Welding experiments were conducted. The DWAl 20® extruded plank, PE2632, 30v/o B_4C/6061, was prepared for welding by beveling adjacent edges. Butt-welding parameters were varied as indicated in Table 3. Sample material was cut across the weldments, and tensile tests were conducted. Test results are presented in Table 4.

At first observation, it appears that the 5000 series weld rod is best for this application. However, these preliminary trials were brief with a small amount of data produced. Experiments should be continued.

Visual inspection of the magnified photomicrograph shown in Figure 42 demonstrates the typical lack of voids attendant with all weldments of B_4C - reinforced MMC material, an attribute of value to both conventional and inertia weldments.

The welding evaluation was included in the event that end fittings were fabricated by welding DWAl 20 to itself or to conventional metal, and to facilitate ready repair.

2.4.1.4 Mechanical Fasteners. The principal interest in mechanical fasteners is for application in truss assembly whereby tubular components are installed into opposite, rigidly-positioned end fittings. (In the space environment, repair replacement is facilitated by mechanical means).

Of special interest is the union-type connector. This connector is similar to a standard iron pipe union but significantly lighter. One of the candidate bonding methods was used to fix DWAl 20® terminators to the tubes and end fitting appendages. Design of the union type connector is described in Figures 43 through 46, including nominal dimensions. The exact dimensions were verified after measurement of finished tube components.

Manufacture of the finished union-type connector, illustrated in Figure 47, involved extrusion of round bar preform stock, machining to near net, threading, and tapping. The resulting connector is lighter and stronger than the equivalent aluminum unit, with half the coefficient of thermal expansion and nearly twice the stiffness.

Solder: Kester 95Sn/5Ag

Figure 41. Woven Solder Mat to Facilitate Installation Between Cylindrical Mating Surfaces to be Solder-bonded

Table 3. Welding Parameter Variations, to Join Plates of PE2632, 30v/o B_4C/6061

1.	Rod: 1100 Al Gas: Helium Current: DC Speed: 1 min. per inch
2.	Rod: 4043 Al Gas: Argon Current: AC Speed: 30 sec. per inch
3.	Rod: 4043 Al Gas: Helium Current: DC Speed: 1 min. per inch
4.	Rod: 5556 Al Gas: Argon Current: AC Speed: 1 min. per inch
5.	Rod: 5356 Al Gas: Argon Current: AC Speed: 1 min. per inch

Table 4

TEST DATA SUMMARY
FOR PE-2632 Weldment
SERIAL NUMBER

JOB NUMBER 348 DATE 6 / 22 / 87
SPECIMEN DESCRIPTION 30v/o B_4C/6061 PE-2632

TEST NO.	I. D. NO.		UTS	Y. P.	P. L.	E	Ef	R. A.	HR
17791	1.1		22.13	--	10.86	--	.212	--	38
17837	1.2	T6	26.31	--	--	--	.124	--	81
17838	1.3	T6	20.24	--	--	--	.106	--	80.5
17792	2.1		23.52	--	14.34	--	.216	--	37.5
17839	2.2	T6	22.08	--	--	--	.112	--	78.5
17840	2.3	T6	24.61	--	--	--	.131	--	81.5
17793/1784	3.1		22.93/23.86	9.28	7.53	--	1.11+/.125	--	32/80
17842	3.2	T6	16.63	--	--	--	.09	--	.77
17843	3.3	T6	18.12	--	--	--	.110	--	74
17794	4.1		28.67	--	14.20	--	.444	--	36
17844	4.2	T6	33.72	--	31.05	--	.175	--	79
17845	4.3	T6	38.73	--	36.24	--	.228	--	80
17795	5.1		32.13	28.12	12.13	--	.535	--	38
17846	5.2	T6	30.77	--	--	--	.167	--	80.5
17842	5.3	T6	34.27	--	28.77	--	.182	--	80

HIGH

LONG.										
TRANS										

LOW

LONG.										
TRANS										

AVERAGE

LONG.										
TRANS										

COMPLETED BY: Kenneth Ellison Dewey

6-14-87 TEST LAB FORM NO. 1007

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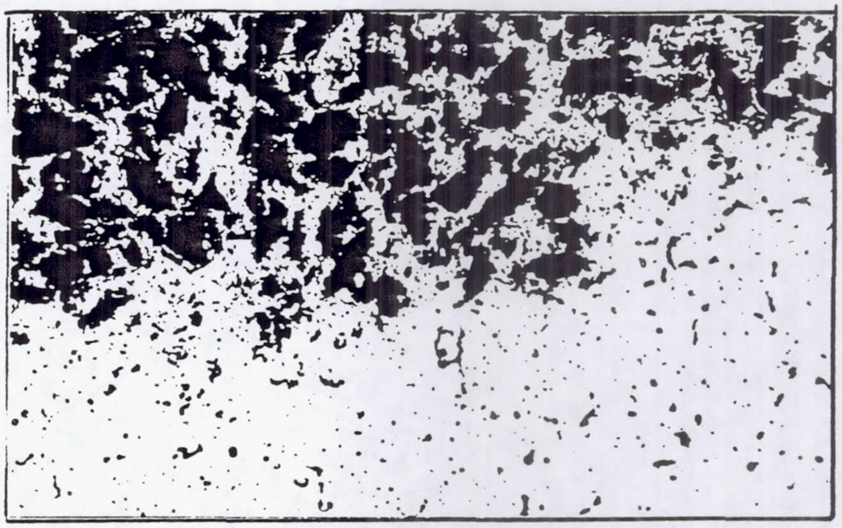
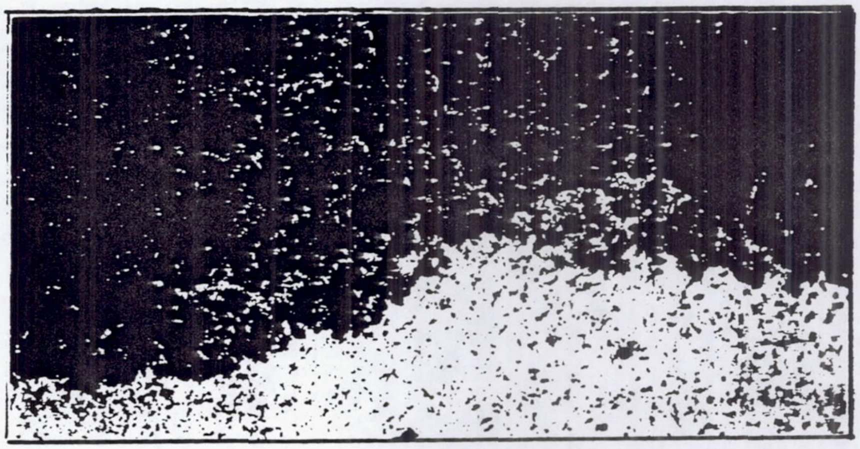
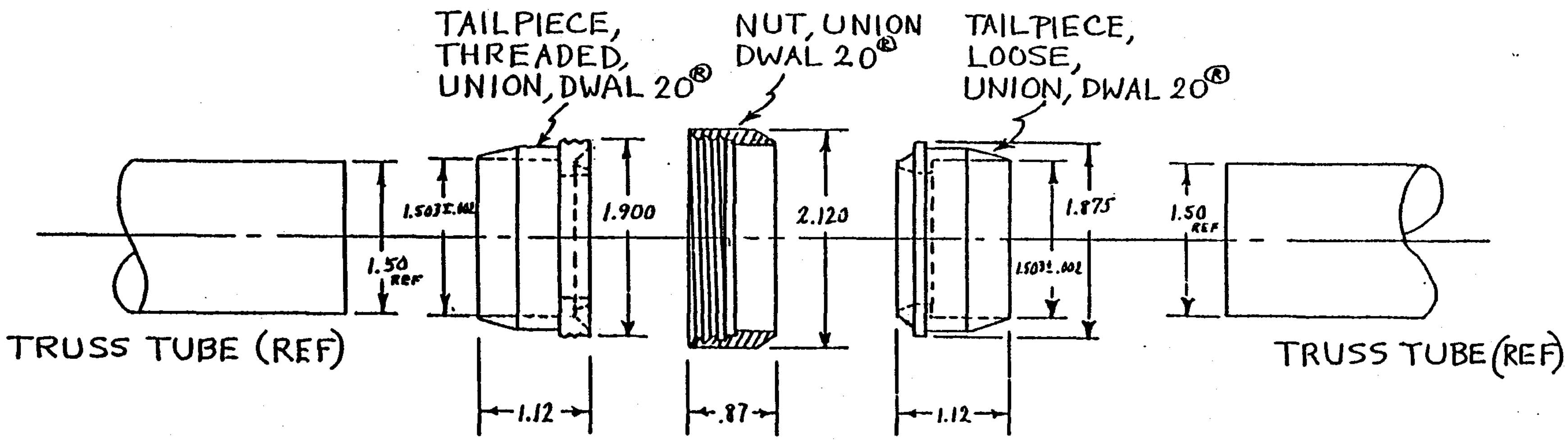


A. Magnification 300X



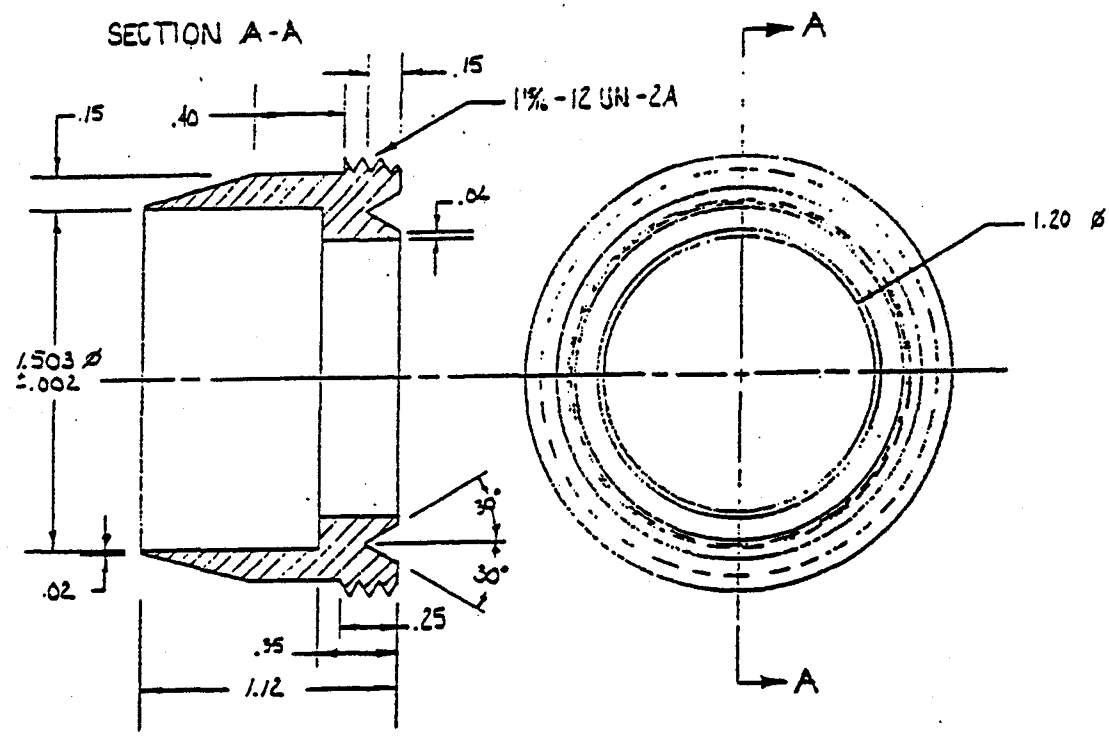
B. Magnification 150X

FIGURE 42. Metallography of 30v/o B_4C/6061 DWAl 20® Weldment, 5356 Al Weld Rod, Argon Gas, AC Current.



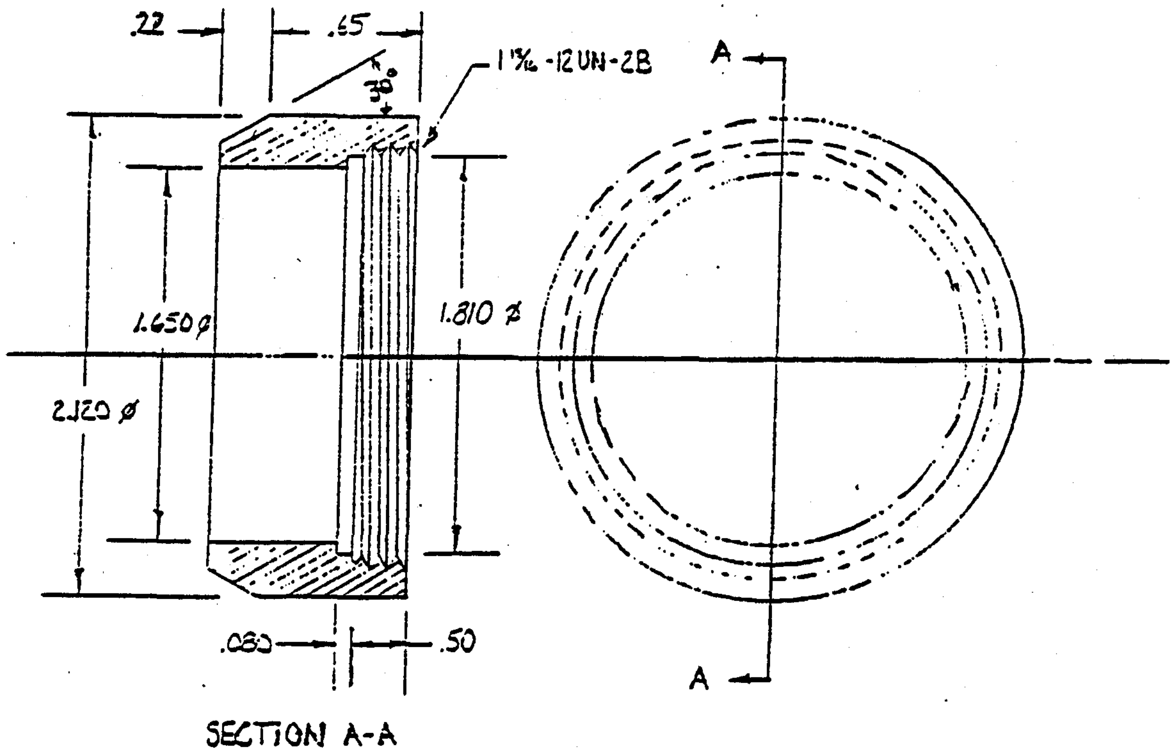
ALL LINEAR DIMENSIONS INCHES

Figure 43. Union Type Connector, Constructed of DWAl 20® MMC.



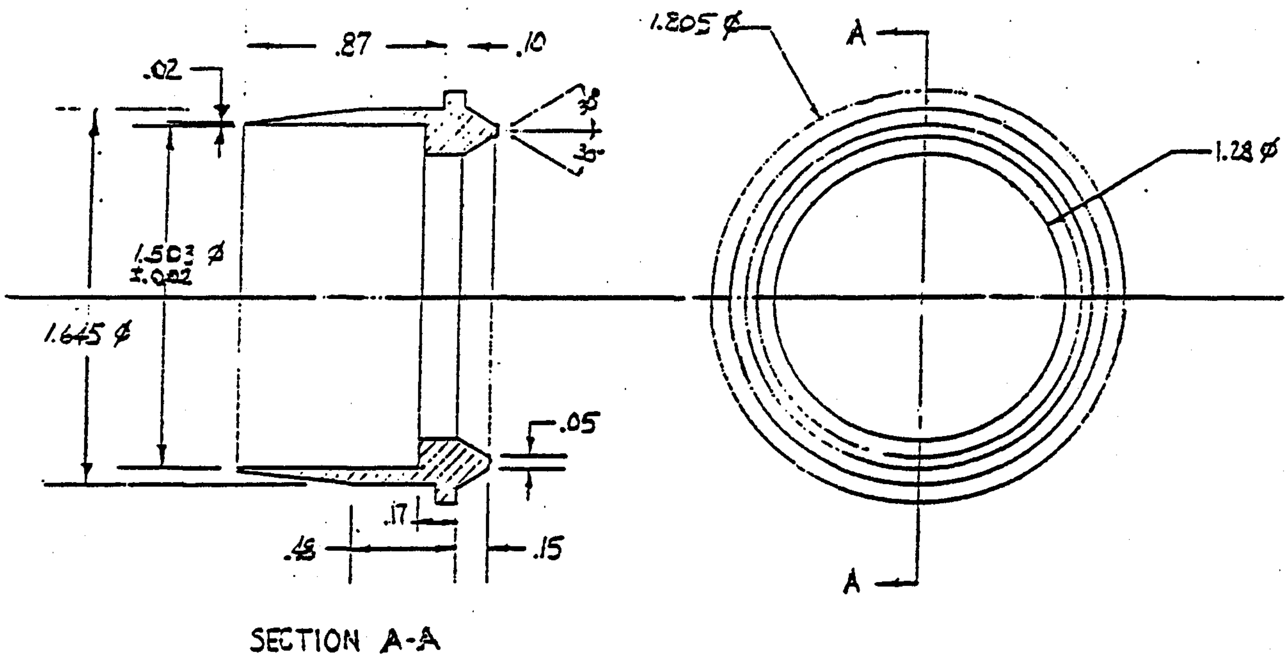
ALL LINEAR DIMENSIONS INCHES

Figure 44. Union Type Connector Part, Threaded Tailpiece.



ALL LINEAR DIMENSIONS INCHES

Figure 45. Union Type Connector Part, Nut.



ALL LINEAR DIMENSIONS INCHES

Figure 46 Union Type Connector Part, Loose Tailpiece.

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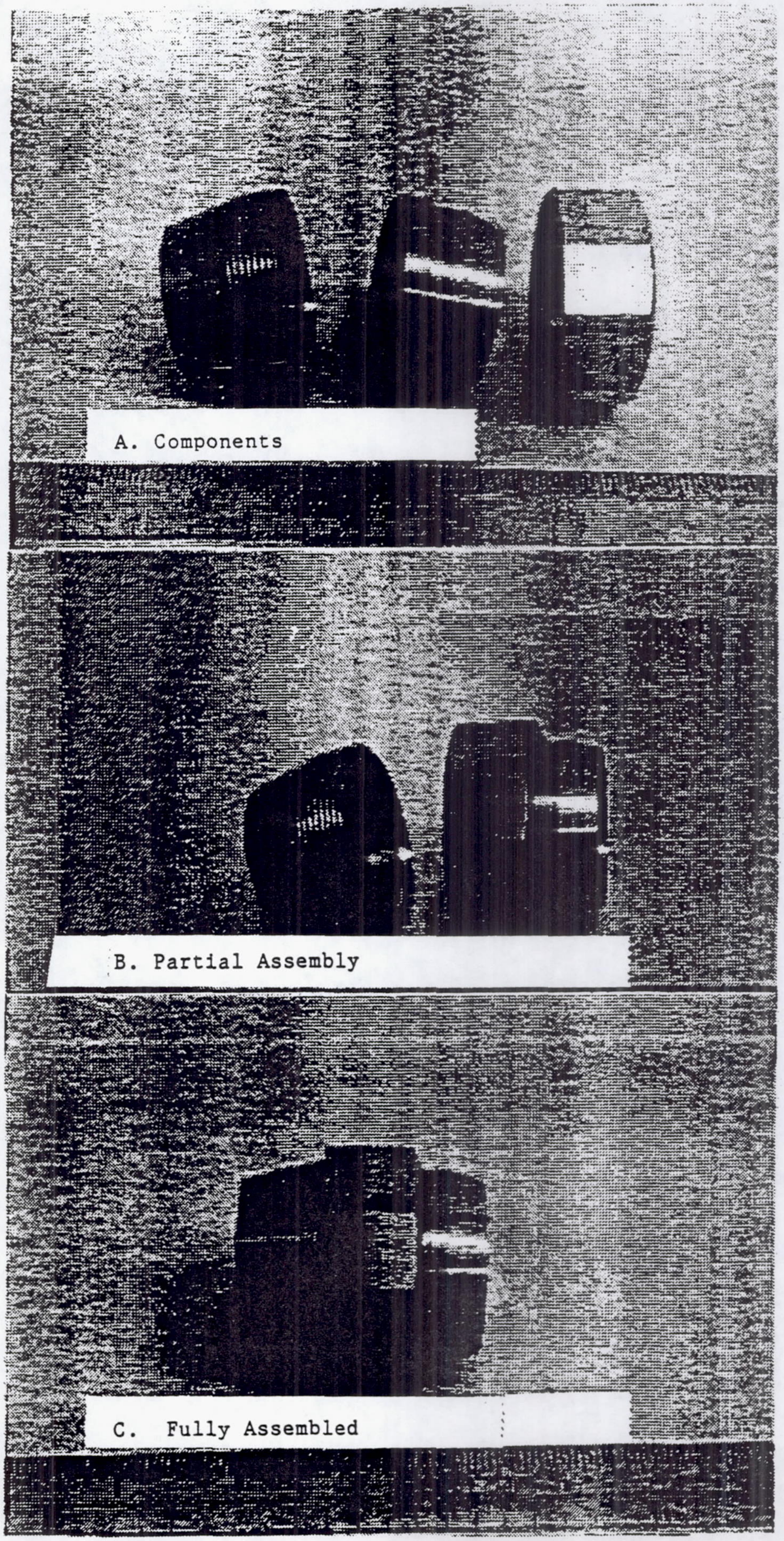

Figure 47. Union-Type DWA1 20® Assembly Connector

Quick-connect mechanical fasteners are also of interest but not included herein, as they were felt to be outside the program scope. The quick-connect when designed properly, eliminates turning to secure, and attendant hand fatigue.

2.4.1.5 Summary of Joining Methods Evaluated. After evaluating results of the joining methods, DWA arrived at the conclusion that adhesive bonding was the most straight forward and logical method to use, based primarily on wide industry employment. The following synopsis provides selection rationale:

A. Solder-bonding shows high promise as an excellent future approach to joining space truss elements into the space station structure. However, a number of research activities are required before the use of solder-bonding could be recommended.

   (a) continued research in methods of applying the solder;

   (b) improvement in the methodology of presolder plating of the surfaces to be bonded;

   (c) continued study of the most efficient spacing between solder-bonded parts;

   (d) development of tools for field space use in the application of solder-bonding.

B. Welding is not applicable to the present design. However, testing demonstrated excellent welding response of B_4C reinforced DWAl 20®, enabling weld repair of discontinuous ceramic reinforced MMC space truss components.

C. Mechanical Fasteners will prove to be indispensible in future space structure assemblies, and for the media transfer conduit planned for manned space stations, beyond the scope of this program.

Final selection of adhesive bonding for the MMC truss assembly, utilizing Epibond 1210 was based on previous industry experience and ease of application.

A future R&D effort should involve comparative testing of the thermal cycling effects on structural integrity and CTE with truss assemblies employing adhesive bonding and the other joining options.

2.4.2 Truss Assembly

Having selected adhesive bonding as the method of joining end fittings and assembly sleeves to the tubular components, truss assembly was undertaken.

2.4.2.1 System Analysis. Analysis of truss assembly considerations was conducted to estimate penetration of tube ends into end fitting appendages and to establish the compromise value of graphite reinforcement crossply angle to be incorporated in the final tubes.

DWG coefficient of thermal expansion (CTE) test data were reported in a previous section. The CTE values were reduced from raw test data as a function of DWG crossply and are presented in Figure 6. Further, estimated CTE values expected from B_4C/6061 DWAl 20® are shown in Figures 9 and 10 as influenced by the ceramic particulate reinforcement level. The 30v/o B_4C level is being incorporated in 6061 aluminum to provide preform material for strong, rigid end fittings; the corresponding estimated value for CTE is 7.2 ppm/°F per degree Fahrenheit.

Utilizing the DWG tube CTE values and DWAl 20® end fitting CTE values, the effective CTE for tubular elements (one tube component between two end fittings) was calculated for each part of the truss assembly.

Tube protrusions into the end fittings are illustrated in Figures 48 and 49 showing batten #2 and batten #1, respectively. For the truss configuration pictured in Figure 3, each of the truss tube components protrudes into the end fitting through a different appendage at varying depth. Theoretically each of the associated tube components must then be fabricated with a different crossply of graphite fiber reinforcement if absolute zero CTE was required of the truss assembly. However, for the thermal stability criterion of 0°±1 PPM/°F, the objective is achievable with a single Gr/Al crossply tube design.

Values of thermal expansion coefficient for the effective tube component lengths were calculated by applying the rule of mixtures:

$$\text{Tubular Element CTE} = (L/O)_T \, CTE_T + [1-(L/O)_T] \, CTE_E$$

Recalling that for the desired allowable maximum CTE value for the tubular element, CTE = 0, the above equation is solved for CTE_T by substituting calculated and measured values of the following variables:

$(L/O)_T$, calculated length percent of tube.
CTE_T, measured thermal expansion coefficient for tube.
CTE_E, estimated thermal expansion coefficient for end fitting.

The crossply values of the required tube components (battens, longerons, and diagonals) to achieve 0 CTE in the truss are all slightly different. Therefore to simplify manufacture, the single crossply value of ±12° was selected for all of the tubular components.

2.4.2.2 <u>Assembly</u>. Before bonding tubes to the end fittings, the total truss bay was assembled as shown in Figure 50. A rectangular box frame was welded-up out of aluminum angle such that the bay assembly could be placed inside the box frame. Brackets were provided to secure the truss bay within the box frame. These brackets were adjustable to permit the truss bay to be assembled with the necessary accuracy and held securely during subsequent bonding operations, as well as shipping.

Initially, the top and bottom sub-assemblies were bonded, each consisting of three battens and three end fittings formed into an equilateral triangle as illustrated in Figure 51. Six aluminum adapter feet were next fabricated to fit into the open ends of the end fittings installed at the top and bottom

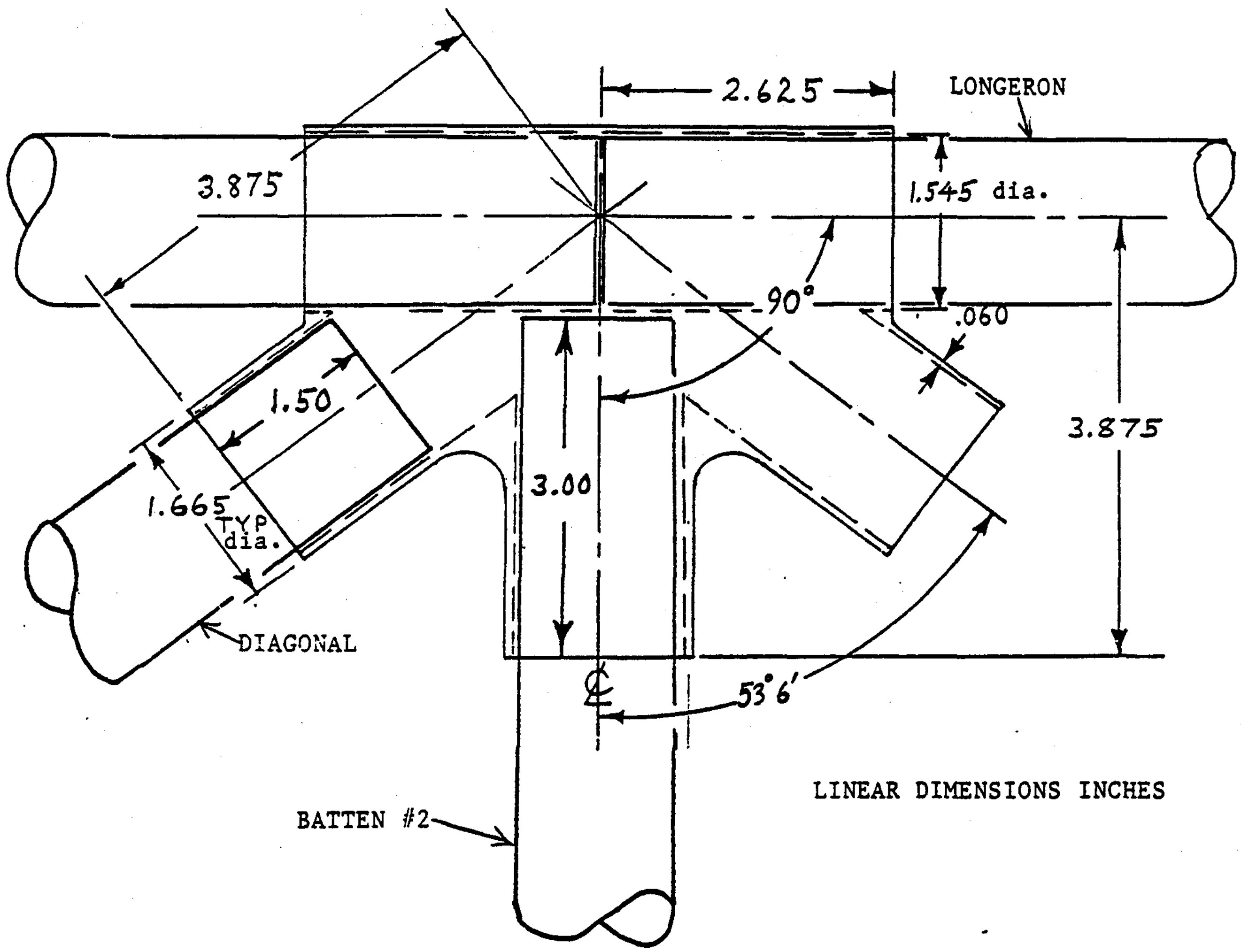

Figure 48. Tube Protrusions into End Fitting, Showing Batten #2.

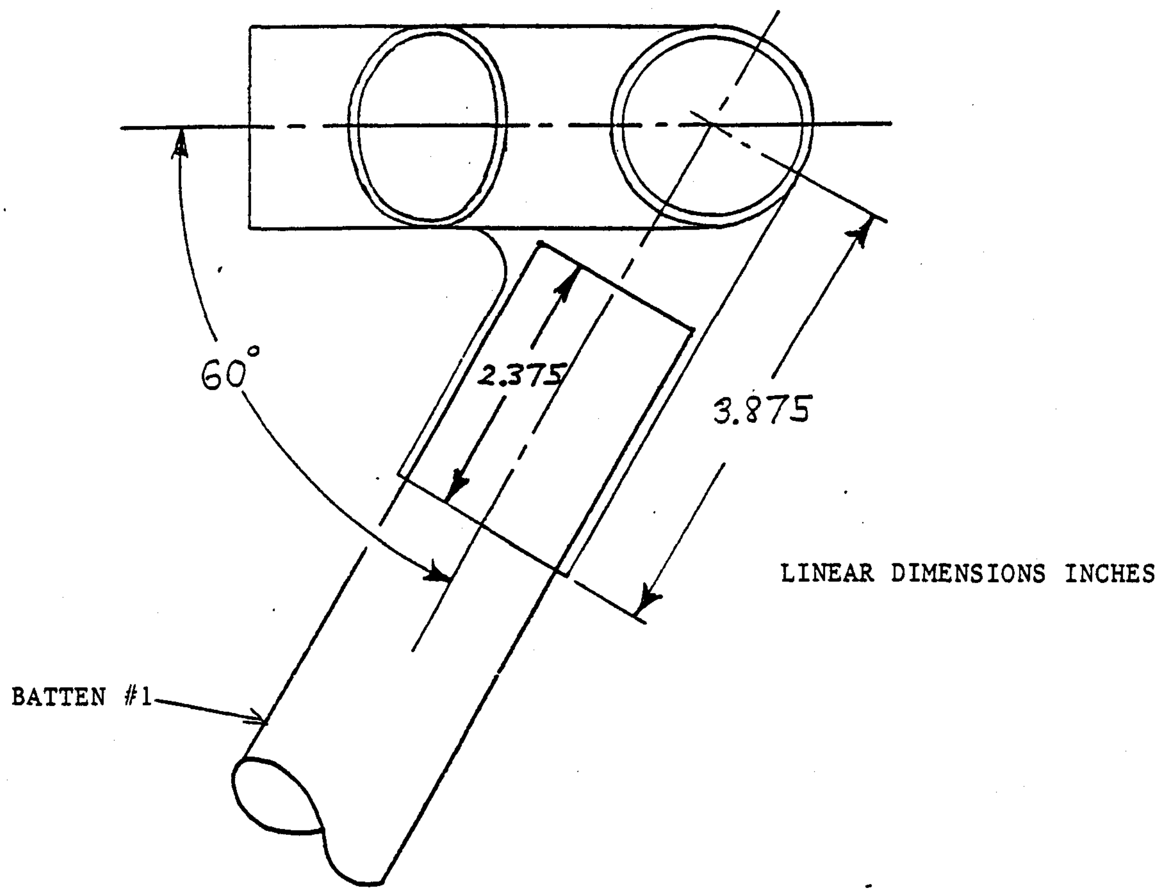

Figure 49. Tube Protrusion into End Fitting, Showing Batten #1

Table 5. Calculated Tube Crossply Required to Meet Combined CTE = 0; Recommended for Tubular Element.

STRUCTURAL TUBE COMPONENT	EFFECTIVE TUBE LENGTH inches	TUBE LENGTH FRACTION $(L/O)_T$	CALCULATED TUBE CTE, α_T, REQUIRED PPM/°F	TUBE CROSSPLY REQUIRED Degrees
Batten	30.94	.860	-.031	±17
Longeron	45.37	.945	+.633	±7
Diagonal	53.75	.896	+.269	±12

NOTES: 1. Calculated for Tubular Element $\alpha_c = 0$, so that:

$$\alpha_T = \frac{1 + [(L/O)_T - 1]\ \alpha_E}{(L/O)}$$

2. Read from Figure of α_T vs. Tube Crossply angle, degrees.

3. Average of Battens #1 and #2, defined in Figures 48 and 49, respectively.

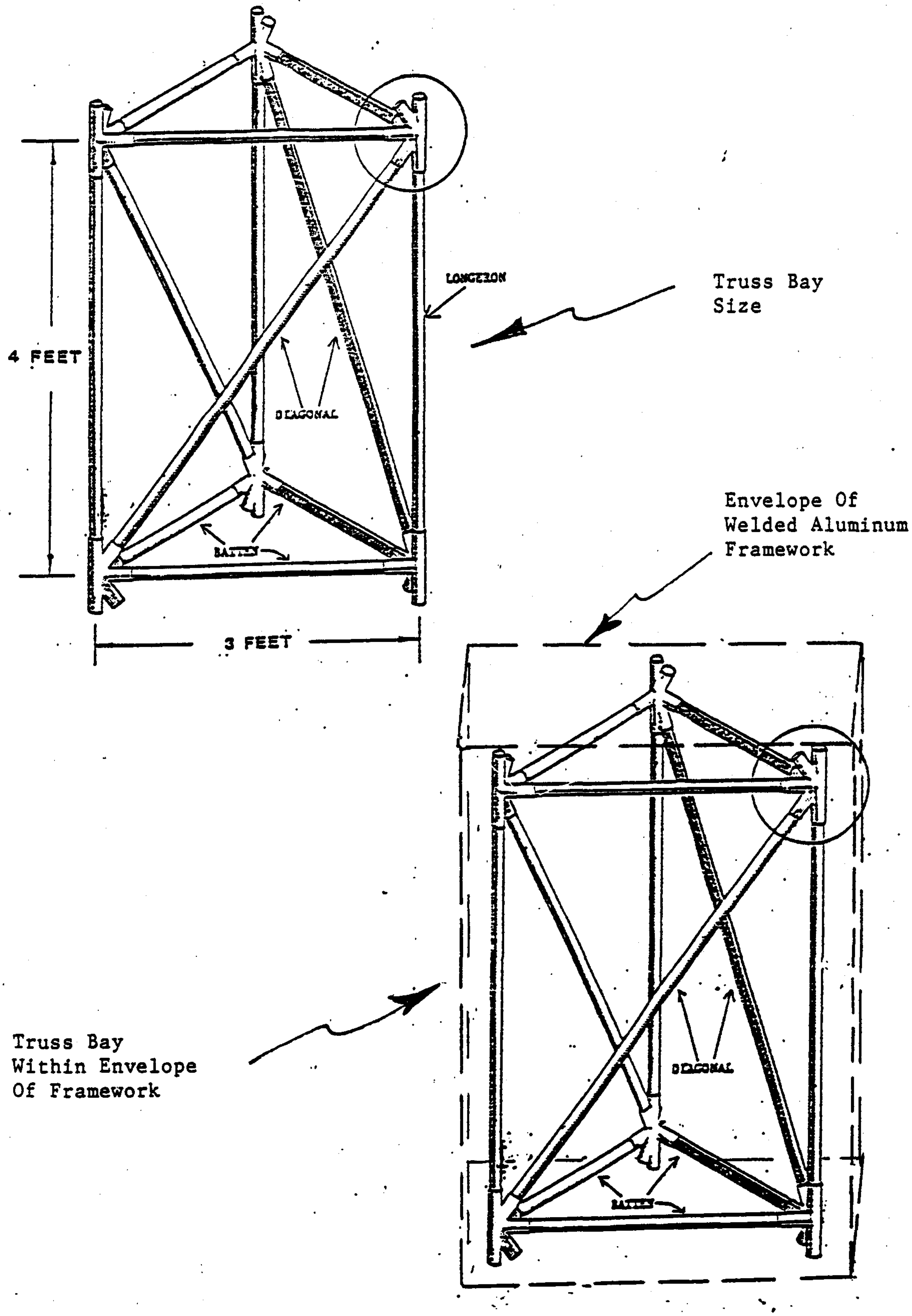

Figure 50. Method of Encapsulating Truss Bay in a Frame Fixture, for Assembly and Shipping

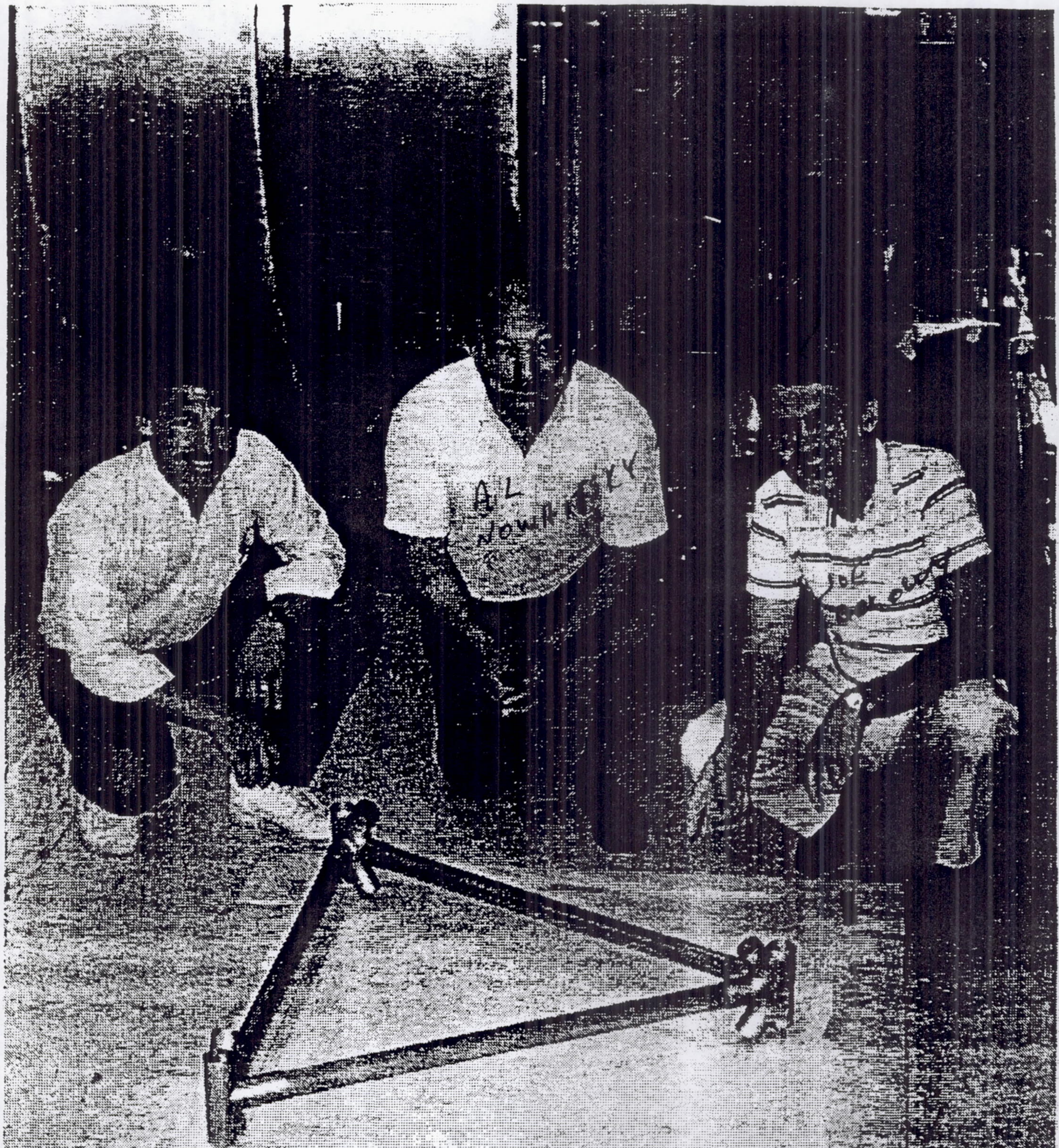

Figure 51. Equilateral Top/Bottom Sub-Assembly of Space Truss

of the longerons. These adapters facilitated assembly of the remaining six tubes; i.e., the three longerons and the three diagonals. The three longerons were bonded to the top and bottom sub-assemblies providing the specified height. Next, each diagonal half-length was inserted into a diagonal appendage and secured to the opposite diagonal half-length by a DWAl 20® sleeve positioned halfway between the two end fittings. The end fittings and sleeves were finally secured in place to form the completed truss illustrated in Figure 52.

2.5 SYSTEM TEST

The completed space truss was secured inside the assembly rig, crated to prevent damage in transit, and shipped to the test facility, Composite Optics, Inc. (COI), located in San Diego, California.

2.5.1 <u>CTE Testing</u>

At COI, the truss was positioned in an insulated, cylindrical environmental test chamber. A standard of the same length as the truss, made of low expansion material and kept at constant, relatively high, temperature, was fitted to the truss. Compared with the standard, measurements of the truss movements were absolute.

Inside the chamber, the environment was heated by strip heaters which were activated in accordance with thermocouples attached to the truss longerons and coupled to controllers outside. Heat was circulated within the shroud by nitrogen gas, introduced cold at the upper end and heated appropriately by the strip heaters. Gas stratification was prevented by a forced circulation system.

Measurements of thermal strain were conducted in accordance with laser/optical lever principles. Results are presented in Figure 53 wherein strain in μ-inch per inch (also referred to as "parts per million," or PPM) is plotted against temperature in degrees Fahrenheit. From the graph it is observed that

CTE = .598 PPM/°F for temperature change of -149.6°F to +147.4°F

and, CTE = .745 PPM/°F for temperature change of -97.1°F to +147.4°F

The above CTE values had to be corrected for the extended end fittings between which the measurement was taken, as described in Figure 54.

It was not practical to measure the truss CTE between the top and bottom horizontal tube centerlines. Accordingly, the measurement was made from the bottom extremity to the top of the upper longitudinal appendage as shown. The correction is therefore implemented as follows:

<u>Calculate total change in length, ΔL</u>

$$\Delta L_T \times CTE_T \times L_T \times \Delta T$$

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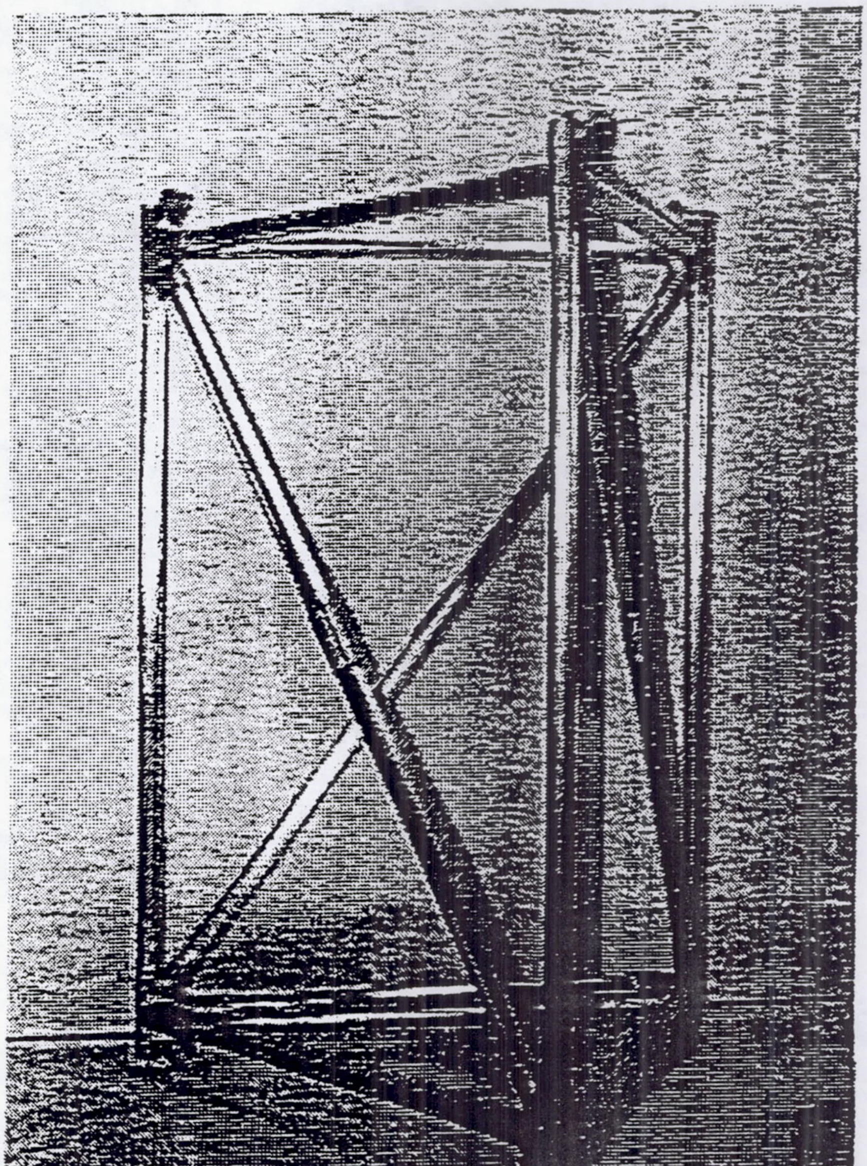


Figure 52. Completed Space Truss Bay, Thermally Stable, Composed of DWG Tubes Bonded to DWAl 20® End Fittings and Assembly Sleeves.

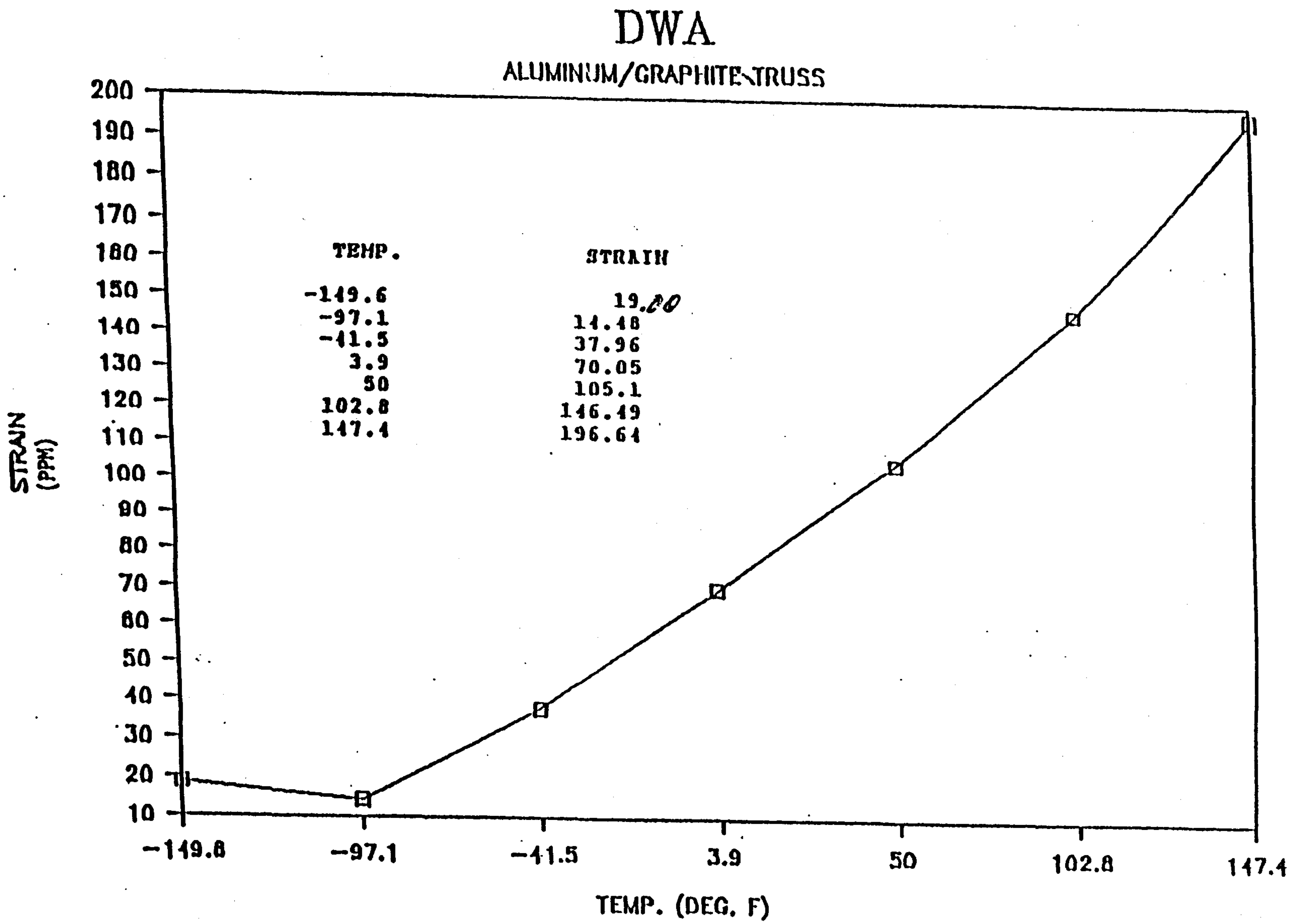


Figure 53. Truss CTE Measurements Made at COI, San Diego, California

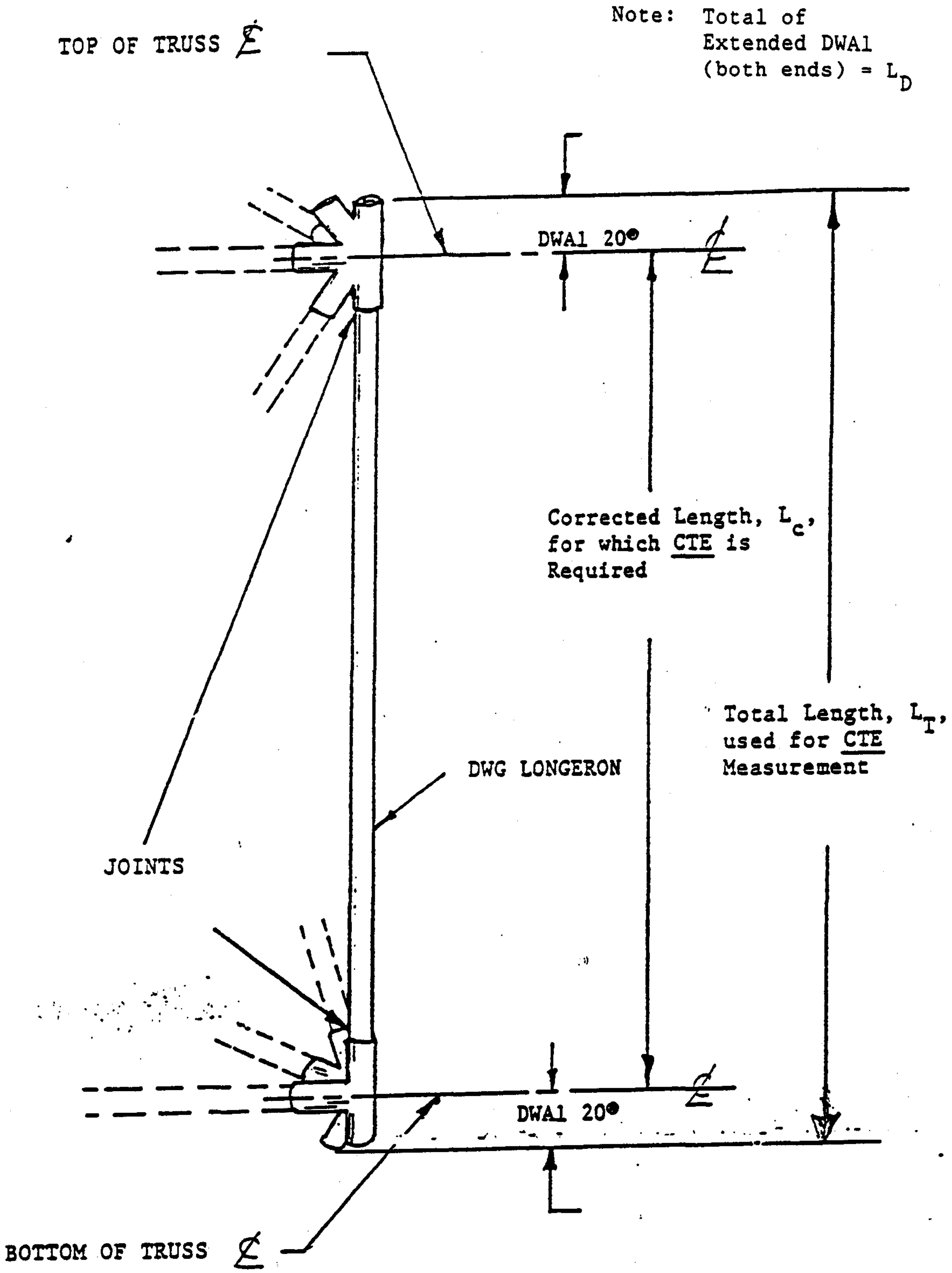


Figure 54. Lengths Involved in CTE Determination (Typical Tubular Element)

Calculate corrected ΔL, ΔL_C

$$\Delta L_C = \Delta L_T - \Delta L_D$$

Calculate corrected length, L_C

$$L_C = L_T - L_D$$

Calculate corrected CTE, CTE_C

$$CTE_C = \Delta L_C / L_C / \Delta T$$

Where Subscripts: T = total length (used in CTE measurements)
C = corrected
D = DWAl 20®

The nominal (room temperature) lengths were measured to be:

L_T = 54 inches
L_D = 5.875 inches
$L_C = L_T - L_D$ = 54 - 5.875 = 48.125 inches

For ΔT = -149.6°F to +147.4°F = 297°F, the value of CTE determined from Figure 54 is CTE_T = .598 PPM/°F.

ΔL_T ~~ΔL_D~~ = .598 x 10^{-6} x 54 x 297 = <u>.009591 inches</u>   CTE x L x ΔT =

ΔL_C = .009591 - .01256 = -.002969 inches

L_C = 48.125 inches   CTE of B_4C = 7.19E

CTE_C = -.002969/48.125/297
= <u>-.2077 PPM/°F</u>

$\Delta L_D = 7.2 \times 10^{-6} \times 5.875 \times 297$

Similarly, for ΔT = -97.1°F to +147.4°F = 244.5°F, for which:

CTE_C = -.0428 PPM/°F

Summarizing,

Temperature Range	Measured CTE	Corrected CTE
-149.6°F to +147.4°F	.598 PPM/°F	-.2077 PPM/°F
-97.1°F to +147.4°F	.745 PPM/°F	-.0428 PPM/°F

2.5.2 Bending Measurement

During CTE measurement, minor bending distortion was detected as a result of temperature change. However, movement of the truss did not exceed about 1/4°. Bending measurements are plotted in Figure 55 against temperature.

The minor rotation of the truss is probably attributable to a small length difference in the longitudinal members produced inadvertently during final assembly of the truss.

3.0 CONCLUSIONS AND RECOMMENDATIONS

This program demonstrated that a near zero CTE G/Al truss structure can be successfully designed and fabricated. Thermal stability of the metal matrix composite truss bay assembly was demonstrated by system CTE test. The adhesive-bonded assembly was shown to be adequate, while other joining options appear to be feasible but need more development.

In the quest for minimum CTE, the discontinuous ceramic particulate reinforced MMC can be improved by increasing the level of reinforcement. For the continuous reinforced graphite-aluminum tubes, the required crossply values can be reduced (for some minimum CTE) by such means as:

a. using higher modulus continuous fibers in the tubes,
b. using higher tube fiber volume fraction.
c. modifying the end fitting design to shorten the appendages,
d. adjust tube protrusions into end fitting appendages.

Recommended continuing and future R&D should include:

a. Expanded studies into assembly joining methods, in particular metallic bonding, erectable and foldable components, and replaceable units;

b. Scaling to larger component sizes, telescoping assemblies, and multiple bay structures. Changes in the configuration of the truss (and end fittings) may be conducive to more efficient erectability.

c. Development of reliability and reproducibility data in the manufacture and dimensional stability of truss structures and components.

d. Production of simpler, lower cost truss structure: When low (but not zero) CTE is desired, lower stiffness graphite reinforcement (e.g., P75) in aluminum or extruded DWAl 20® tube members, plus simpler discontinuous-ceramic reinforced DWAl 20® end fittings, could provide for minimum cost welded assemblies.

e. Combined thermal and mechanical load testing of assembled truss sections and expanded full bay sections.

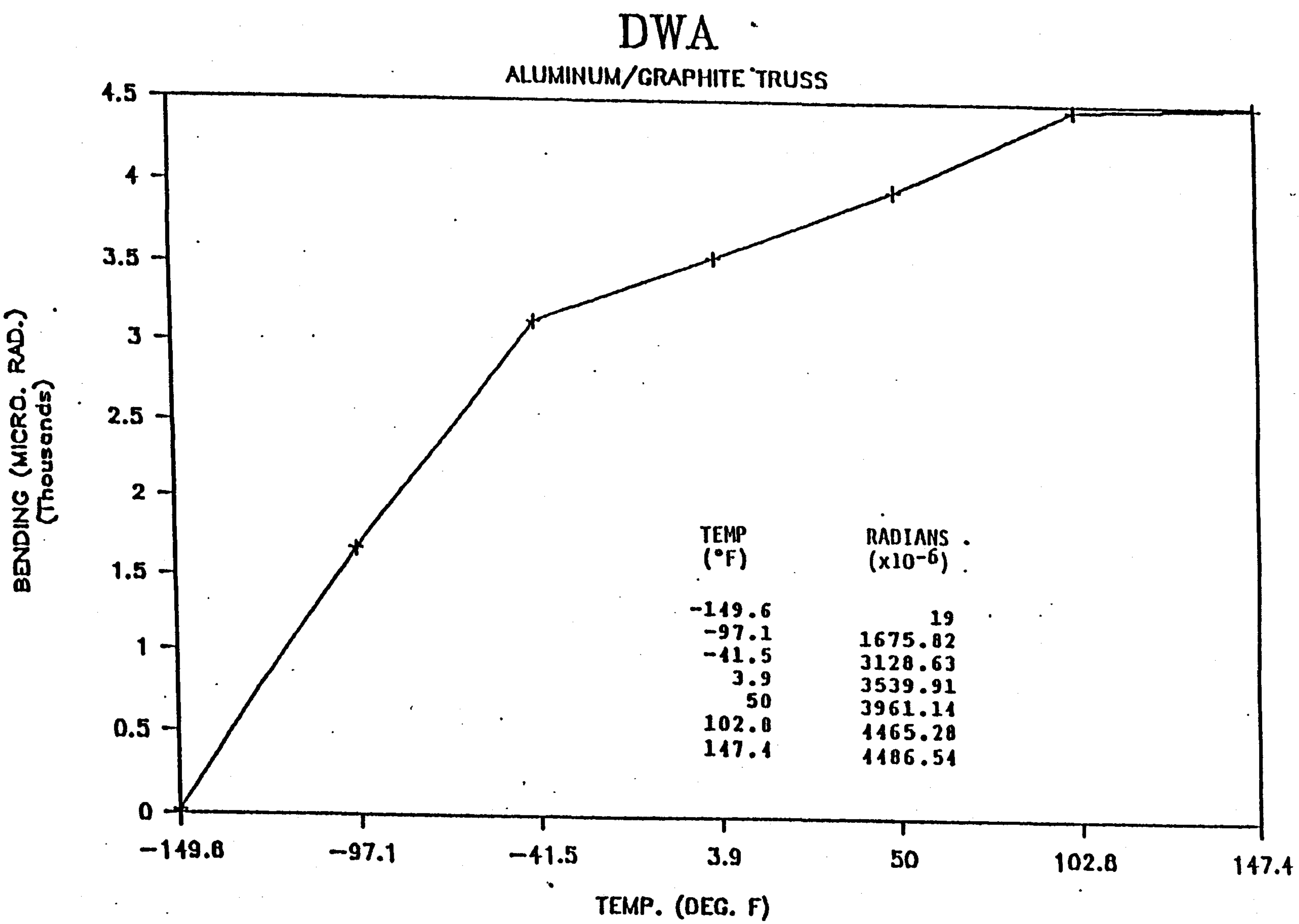


Figure 55. Truss Bending Measurements Made at COI Simultaneously with CTE Measurements

APPENDIX A

Test Results of CTE Measurements

Conducted by Harrop Industries, Columbus, Ohio

(All Samples P100 Graphite Reinforced
6061 Al Composite)

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

TEST NO.: HL-2549

SAMPLE: D1518-L1

SIZE: 1.998"

Y-AXIS SCALE: 0.04%/in.

MODE: Cool/Heat/Cool

RATE: 3°C/min.

ATM.: Static Air

RUN NO.: 1

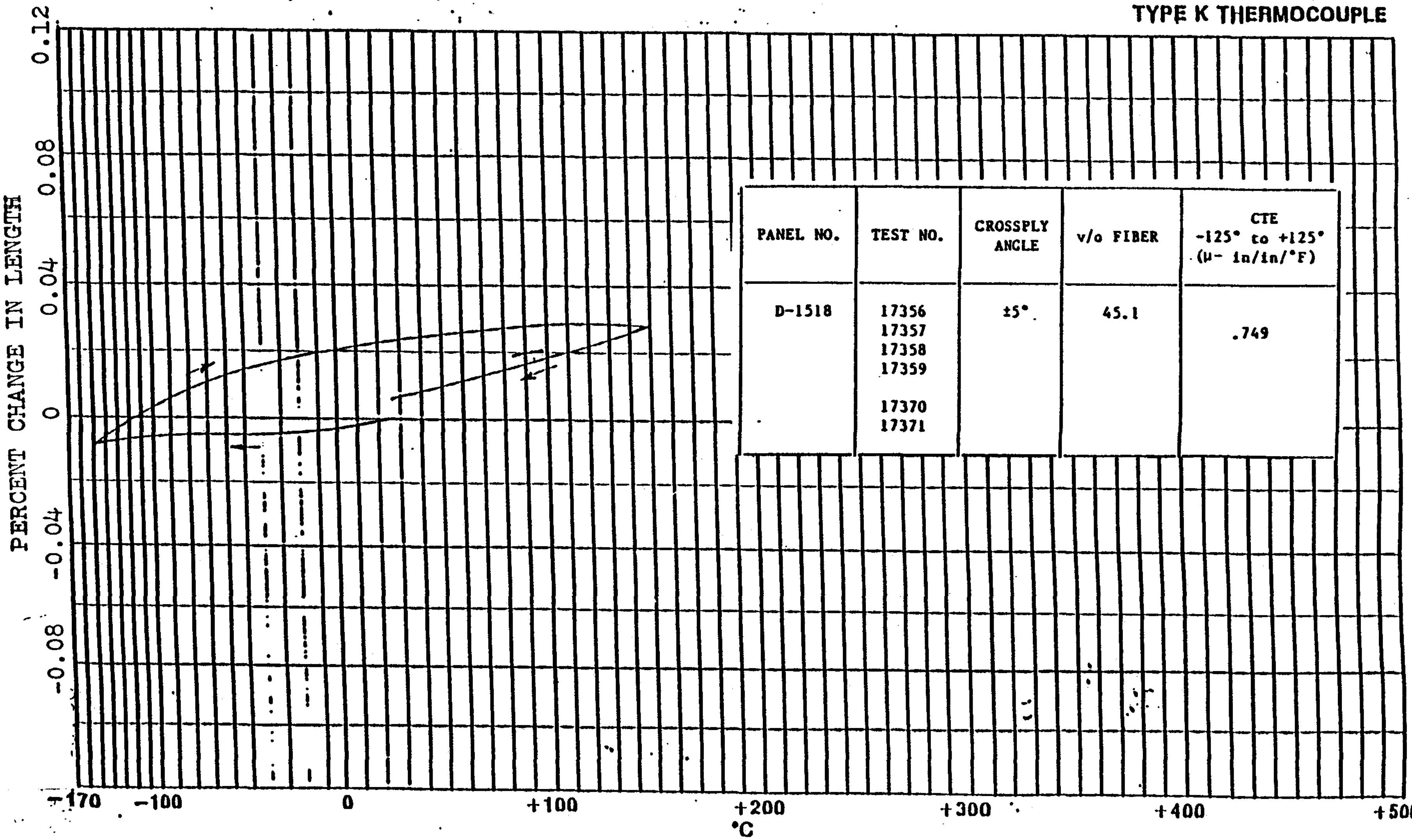
OPERATOR: DED

DATE: 5-22-87

REMARKS:

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1518	17356 17357 17358 17359 17370 17371	±5°	45.1	.749

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

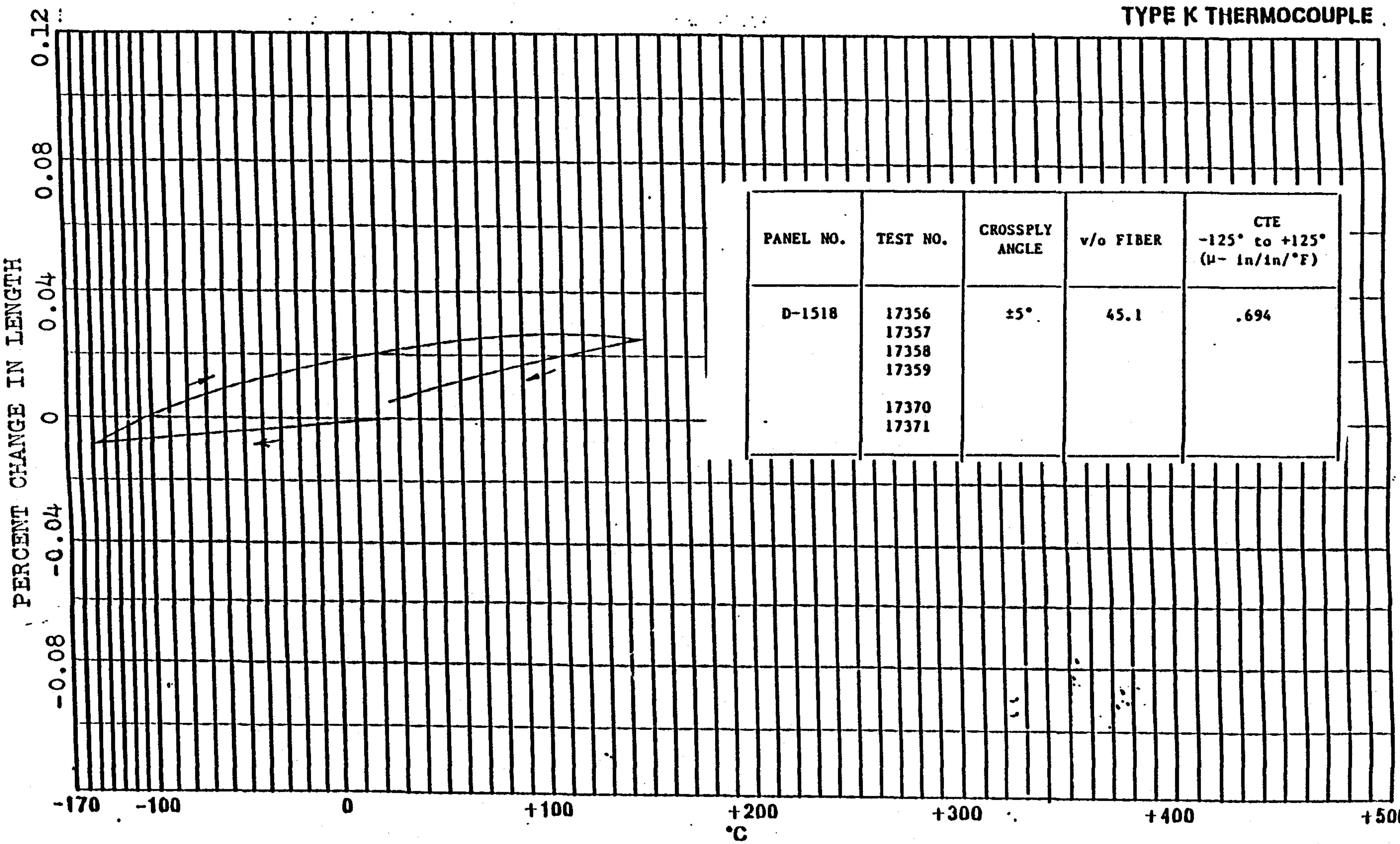
SAMPLE: D1518-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.006" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1518	17356 17357 17358 17359 17370 17371	±5°	45.1	.694

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

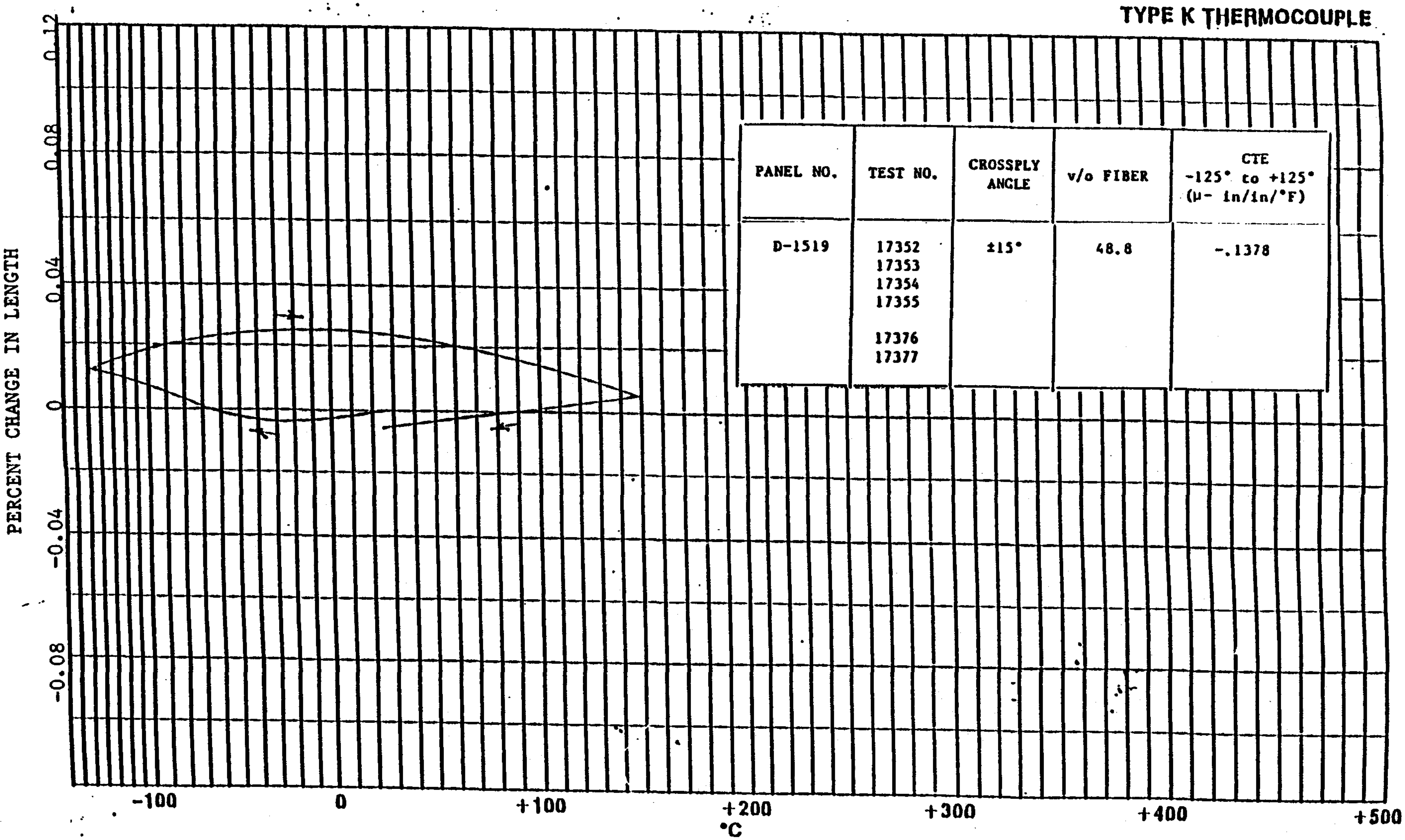
SAMPLE: D1519-L1
MODE: Cool/Heat/Cool
RUN NO.: 1
REMARKS:

SIZE: 2.014"
RATE: 3°C/min.
OPERATOR: DED

TEST NO.: HL-2549
Y-AXIS SCALE: 0.04%/inch
ATM.: Static Air
DATE: 5-22-87

SOURCE: DUA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1519	17352 17353 17354 17355 17376 17377	±15°	48.8	-.1378

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

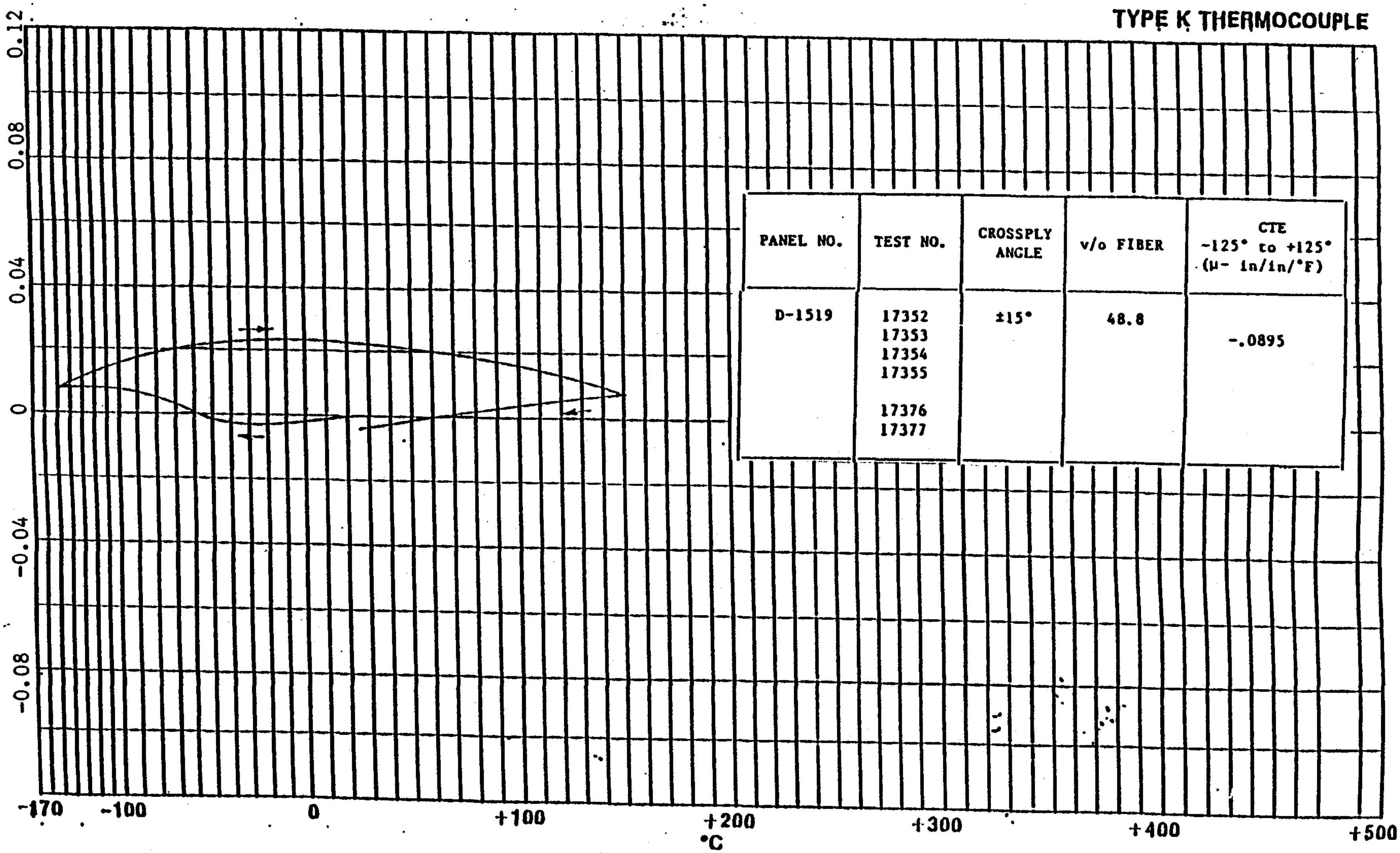
SAMPLE: D1519-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 1.994" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2949 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1519	17352 17353 17354 17355 17376 17377	±15°	48.8	-.0895

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

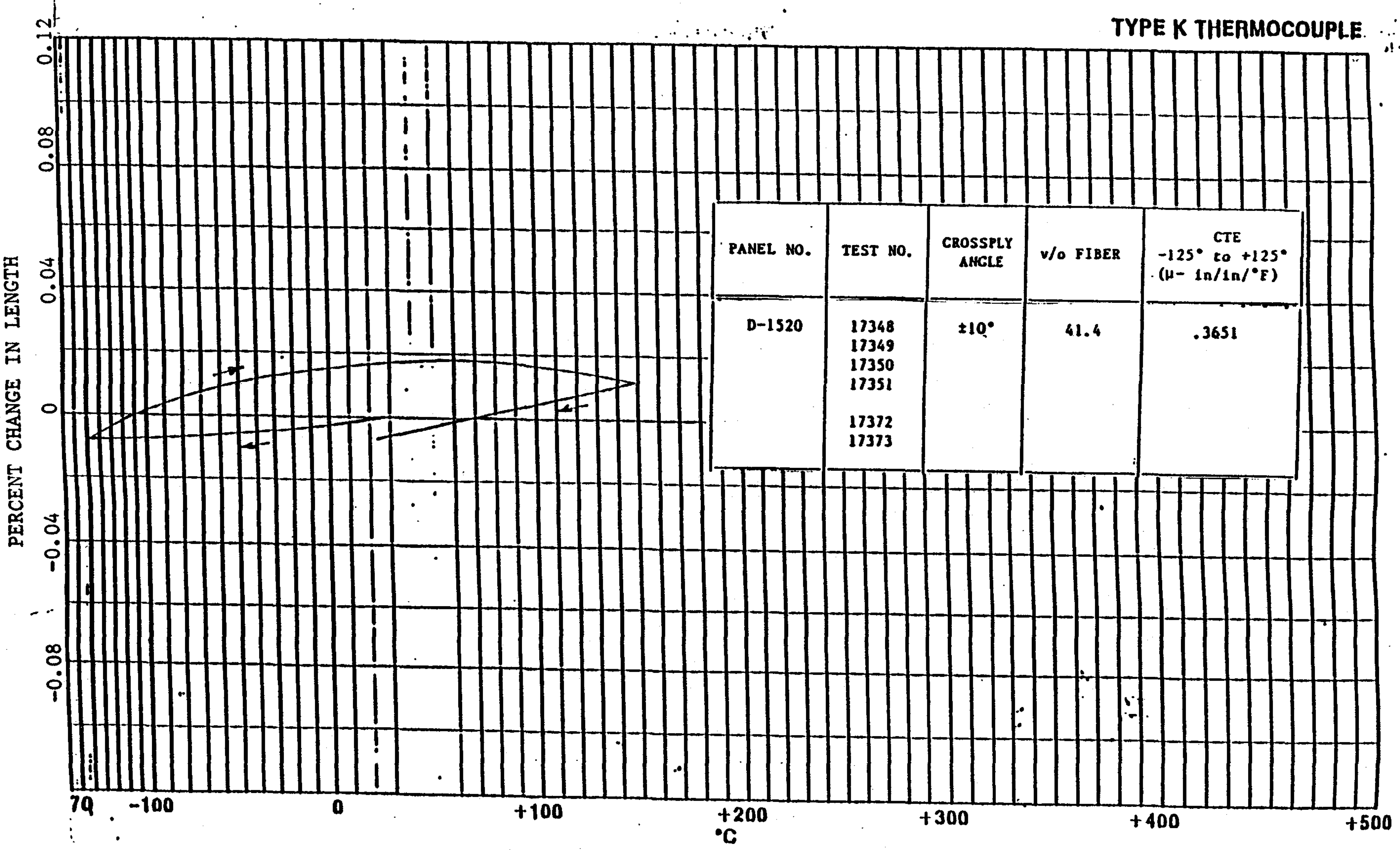
SAMPLE: D1520-L1 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.013" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1520	17348 17349 17350 17351 17372 17373	±10°	41.4	.3651

THERMAL DILATOMETRIC ANALYSIS (TDA)

HARROP INDUSTRIES, INC.

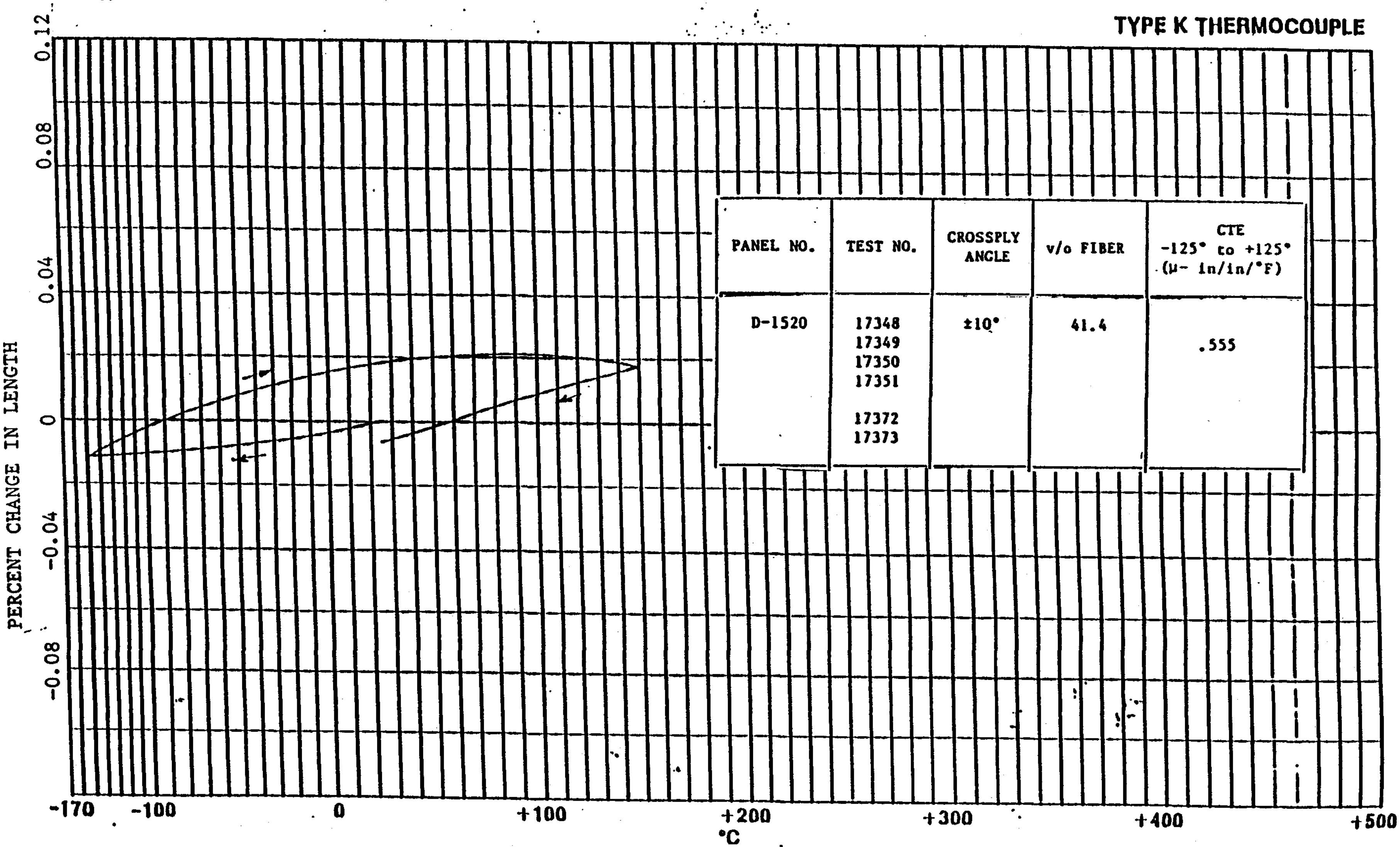
SAMPLE: D1520-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.003" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1520	17348 17349 17350 17351 17372 17373	±10°	41.4	.555

THERMAL DILATOMETRIC ANALYSIS (TDA)

HARROP INDUSTRIES, INC.

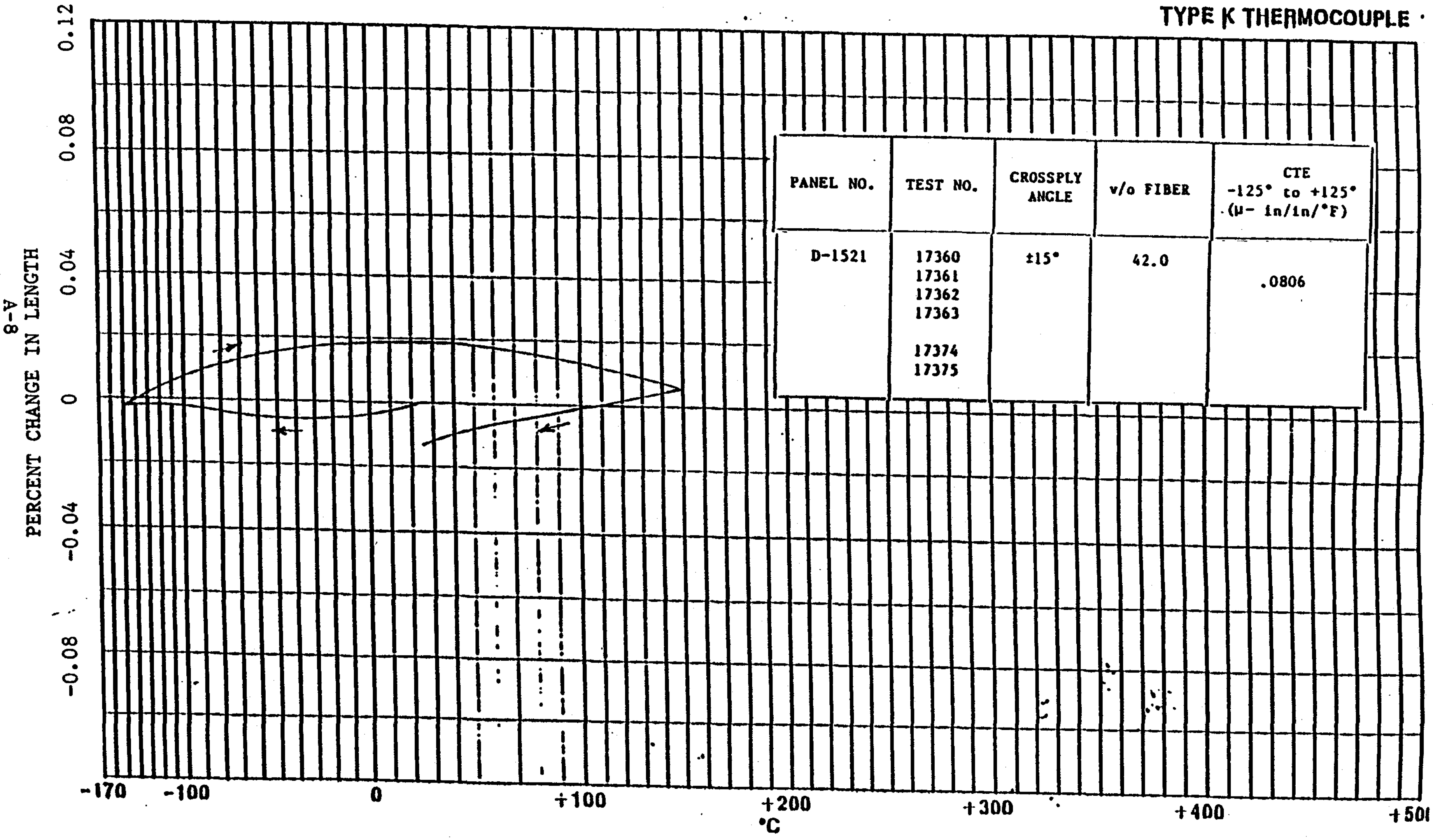
SAMPLE: D1521-L1 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.009" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1521	17360 17361 17362 17363 17374 17375	±15°	42.0	.0806

A-8

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

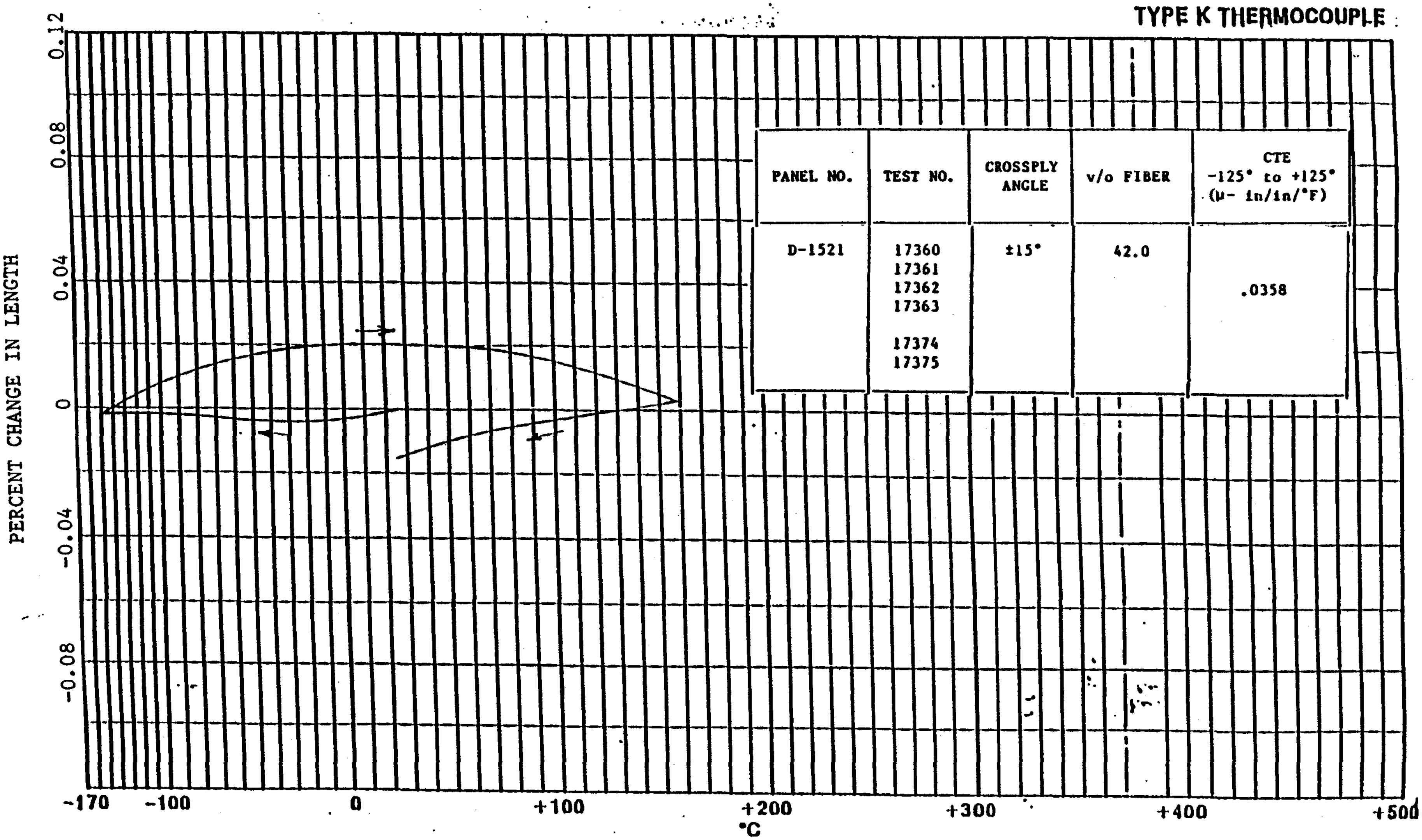
SAMPLE: D1521-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.005" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1521	17360 17361 17362 17363 17374 17375	±15°	42.0	.0358

THERMAL DILATOMETRIC ANALYSIS (TDA)

HARROP INDUSTRIES, INC.

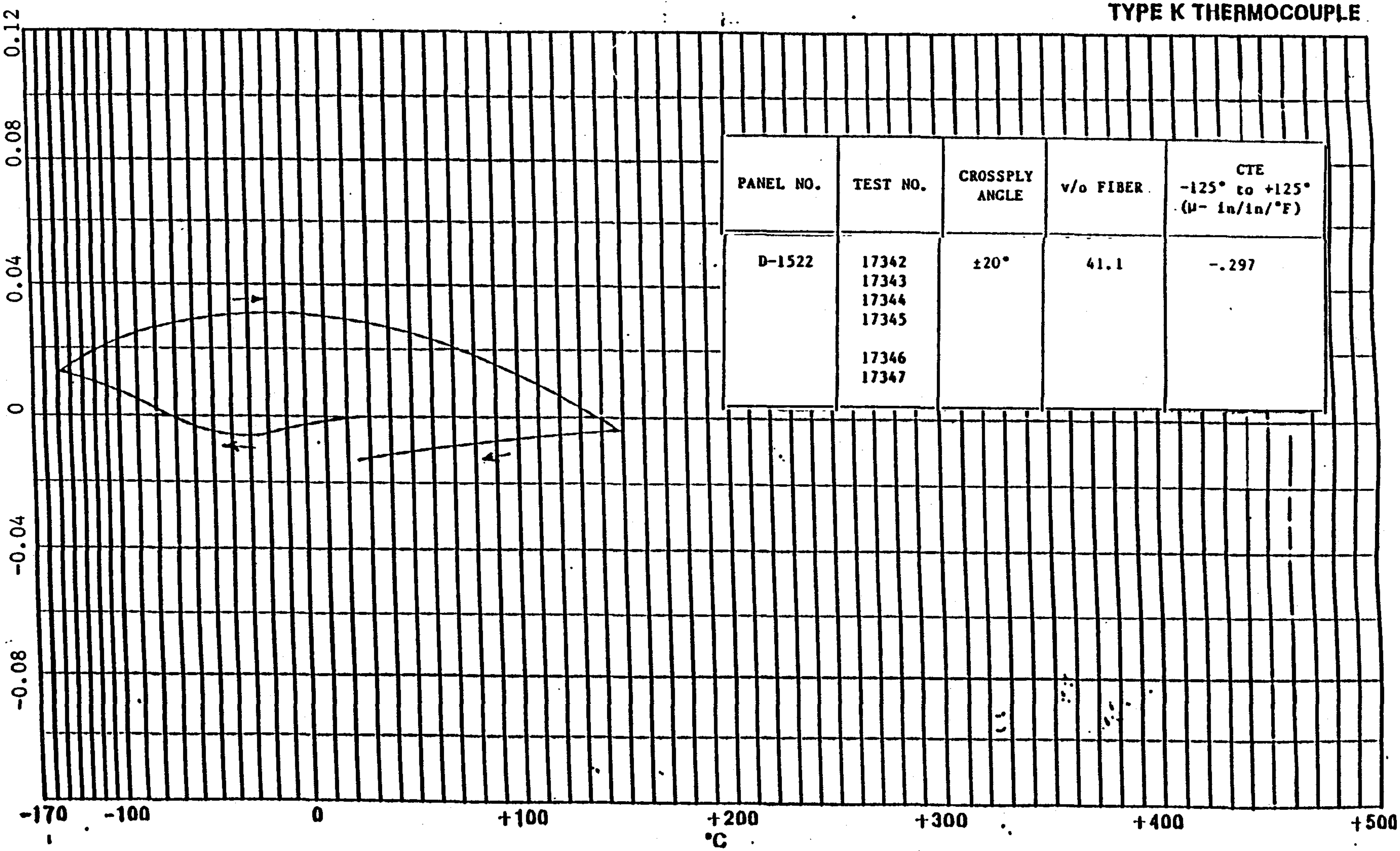
SAMPLE: D1522-L1 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.000" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1522	17342 17343 17344 17345 17346 17347	±20°	41.1	-.297

A-10

THERMAL DILATOMETRIC ANALYSIS (TDA)

HARROP INDUSTRIES, INC.

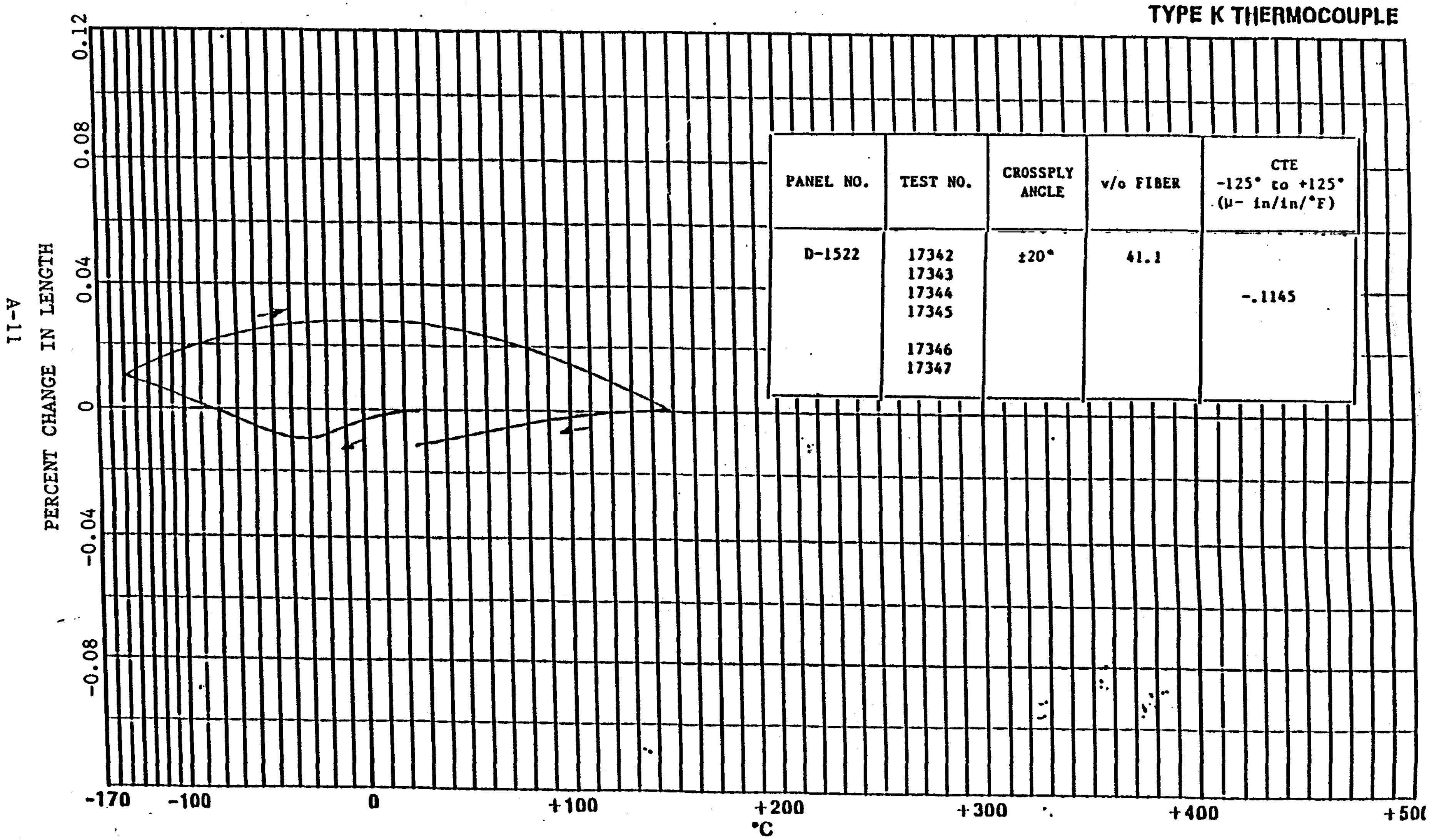
SAMPLE: D1522-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.020" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1522	17342 17343 17344 17345 17346 17347	±20°	41.1	-.1145

A-11

HARROP INDUSTRIES, INC.

THERMAL DILATOMETRIC ANALYSIS (TDA)

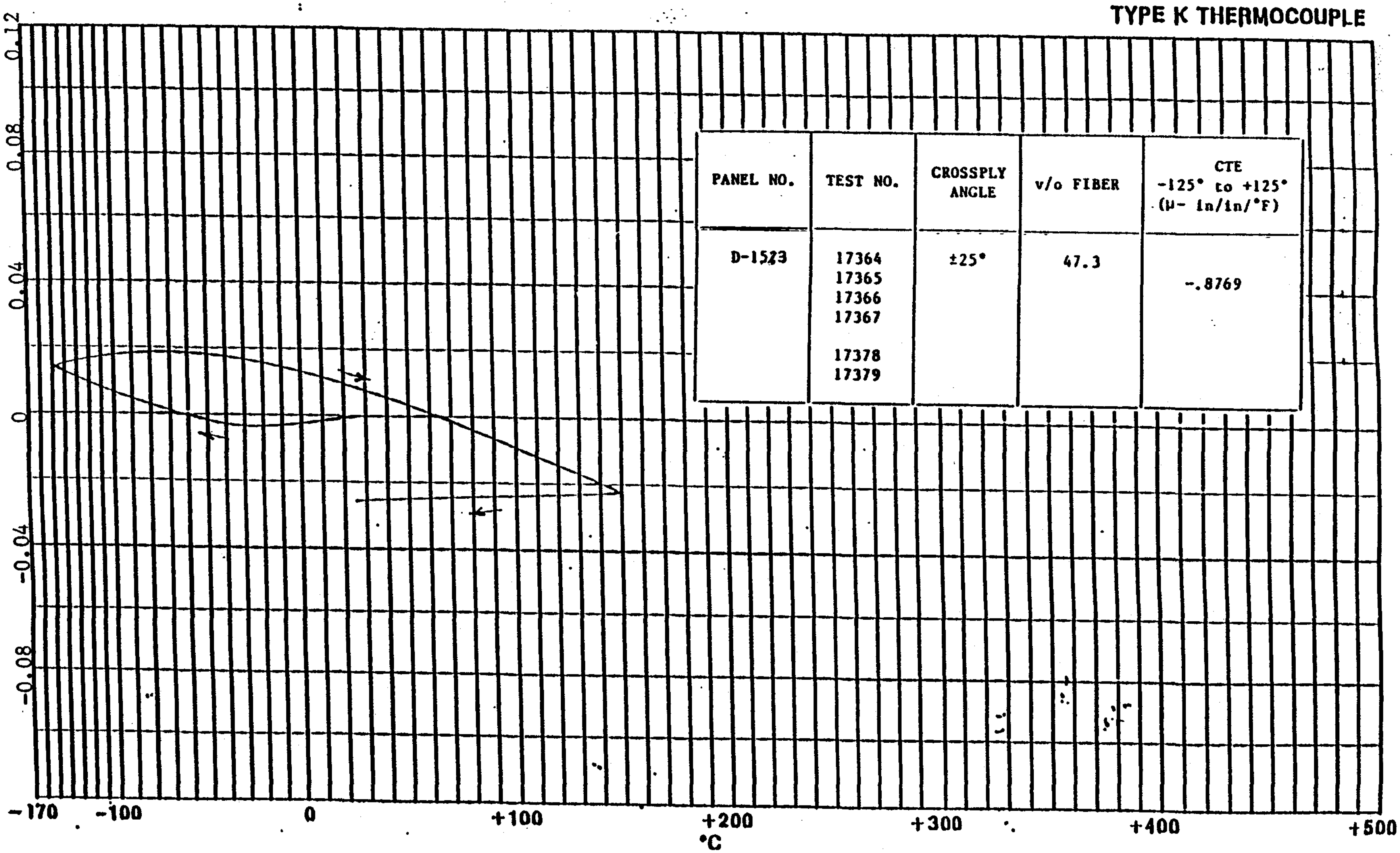
SAMPLE: D1523-L1 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.000" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1523	17364 17365 17366 17367 17378 17379	±25°	47.3	-.8769

C-2

THERMAL DILATOMETRIC ANALYSIS (TDA)

HARROP INDUSTRIES, INC.

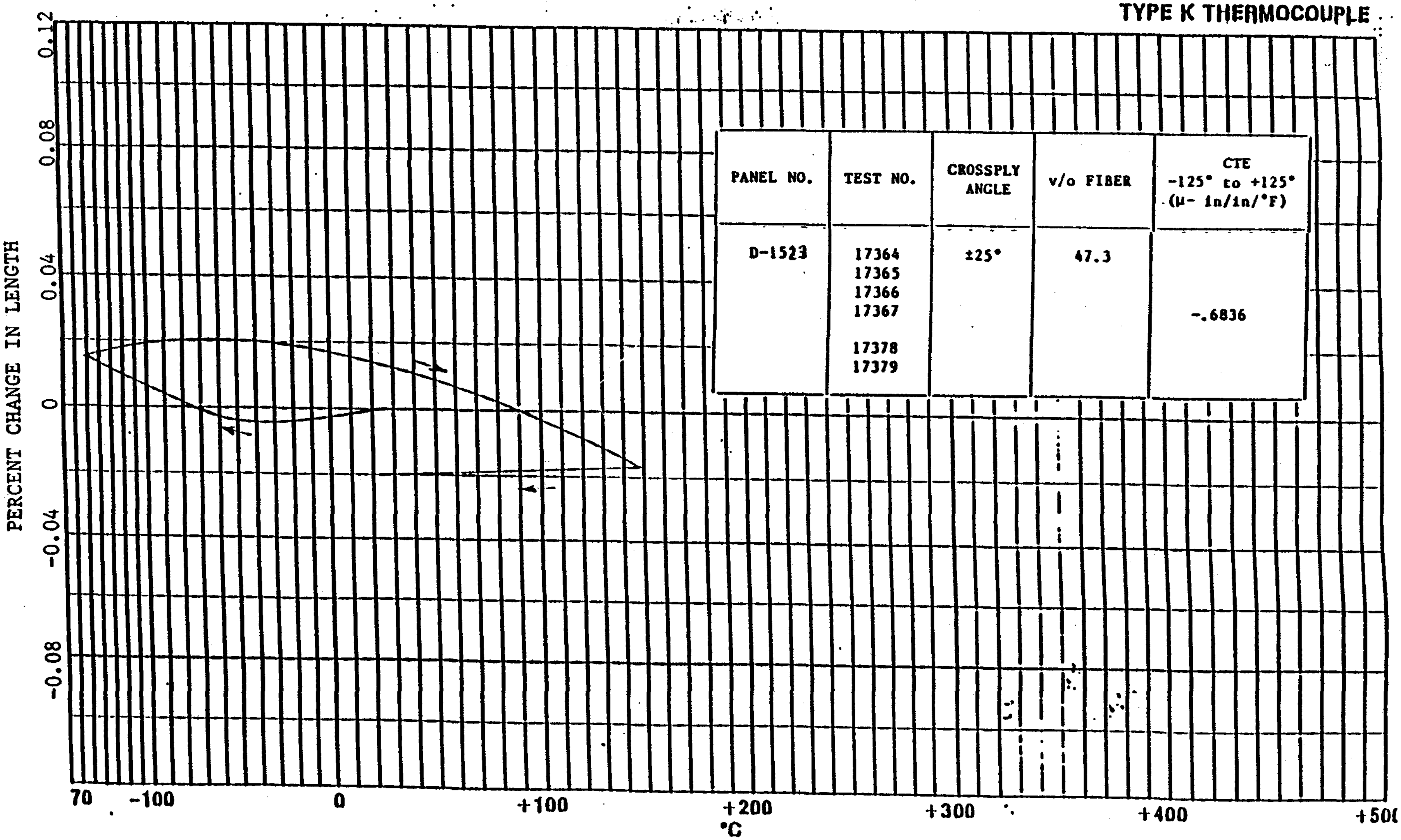
SAMPLE: D1523-L2 MODE: Cool/Heat/Cool RUN NO.: 1 REMARKS:

SIZE: 2.010" RATE: 3°C/min. OPERATOR: DED

TEST NO.: HL-2549 Y-AXIS SCALE: 0.04%/in. ATM.: Static Air DATE: 5-22-87

SOURCE: DWA COMPOSITES

TYPE K THERMOCOUPLE



PANEL NO.	TEST NO.	CROSSPLY ANGLE	v/o FIBER	CTE -125° to +125° (μ- in/in/°F)
D-1523	17364 17365 17366 17367 17378 17379	±25°	47.3	-.6836

APPENDIX B

Test Results of Space Truss Measurements

Conducted by:

Composite Optics, San Diego, California

COI-0688-5398
June 16, 1988

COMPOSITE OPTICS, INCORPORATED

METAL MATRIX TRUSS
THERMAL EXPANSION (LONGITUDINAL)
AND BENDING MEASUREMENTS:
END–TO–END

Prepared for:

DWA COMPOSITE SPECIALTIES, INC.
Chatsworth, CA

Prepared by:

Helmuth H. Dorth
H. H. Dorth

COMPOSITE OPTICS, INCORPORATED
San Diego, CA

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METAL MATRIX TRUSS

EXPANSION & BENDING TEST:

END—TO—END

1.0 SCOPE

To characterize the longitudinal thermal expansion and bending of a metal matrix truss over the temperature range -150 to 150°F.

2.0 APPROACH

The test structure was placed into an environmental chamber whose temperature could be controlled over the requisite range (-150°F to 150°F).

A standard of the same length was fabricated/fitted to the truss by which the truss's longitudinal expansion/ bending would be judged. Since the standard was made of low expansion material and kept at constant temperature (165°F), no movements should be attributed to it. In this case, all measurements became absolute and are inherent to the truss structure's characteristics.

The relative movements between the truss and standard are measured by an optical dilatometer technique which depends on laser illumination of its optics.

3.0 TEST SCENARIO

After receipt of the customer-furnished truss, a reference standard was trimmed to fit the test specimen's length.

This reference standard (Figure 1) was fabricated from low expansion ($.20 \times 10^{-6}$ in/in/°F) graphite/epoxy which was wrapped with heater tape. The heaters were divided into three thermally controlled zones, each with its own instrumentation and thermal controller. The standard was then thermally insulated and placed inside the truss structure at its centroid (Figure 2).

The bottoms of the standard and test specimen rested on the same datum plane and were isolated from it by sitting on three glass blocks. Each leg of the standard (a tripod) was supported in close proximity of a truss longeron so that both would experience the same external influence, if any. The truss structure rested on the glass blocks by contact with the diagonal portion of the end fittings.

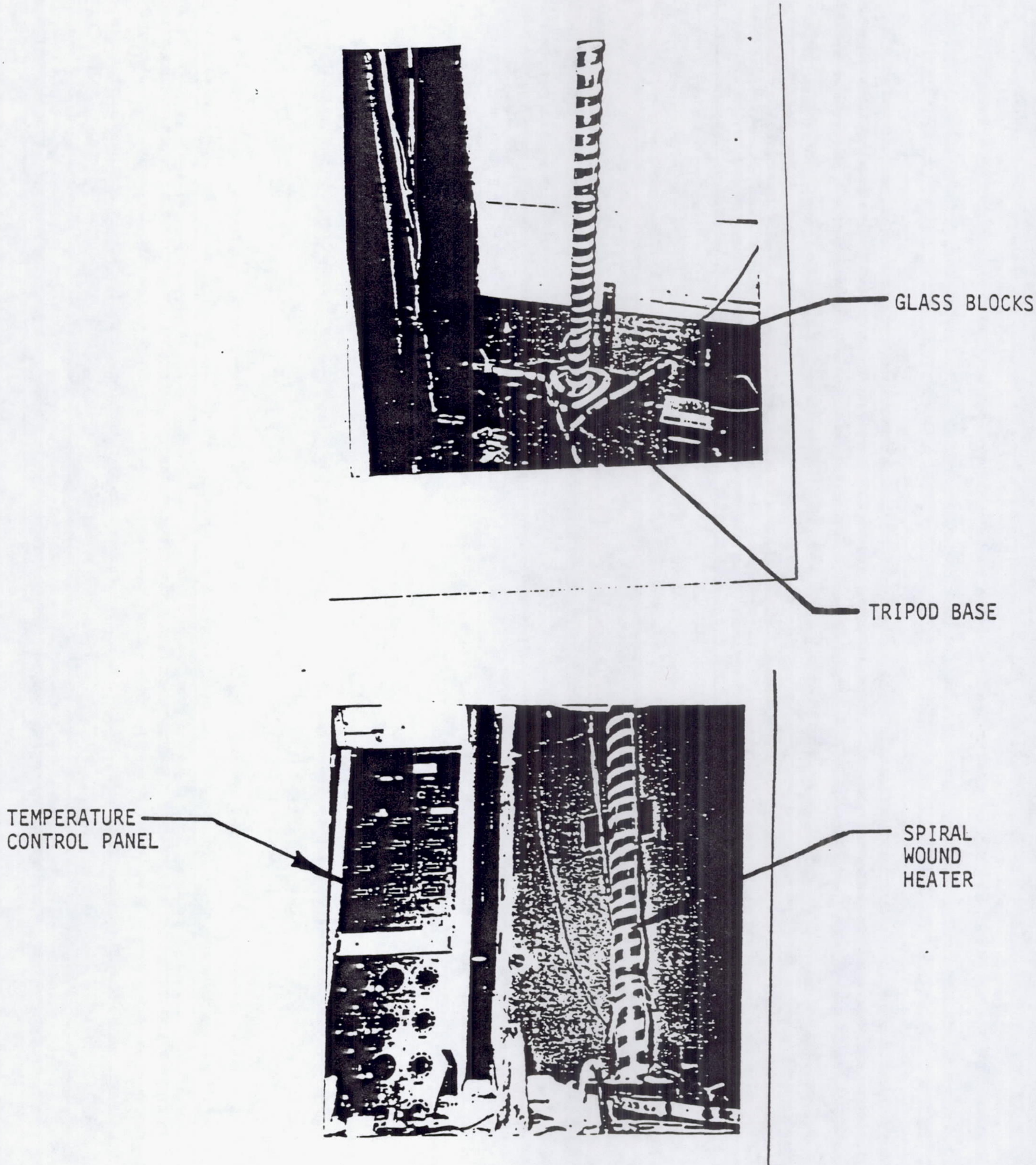


FIGURE 1. REFERENCE STANDARD

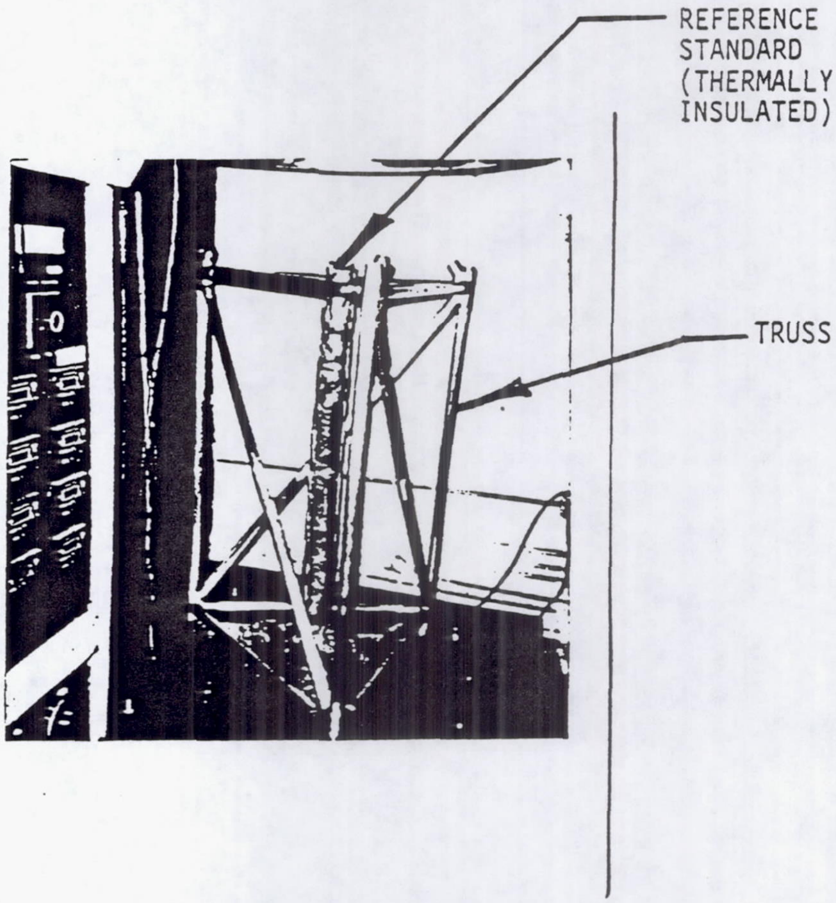


FIGURE 2. REFERENCE STANDARD/TRUSS STRUCTURE

3.0 TEST SCENARIO (continued)

At the upper end, a reference datum was fitted (Figure 3) that extended from the truss's centroid to the longitudinal portions of each end fitting. The reference standard protruded through this reference datum plane. It was at this location that the relative movements between test specimen and standard would be ascertained.

Each longeron of the truss was instrumented with thermocouples along its length so that thermal gradients could be detected and minimized by activating the appropriate heating zones of the environmental shroud.

After completing all instrumentation and power connections, the environmental shroud was lowered and sealed at its bottom.

The shroud has four separate heating zones along its longitudinal axis, each independently controlled. As temperature gradients are sensed, the heating controllers activate the appropriate heaters along the elevation in order to maintain a constant environment. At the upper end of the shroud, a plenum introduces cold nitrogen gas when required. It is this interplay between heating and nitrogen gas introduction that required temperature during the test sequence are reached and maintained. To avoid nitrogen gas stratification, a forced circulation system below the lower datum plane maintains gas movement. The test was conducted under the guidance of "Coefficient of Thermal Expansion (Longitudinal), Bending and Twist Measurements of Large Structures" (COS-88-148). The optical principles that govern measurement techniques using the optical dilatometer are delineated in "Thermal Expansion Measurements," COS-86-037CR.

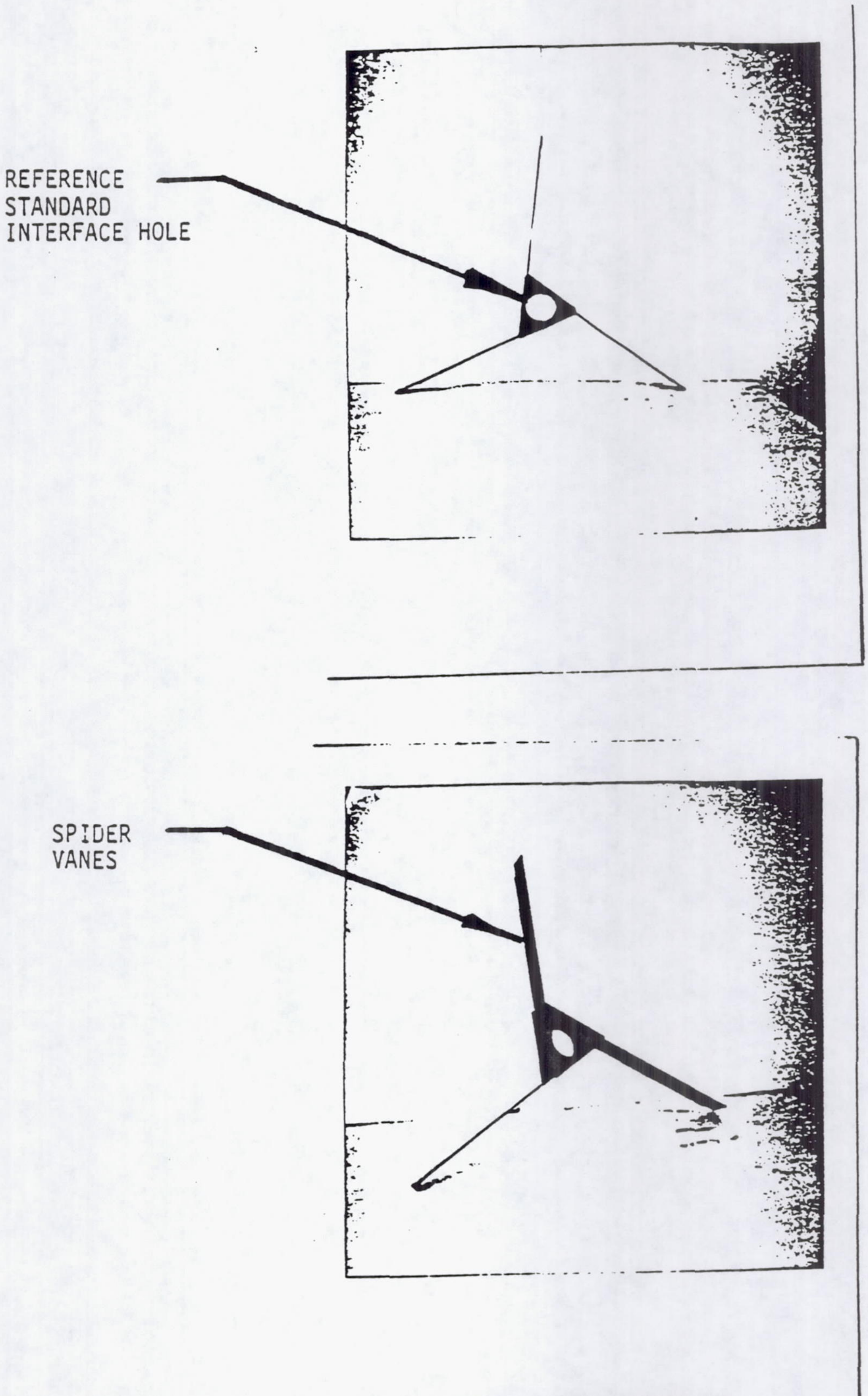


FIGURE 3. UPPER DATUM REFERENCE

4.0 TEST PLAN & PROCEDURES

COMPOSITE OPTICS, INCORPORATED 9617 Distribution Avenue, San Diego, CA 92121	SPECIFICATION NO. COS-88-148	REV.
	DATE June 16, 1988	
	CONTRACT NO.	

COEFFICIENT OF THERMAL EXPANSION (LONGITUDINAL), BENDING AND TWIST MEASUREMENTS OF LARGE STRUCTURES

TEST SPECIFICATION/PROCEDURES

PREPARED BY Helmuth H Dorth
H. H. Dorth, Dir., Mat'ls Lab.

APPROVED BY G.E. Pynchon 6/16/88
G.E. Pynchon, Vice President

APPROVED BY ____________

APPROVED BY ____________

SPECIFICATION CHANGES

INCORP.	CHECK	APPROVED	DATE	REV.	REV. PACKAGE	RELEASE

COEFFICIENT OF THERMAL EXPANSION (LONGITUDINAL), BENDING AND TWIST MEASUREMENTS OF LARGE STRUCTURES

TEST SPECIFICATION/ PROCEDURES

1.0 SCOPE

This specification details the plan and procedures for the measurement of the coefficient of thermal expansion (CTE), bending and twist in large structures.

2.0 APPLICABLE DOCUMENTS

The following documents in their current issue form a part of this specification to the extend applicable herein:

<u>COI Documents</u>

COS-84-037CR Thermal Expansion Measurements

3.0 TEST OBJECTIVES

The objective of this specification is the delineation of a method to measure the changes in length (CTE), bending and twist of various large structures.

4.0 TEST METHOD

Measurements of thermal strain in three axes are made by comparing the motion of the test specimen to a reference standard employing the laser/optical lever principal's described in COS-84-037CR (Appendix A).

The test structure and reference standard are mounted in a thermal chamber and instrumented with optics/thermocouples and dried for 24 hours at 250°F in a Nitrogen atmosphere (unless otherwise specified). Subsequent to dry-out the structure is exposed to the CTE measurement profile and measured for axial strain, bending and twist.

5.0 TEST FACILITY

5.1 Test Chamber

The test chamber is a cylinder whose diameter and length are 48" x 70" respectively. The chamber is sealed at the top and has a glass view port at the center. The bottom is open and seals against a flat plate datum. The external surfaces of the chamber are insulated. Forced air circulation fans with associated ducting are underneath the bottom datum plate.

The chamber is fitted with a coiled LN_2 cooling plenum which runs around the top of its interior to provide cooling. Interior to this coil an aluminum shroud fitted with heaters (divided into zones) provide the chamber the capability to reach and stabilize at any desired temperature plateau.

Associated with the test chamber are a bank of thermal controllers and variable transformers for accurate thermal control (along its length)to minimize temperature gradients. In addition appropriate temperature readouts, and strip chart recorders are used to monitor and collect the appropriate data.

The general chamber configuration is shown in Figure 1.

5.2 Reference Standard and Optics

The reference standard is of a length equal to the test specimen. The standard is wrapped with heating tapes, instrumented with thermocouples, insulated and maintained at a constant temperature greater than the specimens upper limit throughout the test sequence.

Both the specimen and reference standard are fitted with fixed and movable ULE glass optics arranged such that a low-power laser light source can monitor their relative motions during the test sequence. The general laser/optical configuration is shown in Figure 2.

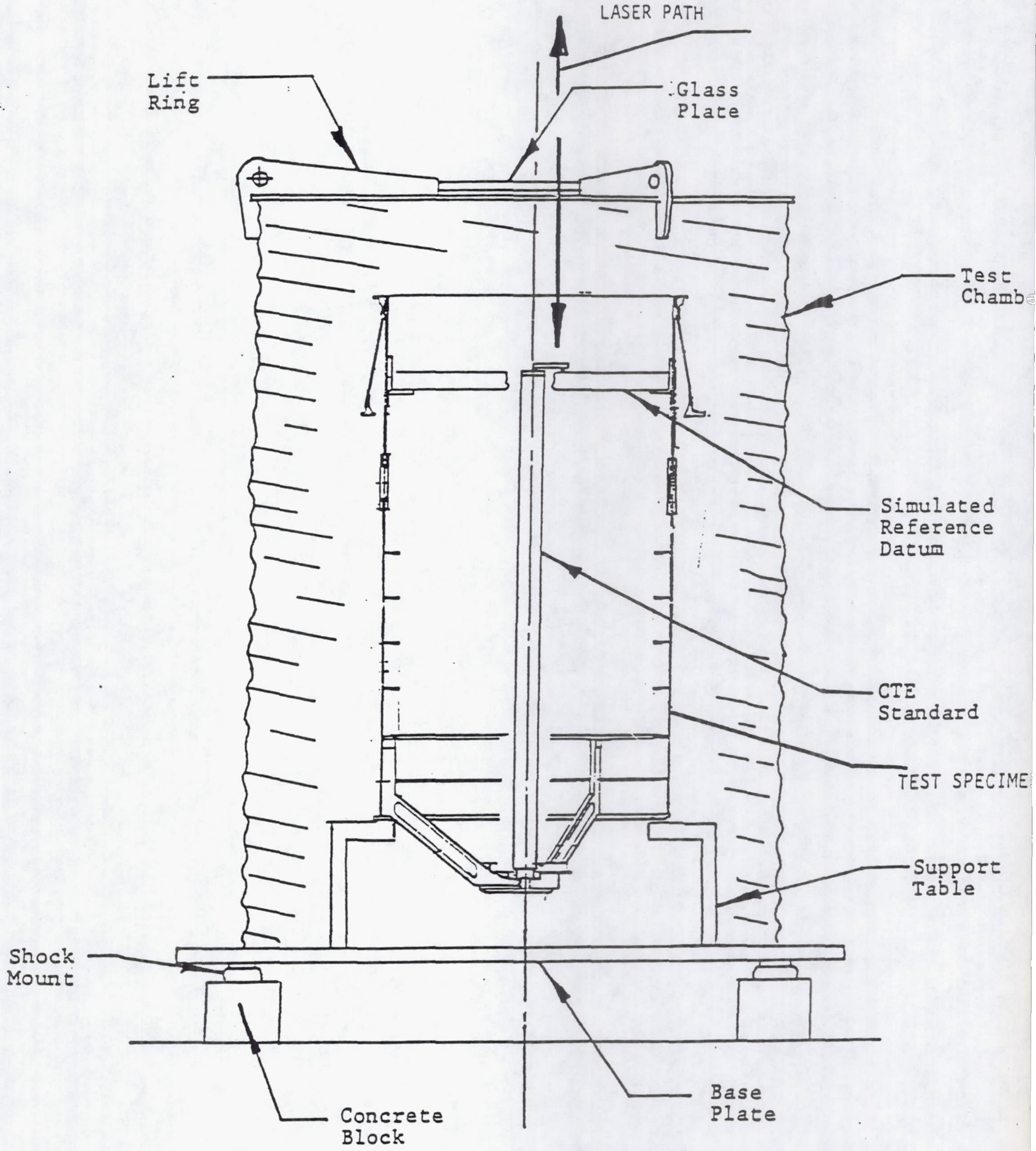


FIGURE 1. TYPICAL TEST CHAMBER SET-UP

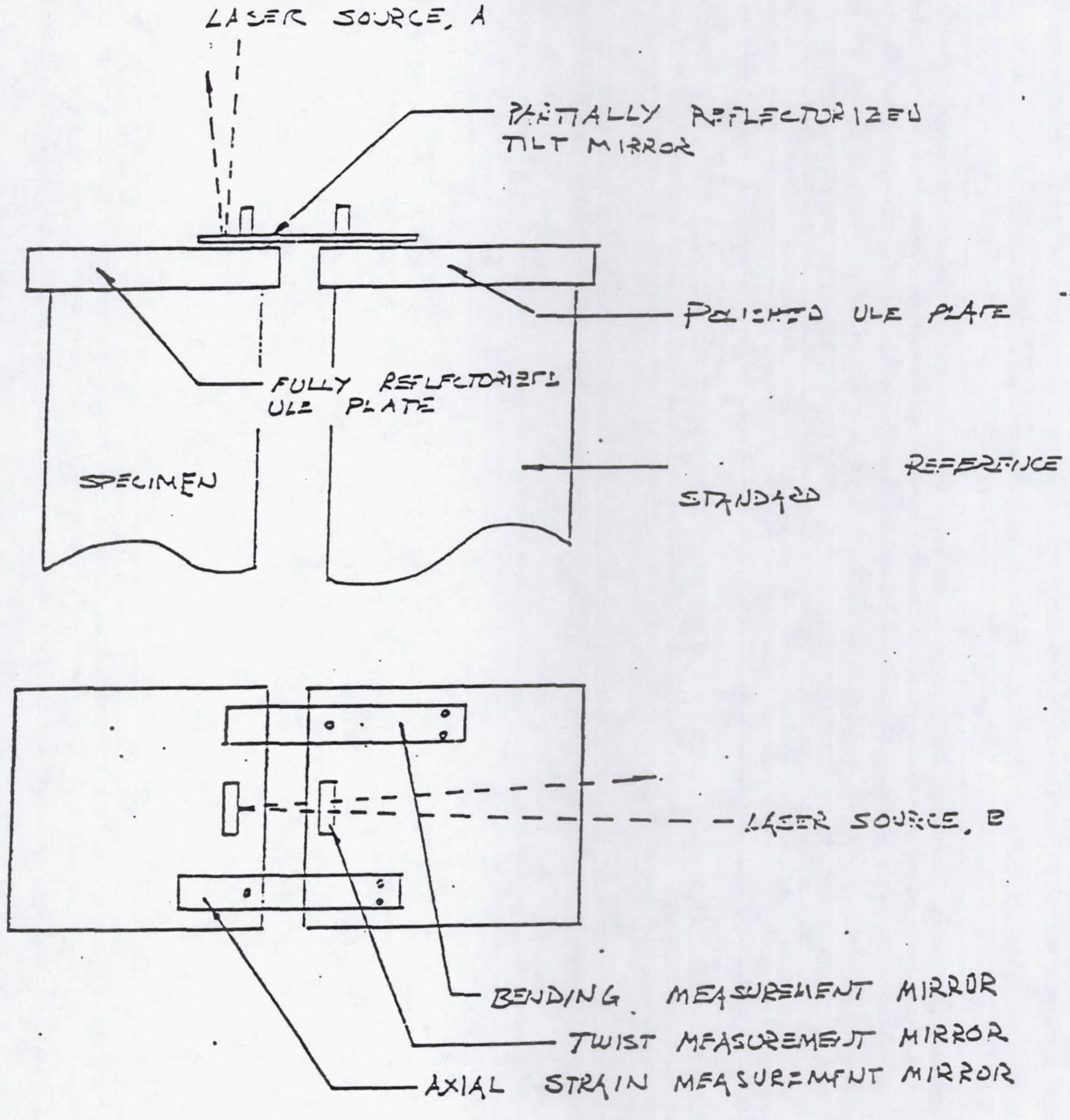


FIGURE 2. GENERAL CONFIGURATION: MEASUREMENT OPTICS

5.3 Laser Source & Recording Screen

Low-power helium-neon lasers are mounted adjacent to the test chamber such that their beams pass through the top and side windows, through the movable optics and reflect into a recording screen also adjacent to the test chamber. The general configuration is shown in Figure 3.

5.4 Temperature Control

All temperatures are monitored using copper-constant Type T thermocouples applied to the test specimen and reference standard. Heat application to the specimen and standard is divided into four (4) equal zones each for maximum control and minimum thermal gradients. Each zone is monitored through automatic proportioning controllers.

The temperature of the specimen is manipulated and stabilized through the alternate and/or simultaneous application of heat and LN_2 to achieve various thermal equilibria as specified.

6.0 TEST PROCEDURE

6.1 Specimen Conditioning

6.1.1 Dry-Out

The test specimen shall be dried at a temperature of $250^{o}+10^{o}F$ for 24 hours minimum (unless dictated otherwise). A minimum of three (3) thermocouples shall be affixed to the specimen, spaced evenly along its length, and used to monitor the temperature profile (actual number depends on the size and complexity of the test structure.

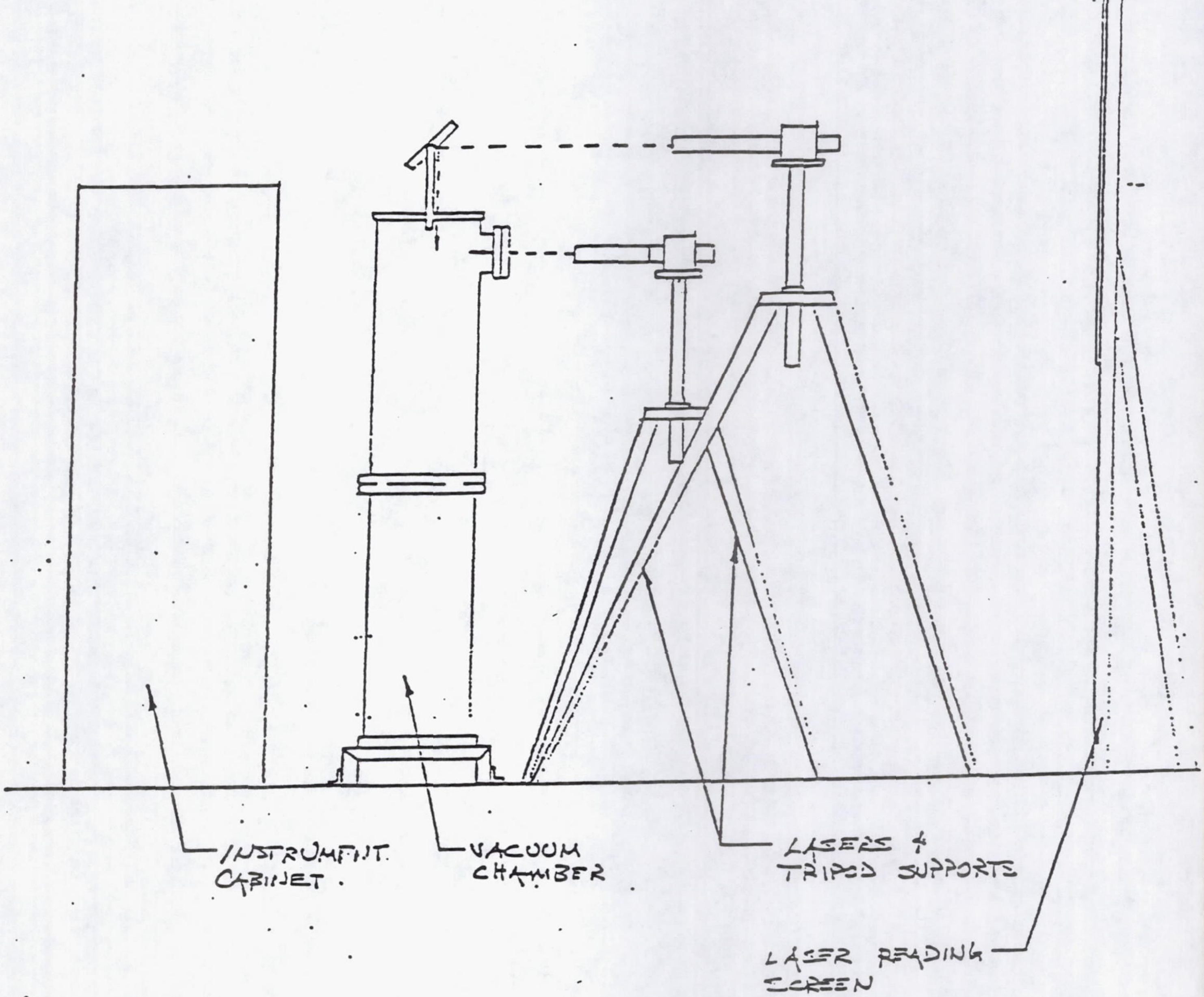


FIGURE 3. GENERAL CONFIGURATION: DIMENSIONAL MEASUREMENTS

6.2 Test Chamber Set-Up

a) Level specimen/standard base and mount specimen and standard in position.

b) Fit standard with heating tapes, thermocouples and insulation. Install wire harness supports.

c) Lower chambers environmental shroud and seal at bottom. Purge with dry Nitrogen gas.

d) Fit measurement optics to specimen and standard. Raise standard temperature to appropriate temperature (at least 15^{o} above test upper limit).

e) Make final adjustments to measurement optics and align lasers. Seal chambers upper access window.

6.3 Measurement Sequence

a) Establish zero strain data reference in all test axes under ambient conditions.

b) Take data in all test axes over the specified temperature profile.

6.4 Data Requirements

6.4.1 General

a) Date/Time

b) Technician comments/signature

6.4.2 Dimensional Measurements

For each data or equilibrium point:

a) Date/Time

b) Temperatures from all thermocouples.

c) Pattern points from laser reading screen for each parameter.

d) Tabular and graphic data summaries.

e) Technician comments/signature.

7.0 TEST REPORTS

A complete test report should include:

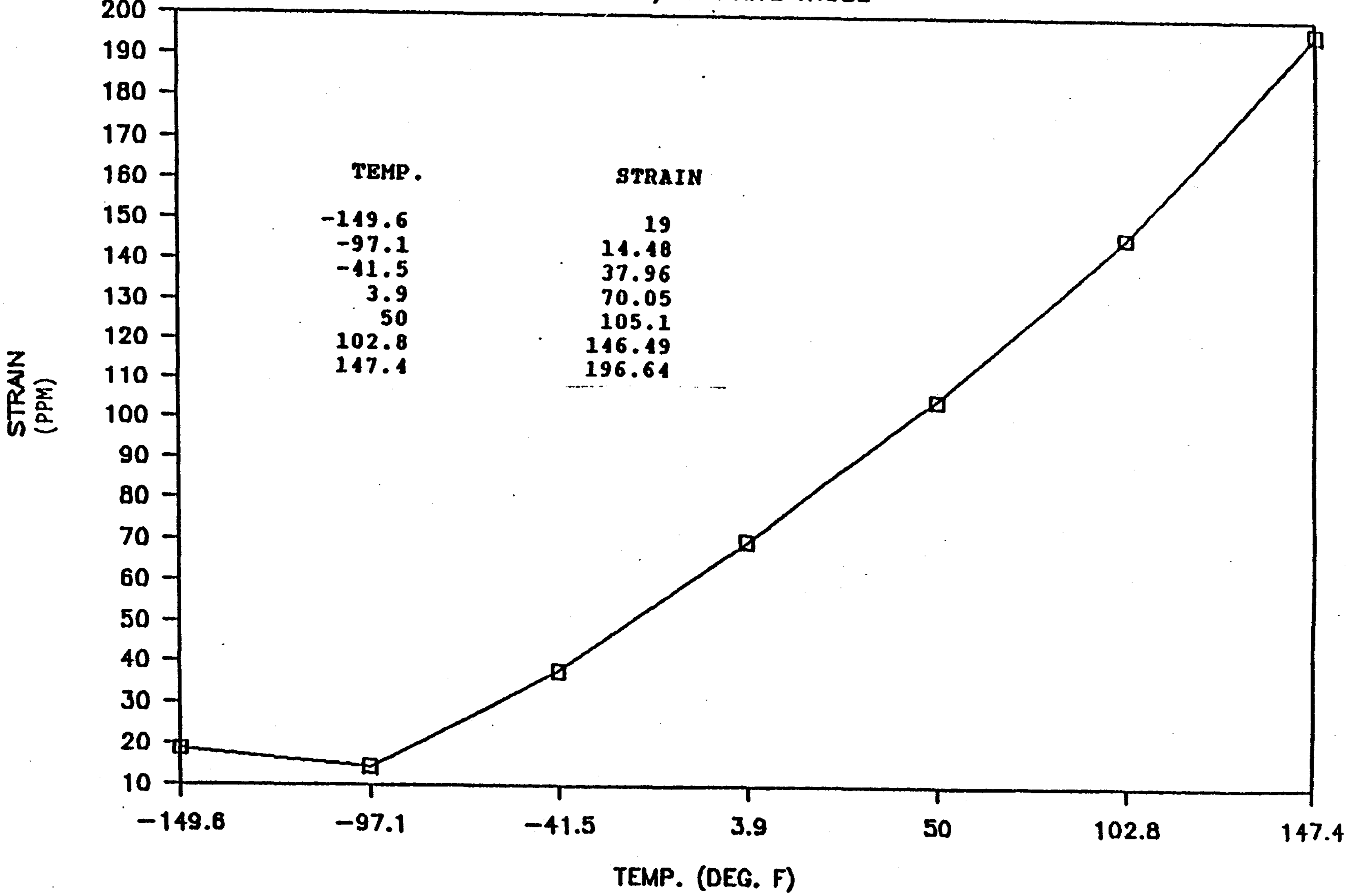
- Raw data sheets
- Graphic and tabular presentation of reduced data
- Data summaries and analysis
- Photographs of test set-ups and instrumentation
- Time/temperature records
- Reports of anomalous conditions

5.0 PHYSICAL PROPERTIES TEST RESULTS

COEFFICIENT OF THERMAL EXPANSION (CTE)
(LONGITUDINAL)

DWA

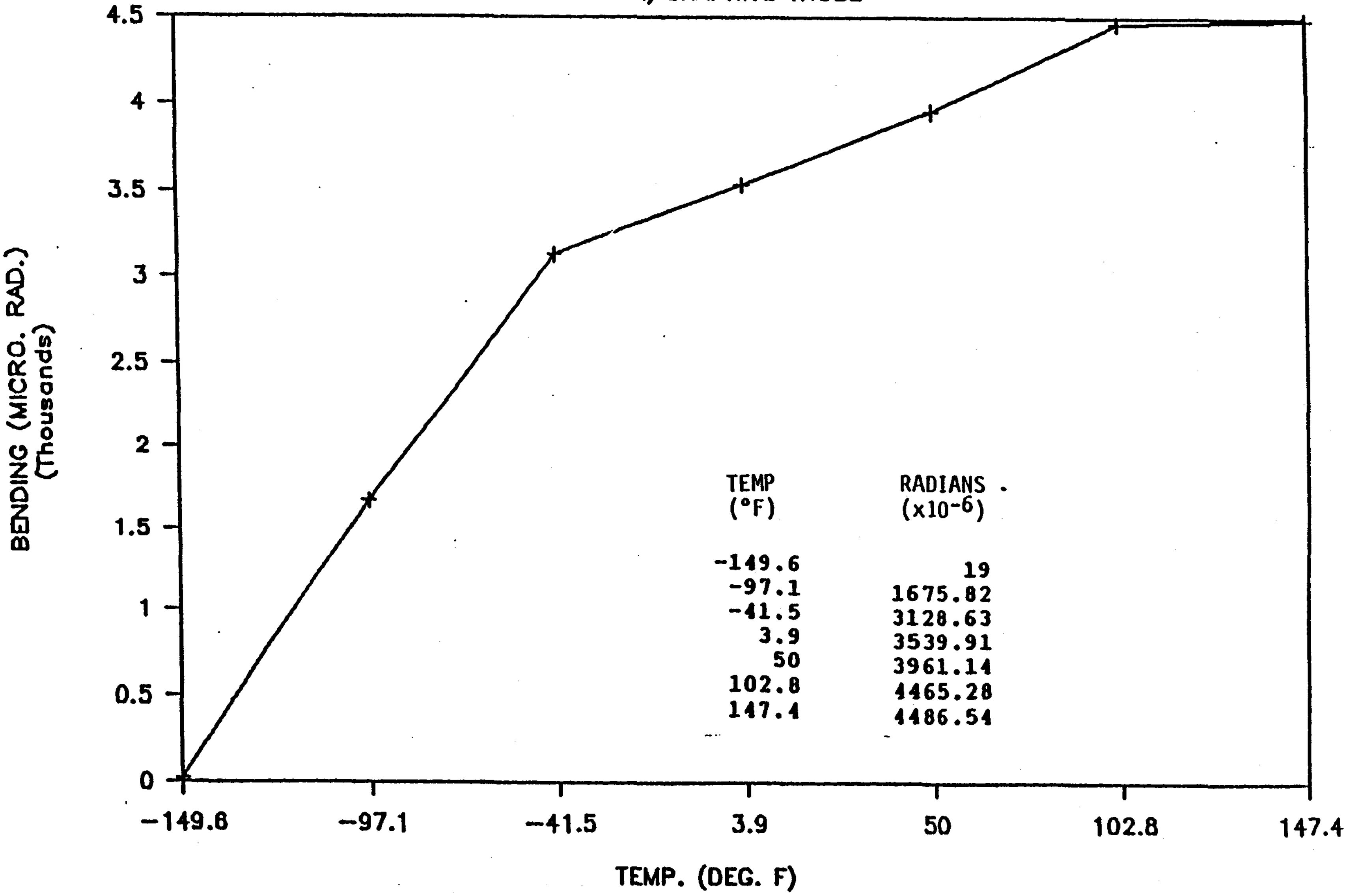
ALUMINUM/GRAPHITE TRUSS



BENDING

DWA

ALUMINUM/GRAPHITE TRUSS



APPENDIX C

Properties of the Metal Matrix Composite Material Used to Fabricate the Component Parts of the Space Truss Assembly

TUBES

Tubes for the demonstration truss were fabricated from DWG, continuous graphite reinforced aluminum.

The graphite was purchased from Amoco Performance Products, Inc., Parma, Ohio, certifying that the carbon fiber was:

Grade P100 S 2k
Shipping Order No. 80044101
DWA P.O. Z0668
Lot 305-J
Mechanical Properties:
 Tensile Strength.................. 290 ksi
 Tensile Modulus................... 107 Mpsi
 Density........................... 2.16 gm/cc
 Yield Strength.................... 0.322 gm/m

The foil used to encapsulate the P100 material was standard conventional 6061 aluminum. For the fiber reinforcement crossply angle of ±12°, the measured tube physical/mechanical properties are:

PART IDENT.	MATERIAL SYSTEM	DIMENSION INS. LENGTH	OD	WALL	MEASURED v/o	CALC. * TENSILE MODULUS
GT-6025-8	P100/6061 Al	52	1.528	.028	38	46.9 msi
GT-6026-9	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6027-10	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6028-11	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6029-12	P100/6061 Al	52	1.529	.028	38	46.9 msi
GT-6068-13	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6069-14	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6070-15	P100/6061 Al	52	1.532	.028	39	47.8 msi
GT-6071-16	P100/6061 Al	52	1.532	.028	39	47.8 msi

*ROM calculating E_{Al} = 10 msi

END FITTINGS

The truss end fittings were manufactured using DWAl 20®, discontinuous ceramic particulate reinforced aluminum. The ceramic particulate was boron carbide (B_4C); the aluminum matrix was atomized 6061.

Properties of the discontinuous MMC used are as follows:

Billet Identification................. PE-2967
Material System....................... 30v/o B_4C/6061
Mechanical Properties of the extruded
 preform material:

TEST NO.	UTS ksi	YP ksi	E msi	%F %
19165	67.25	58.26	17.04	1.97
19166	58.98	52.29	16.20	1.73

The above described DWAl 20® material was extruded at RMI Co., Ashtabula, Ohio. Results of the associated chemical analysis and volume analysis are presented in Figures C-1 and C-2, respectively.

ASSEMBLY SLEEVES

To facilitate installation of the diagonal stiffeners into each of the three vertical sides of the otherwise assembled truss, the procedure involves cutting each of the three diagonals in half, inserting each tube half into opposite end fittings, then sliding the sleeve over the opening between the free ends of the tube halves and securing with adhesive bonding agent. The sleeves were manufactured using DWAl 20®, discontinuous ceramic particulate reinforced aluminum. The reinforcement was boron carbide (B_4C); the aluminum matrix was atomized 6061.

Properties of the discontinuous reinforced MMC used are as follows:

Billet Identification.................. PE-2925
Material System........................ 30v/o B_4C/6061
Mechanical Properties of the extruded
tube material:

TEST NO.	UTS ksi	YP ksi	E msi	ε_f %
19173	65.78	53.83	19.65	1.04
19174	68.88	54.53	19.72	1.58

The above described DWAl 20® material was extruded into tubes at RMI Co., Ashtabula, Ohio. Results of the associated volume analysis is presented in Figure C-3.

METALS TECHNOLOGY, INC.
8955 QUARTZ AVENUE
NORTHRIDGE, CALIFORNIA 91324
(818) 882-6414 (213) 873-7144

CERTIFIED TEST REPORT NO. 23209

January 13, 1988

CUSTOMER: DWA COMPOSITE SPECIALTIES
PURCHASE ORDER NO.: J348 Z0646
JOB NO.: SHIPPER: 348-X23
MATERIAL: 6061 + 30% B4C
SPECIFICATION:

HEAT NO.:
LOT NO.:
SERIAL NO.:
PART NO.: PE 2967

CHEMICAL ANALYSIS

	1
CU	.39
SI	.72
FE	.33
MN	.018
MG	.86
ZN	.044
CR	.013
TI	.034
OE	<.05
OET	<.15
AL	REM.

RESPECTFULLY SUBMITTED

METALS TECHNOLOGY, INC.

Figure C-1. Results of Chemical Analysis Conducted by MTI on End Fitting MMC, 30v/o B_4C/6061.

DWA VOLUME ANALYSIS REQUEST FORM

MATERIAL IDENTIFICATION: P2967 1st 1/3 JOB NO.: 348

MATERIAL DESCRIPTION: 30% B4C/6061 DATE: 8/25 87

___ CONSOLIDATED
_x_ POWDER

ANALYSIS FOR: ____ %

DATE REQUIRED: / /

0	0	0
0	0	0
0	0	0
0	0	0

RESULTS

CONTAINER I.D.: 10%

SAMPLE WEIGHT = 2.0011

FILTER WEIGHT = 0.0937

FILTER & PPT WEIGHT = 0.6837

PPT WEIGHT = 0.59 – ________ = ________

RESULTS: 30.8 % BY VOLUME

COMPLETED BY: RD DATE: 8/25 87

Figure C-2. Results of Volume Analysis Conducted by DWA on End Fitting MMC, 30v/o B_4C/6061.

DWA VOLUME ANALYSIS REQUEST FORM

MATERIAL IDENTIFICATION: ?2925 JOB NO.: 348

MATERIAL DESCRIPTION: 30% B4C/6061 DATE: 4/3/87

___ CONSOLIDATED
✓ POWDER

ANALYSIS FOR: ___ %

DATE REQUIRED: / /

RESULTS

CONTAINER I.D.: 20%

SAMPLE WEIGHT = 2.0555

FILTER WEIGHT = 0.0878g

FILTER & PPT WEIGHT = 0.6980

PPT WEIGHT = 0.6102

RESULTS: 31.0 % BY VOLUME

COMPLETED BY: RD DATE: 4/3/87

Figure C-3. Results of Volume Analysis Conducted by DWA on Assembly Sleeve MMC, 30v/o $B_4C/6061$.