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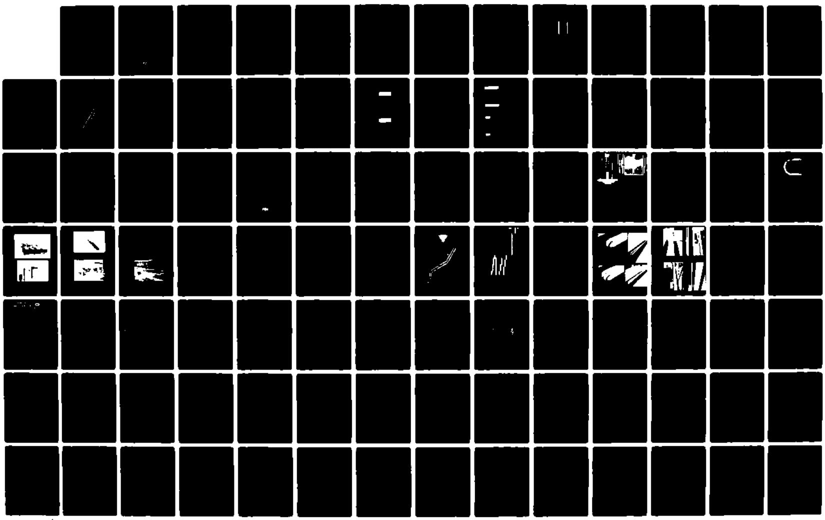

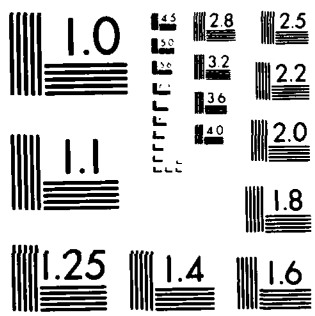

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A136267

CONTRACT NUMBER: DAAK70-81-C-0228

BRIDGE REINFORCEMENT SYSTEM

PHASE III FINAL REPORT

OCTOBER 14, 1983

PREPARED FOR:

U.S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT
COMMAND PROCUREMENT AND
PRODUCTION DIRECTORATE
FORT BELVOIR, VA 22060

SUBMITTED BY

FIBER MATERIALS, INC.
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SUMMARY

The text of this report covers Phase III of Contract Number DAAK70-81-C-0228. The development of a pilot production line and the fabrication of 20 sets of lightweight carbon epoxy tensile bridge elements were the main goals of Phase III.

The design of the bridge element was a result of analysis and testing performed on subscale and full-scale elements in Phases I and II respectively. The configuration chosen was the Racetrack Tensile Element, a filament carbon/epoxy member with metal fittings at each end and attaching hardware.

After a replacement of the original ALMAG 35 end fittings with a stainless steel collar and aluminum face plate configuration, the tensile elements passed the specifications in the static proof testing and were delivered to MERADCOM.

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1.0 INTRODUCTION

This report presents the results of a program to develop light-weight carbon/epoxy tensile elements for modular bridges and to develop and demonstrate the manufacturing process for the resultant design. The program was conducted by Fiber Materials, Inc. (FMI) under Contract Number DAAK70-81-C-0228.

The program consisted of three phases. Phase I consisted of analysis and sub-scale testing to develop a design concept to be built and tested in Phase II. The purpose of Phase II was to verify the full-scale design under both static and cyclic load conditions. Phase III consisted of the development and demonstration of the manufacturing process. The 20 sets of tensile elements produced in Phase III were to be static proof tested by FMI.

Design development and the subsequent pilot production line demonstration were completed. Several design concepts were considered in Phase I and two different concepts were evaluated in Phase II. The manufacturing demonstration and material and labor cost estimates were based on a racetrack configuration that was selected based on manufacturing considerations.

2.0 BACKGROUND

The purpose of this program was to develop a light-weight and economical composite tensile element to replace the metal elements presently being used. Continuous filament winding of the element was desired in order to achieve a low cost and reliable design. Specific goals of the program were simplicity of the tensile element end connection for both end connection fabrication and hand assembly of the reinforcing system. Emphasis was also to be placed on the overall reduction of weight and the number of components.

The performance characteristics required for the tensile elements sets were as follows:

- Tensile Load of 230,000 pounds, 10,000 cycles
- Stiffness of EA = 70,000,000 pounds
- 20 year life span in harsh environment (fresh and salt water, high humidity, sand, mud, ice, temperatures of from -60°F to +160°F)

The production techniques were to be demonstrated by constructing twenty sets of elements and estimating the costs to produce 200, 1000, and 5000 element sets. All twenty sets were to be proof tested to 250,000 pounds to verify the production techniques.

3.0 DESIGN DEVELOPMENT (Phases I & II)

The results of Phases I and II were reported previously and are included in this report as Appendix A. These two phases can best be summarized as consisting of the following primary efforts:

- Selection of the reinforcing fibers
- Selection of the overall configurations
- Design of the end fittings

Fiber Selection The primary fibers that were evaluated include HS carbon (T300), HM carbon (VSB), and Kevlar® 49. Subscale tests were made both separately and in combinations. Based on these tests, HS carbon was selected as offering the best combination of strength, stiffness and production consistency.

Configuration Selection Two basic configurations were evaluated both in Phase I and Phase II. The first concept, the "fiberlink", consisted of one element per set. This design consisted of a continuously wound link on four legs, twisted such that the end fittings were rotated 90°. The advantage of this concept was that it only required one element per set; however, the disadvantages were as follows:

- o very difficult to manufacture
- o expensive tooling
- o complex custom winding equipment
- o difficult to protect from in-service abuse

One element of this type was built full-size and successfully proof tested to 250,000 pounds.

The second concept, the "racetrack", consisted of two identical elements per set. Each element has two straight legs without twist and resembles a racetrack or rubber band in basic shape as shown in Figure 1. Two full-scale elements of this type were made and tested for 10,000 cycles at 230,000 pounds and proof tested at 250,000 pounds. Failure tests conducted on one element after the 27,000 cycle test resulted in a breaking strength of 230,000 pounds or double the design condition. Due to the production and assembly simplicity, this design concept was selected for Phase III of the program.

End Fittings Design Two end fittings were developed in Phase II. The first, which was used in elements tested, was made from 6061-T6 aluminum and was based on a 3½-inch pin diameter. The second design was based

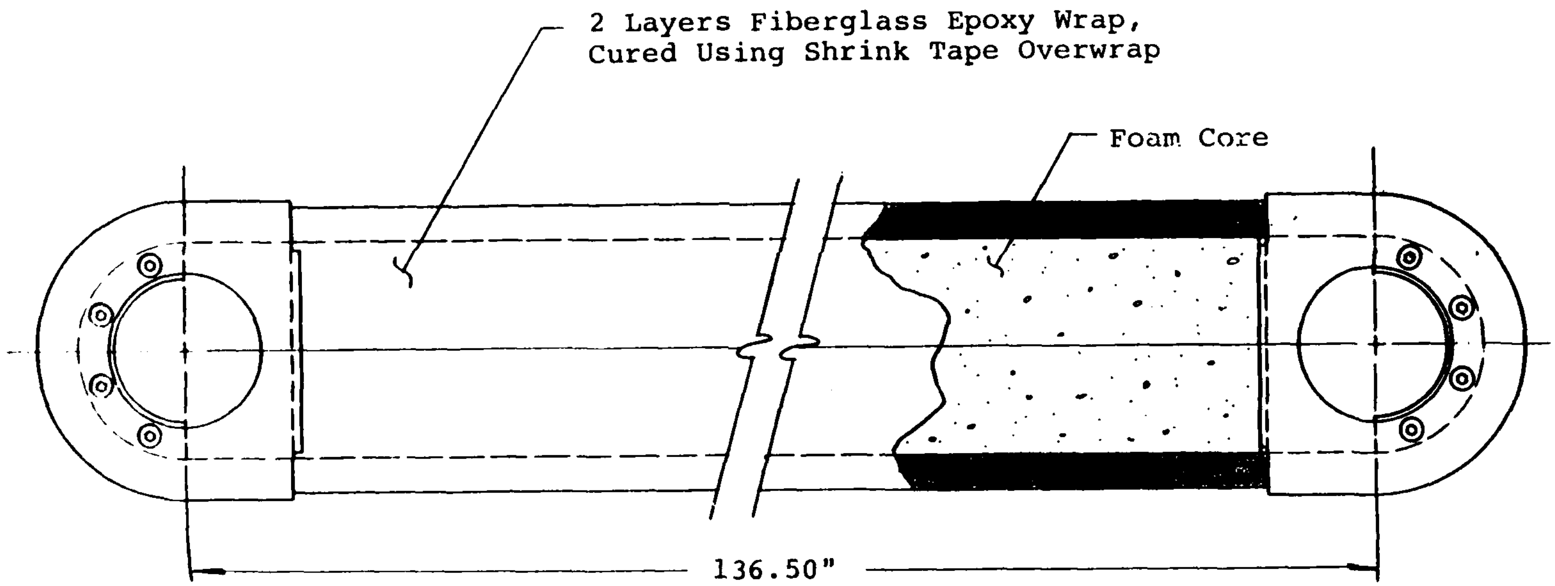

FIGURE 1: Racetrack Tensile Element With Steel/Al End Fittings

on ALMAG 35 and was sized for a 2½-inch pin diameter. The second concept was selected to reduce the weight of the pins and the associated attachment hardware. Experience gained in Phase III showed the concept to be deficient in several aspects and the third concept was developed in Phase III. This final design is discussed in Section 4.

4.0 PRODUCTION DEMONSTRATION (Phase III)

The basic objective of this phase of the program was to develop a pilot production line and demonstrate that the tensile elements could be produced economically. A production run of twenty sets of elements was made. These elements were subsequently proof tested at 250,000 pounds for three cycles with the load held for ten minutes each time.

A continuous filament winding process was selected per the contract statement of work. The method selected is based on rotating the mold on a horizontal axis and using the rotation of the mold to draw the fibers through an impregnator. This process is relatively simple and has the advantage that it can be expanded by adding more stations as the most expensive component in the system is the mold. Production rates can be increased by simply increasing the number of work stations rather than investing in expensive winding machinery. Although the system is simple, expensive machinery would not result in any significant reduction in production time as the controlling factor is the speed that material can be drawn through the impregnator. The concept is illustrated in Figure 2.

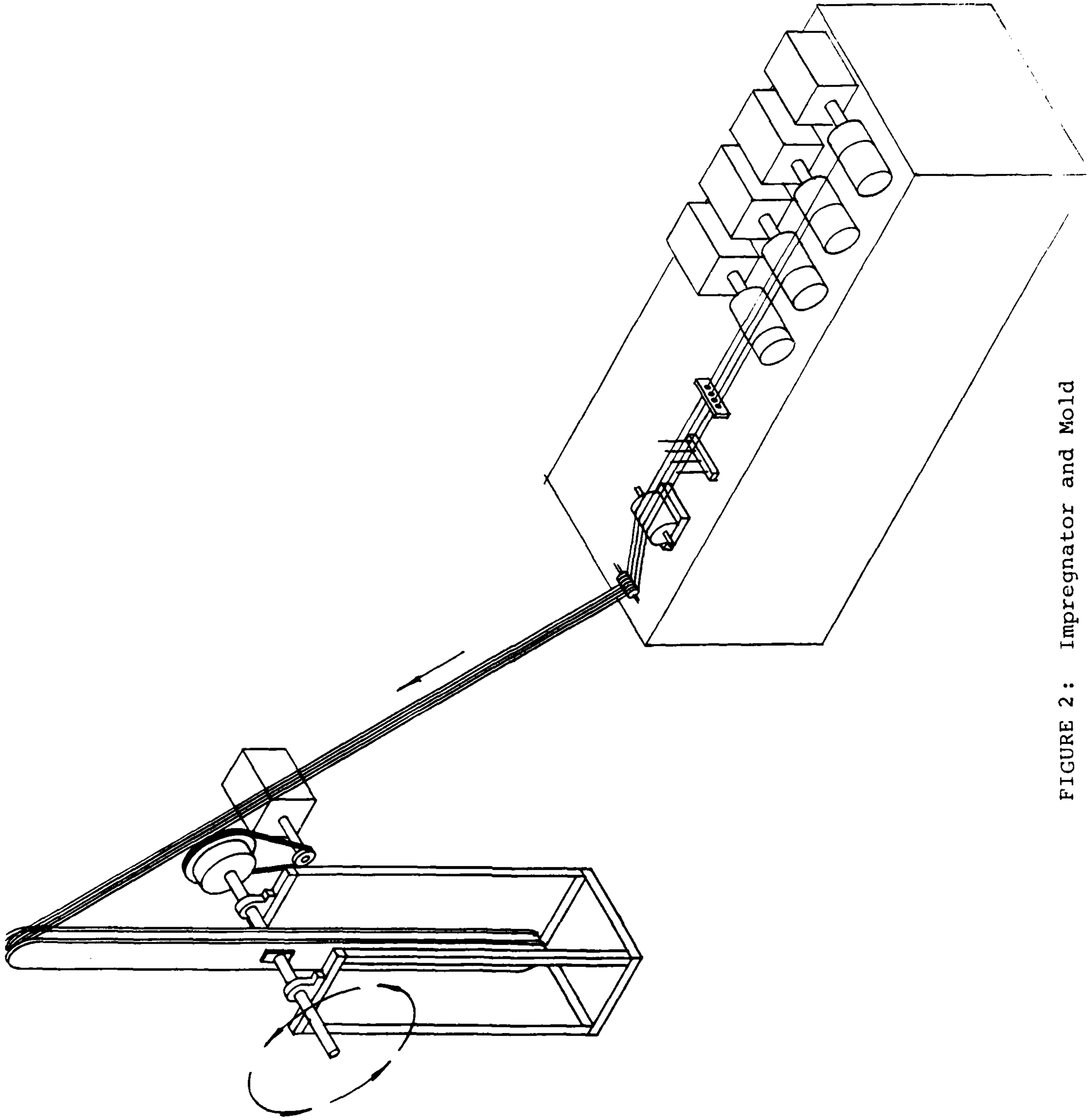

FIGURE 2: Impregnator and Mold

4.1 Process Description

The overall production process consists of the following operations:

- o filament wind the element
- o prepare the element for curing
- o cure at elevated temperature
- o demold
- o install the end fittings
- o install the foam and apply a protective wrap

Filament Winding Three types of equipment are used for this operation:

- o Creels with automatic tension controls to apply an even tension on each strand (10 required).
- o An adjustable impregnator to apply the correct amount of resin to each strand.
- o A variable speed drive to rotate the mold at the desired speed.

Figures 2 and 3 show the schematics for the equipment. Section 4.2 discusses the equipment specifications and/or operating parameters.

Two men are required to wind an element. The first man maintains the impregnator and the second man compacts the composite on the mold. The winding time is approximately 17 minutes per element. Section 4.3 provides a detailed breakdown of the time for each task in the manufacturing process.

Preparation for Curing After the element has been wound, the mold is removed from the winding stand and placed horizontally in a fixture for curing in an

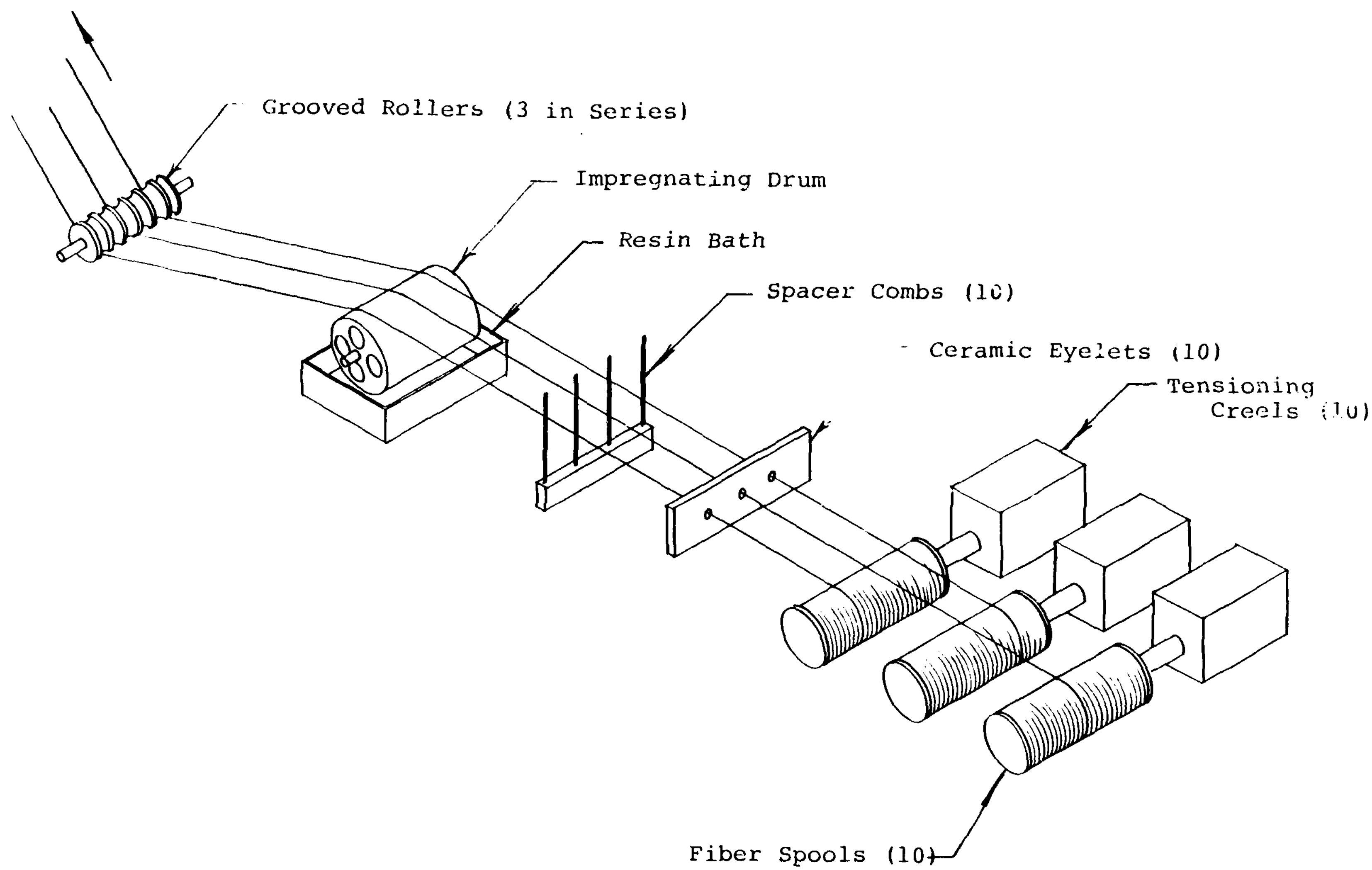

FIGURE 3: Impregnator

oven. At this time, caul plates are placed on top of the composite material. The purpose of the plates is to maintain the compaction of the composite material during the curing process.

Curing the Composite Two elements were cured simultaneously in an air circulating oven. Continuous rotation of the elements was required to prevent run-out of the resin due to the low viscosity of the epoxy just prior to gelling. Rotation was accomplished by using a geared down motor with a shaft projecting into the oven and connecting to one of the molds. The second mold was rotated by a chain driven by the same shaft. Figure 4 illustrates the process.

Demolding the Elements After the elements have been cured in the oven, they are removed and placed on a bench for demolding. This was accomplished by removing the caul plates, the side rails on the mold, the shafts that support the mold while in the oven, and the pins that position the end fittings. After all of these pieces are removed, then the element can be pried from the mold.

Install the End Fittings Installation of the end fittings is done by applying a silicone sealant to the stainless steel half shell then attaching the aluminum cover plates with four screws each.

Application of the Foam and Protective Wrap The foam inserts were made by cutting two-inch thick styrofoam slabs on a table saw. Application of the external wrap was done by manually wrapping the element while it was held in a fixed position. The glass tape was applied dry then impregnated with a room temperature curing epoxy.

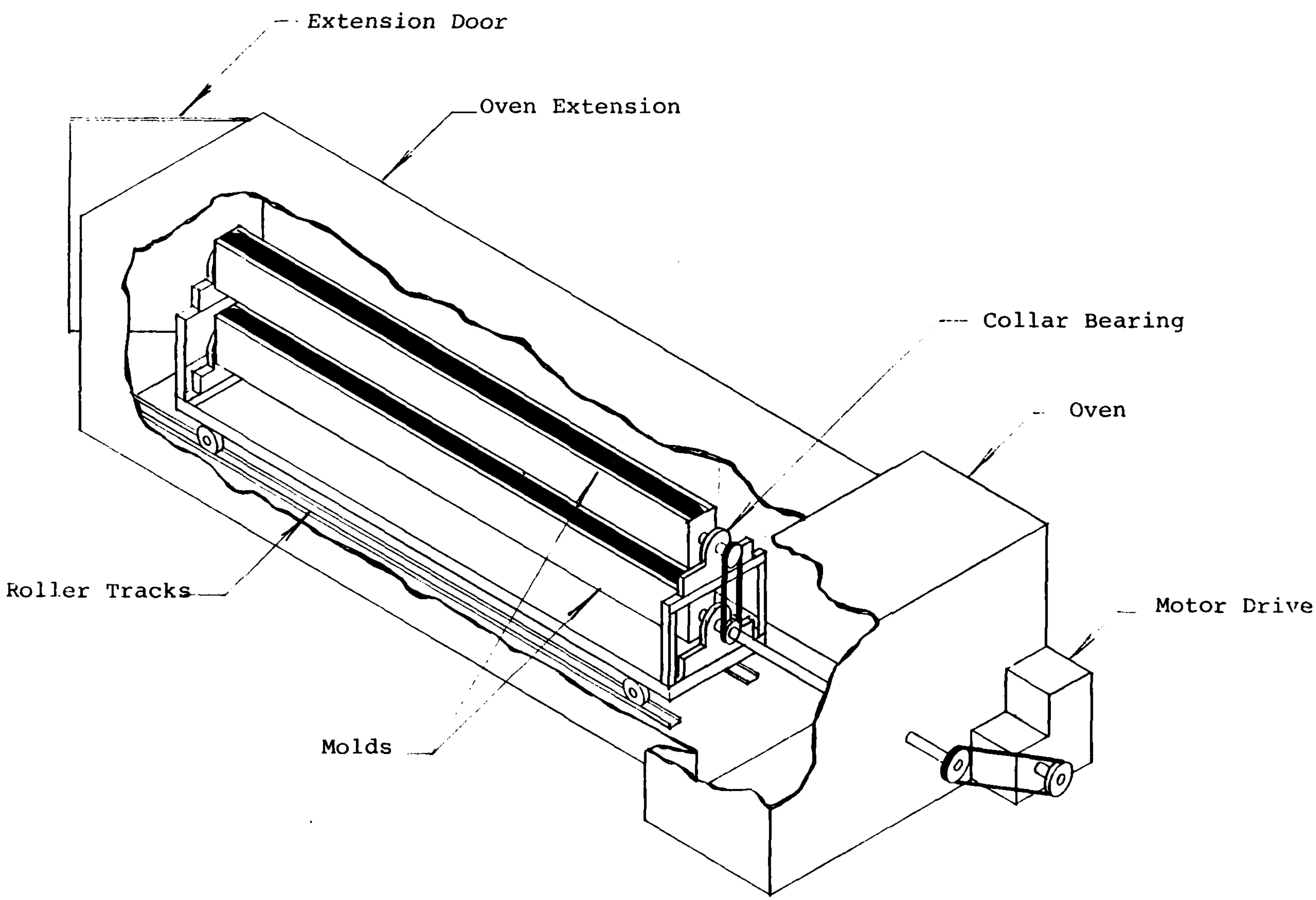

FIGURE 4: Oven

4.2 Equipment and Tooling

The details of the equipment used in the pilot production line are discussed in this section. Critical adjustments on operating settings are discussed where required.

Tensioning Creels Ten magnetic clutches were mounted on a bench. Each clutch had a spindle to accept a three-inch ID spool of carbon fiber. Adjustment of the clutch control enabled the tension in the strand to be varied as desired. The tension was independent of take-off speed.

Type of Clutch	:	Magnetic Power Systems, Model C-1
Tension Settting	:	3 ± ½ pounds
Clutch Controller	:	MACPOWR Model PS-50

Strand Control Control of the strand between the spools and the impregnator was accomplished in two stages. The first stage consisted of ten ceramic eyelets spaced 3/8 inch apart in a staggered horizontal row. The purpose of the eyelets was to feed the strands towards the impregnator in a controlled band of approximately 1/2 the width of the spools. The second stage was a set of vertical wires, ie, a comb, just ahead of the impregnator. The purpose of the comb was to establish the band width of the ten strands at two inches.

Impregnation of the Strands The impregnator used for this program was a unit developed at FMI. It is based on the *doctor blade concept.* Rather than passing the strands through a resin bath, the strands pass over a drum that rotates with its lower portion in a resin bath. The drum picks up a thick layer of resin on its surface due to the high viscosity of the epoxy. As the drum rotates, a carefully adjusted blade removes the excess resin leaving a film thickness equal to the clearance between the blade and the drum. The resin film is in turn picked up by the fibers due to the large surface area of the strands compared to the drum. The advantage of this type of impregnator is that it is relatively insensitive to the speed of the strands in that the film thickness does not vary and the resin/fiber ratio remains relatively constant. The disadvantage is that the system must be kept clean to avoid reducing the gap between the blade and the drum. Due to an unusual amount of fuzz coming from the carbon strands, the impregnator required constant attention.

After the strands leave the drum they pass under and over three sets of grooved rollers. The inside of each groove had a slight radius to cause the fibers to spread out and alternately work the resin into the fibers.

Mold Rotating Equipment   This system consisted of a stand, a variable speed motor with a chain drive, and a rotation counter. The stand was fabricated from angle iron and attached to the work bench. Two split bushings at the top of the stand accepted the shaft attached to the mold.

Motor:	1/2 HP, 1725 RPM
Controller:	Impak V-S Drive Controller, 1/4 to 3/4 HP
Gearbox:	20 to 1 reduction
Chain Drive Reduction:	5.6 to 1 reduction
Operating Mold Speed:	0 to 3 RPM
Mold Surface Speed:	Average of 54 FPM typical

Mold The mold for filament winding the elements is illustrated in Figures 5 & 6 detailed in Drawing Number 730-1075. (See Drawings, Engineering and Associated List). The cross-section of the mold was rectangular. The main frame of the mold was constructed with four 1/4" pieces of carbon steel. Four rectangular strips of steel bolted to the frame defined the borders of the wound part. The aluminum end fittings were designed into the tooling, becoming a part of the tensile element during winding (see Figure 7). The mold rotated away from the impregnator, winding the fiber onto itself.

Oven Curing Apparatus To accommodate the long tensile element mold, a long rectangular extension was added to a large circulating oven. After the mold was removed from the winder, it was fitted with a shaft at each end. Two molds were mounted on bearings, one on top of the other, and slid on tracks into the oven. The molds were rotated by chain drive during cure. The carbon/epoxy elements were cured at 250°F for 4 hours. The oven apparatus is illustrated in Figure 4. After curing the mold was removed from the oven and disassembled, releasing the wound part and the end fittings.

4.3 End Fitting Redesign

The aluminum end fittings designed during Phase II were redesigned in Phase III in order to improve the strength and to facilitate long term service. Initial proof tests resulted in a failure of the aluminum design at the point indicated in Figure 8. A design review of the concept resulted in a total redesign that not only improved the strength but also several other key

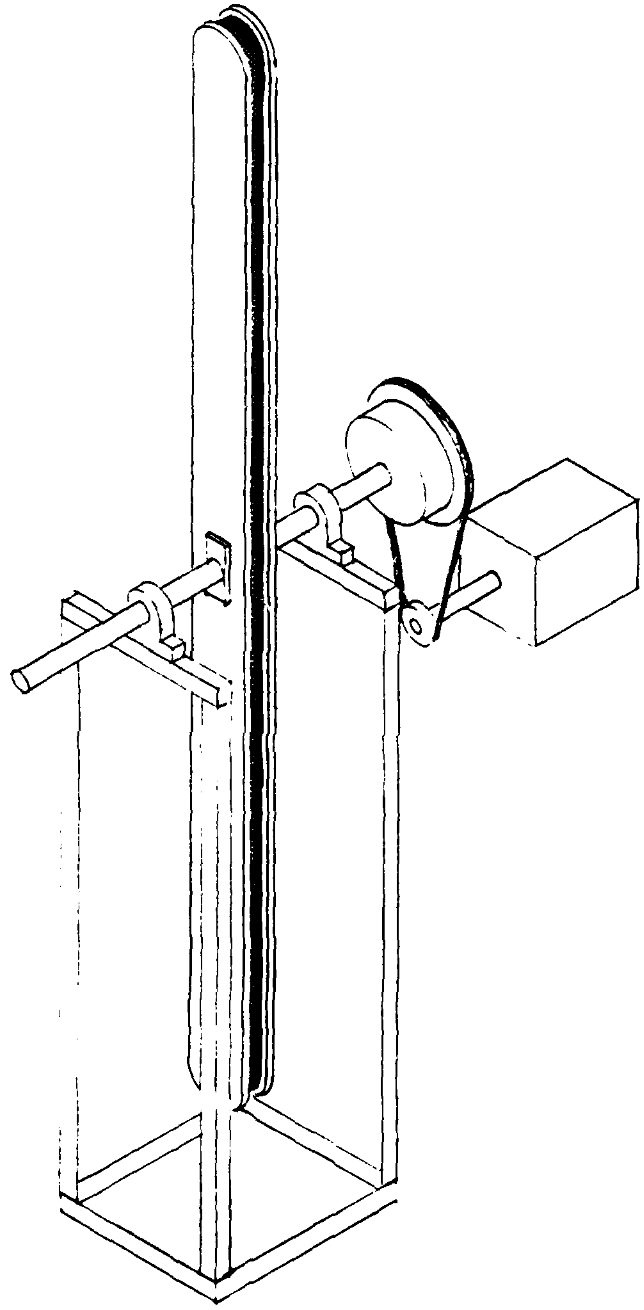

FIGURE 5: Racetrack Mold and Motor Drive

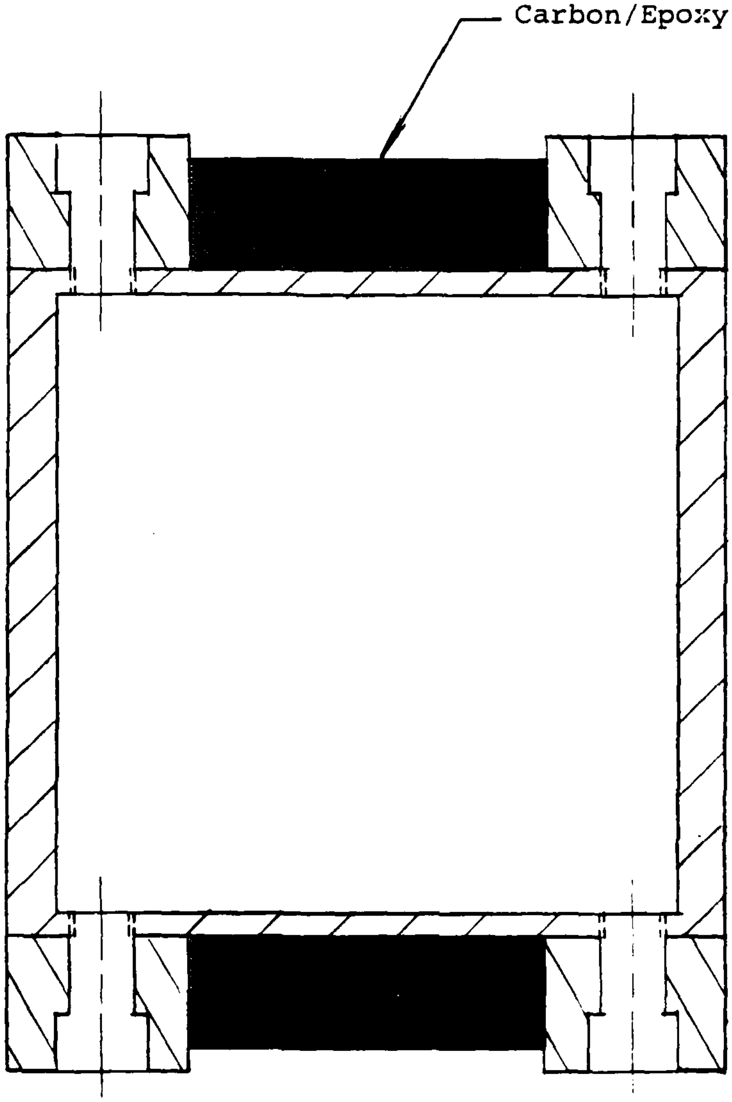

FIGURE 6: Racetrack Mold Cross-Section

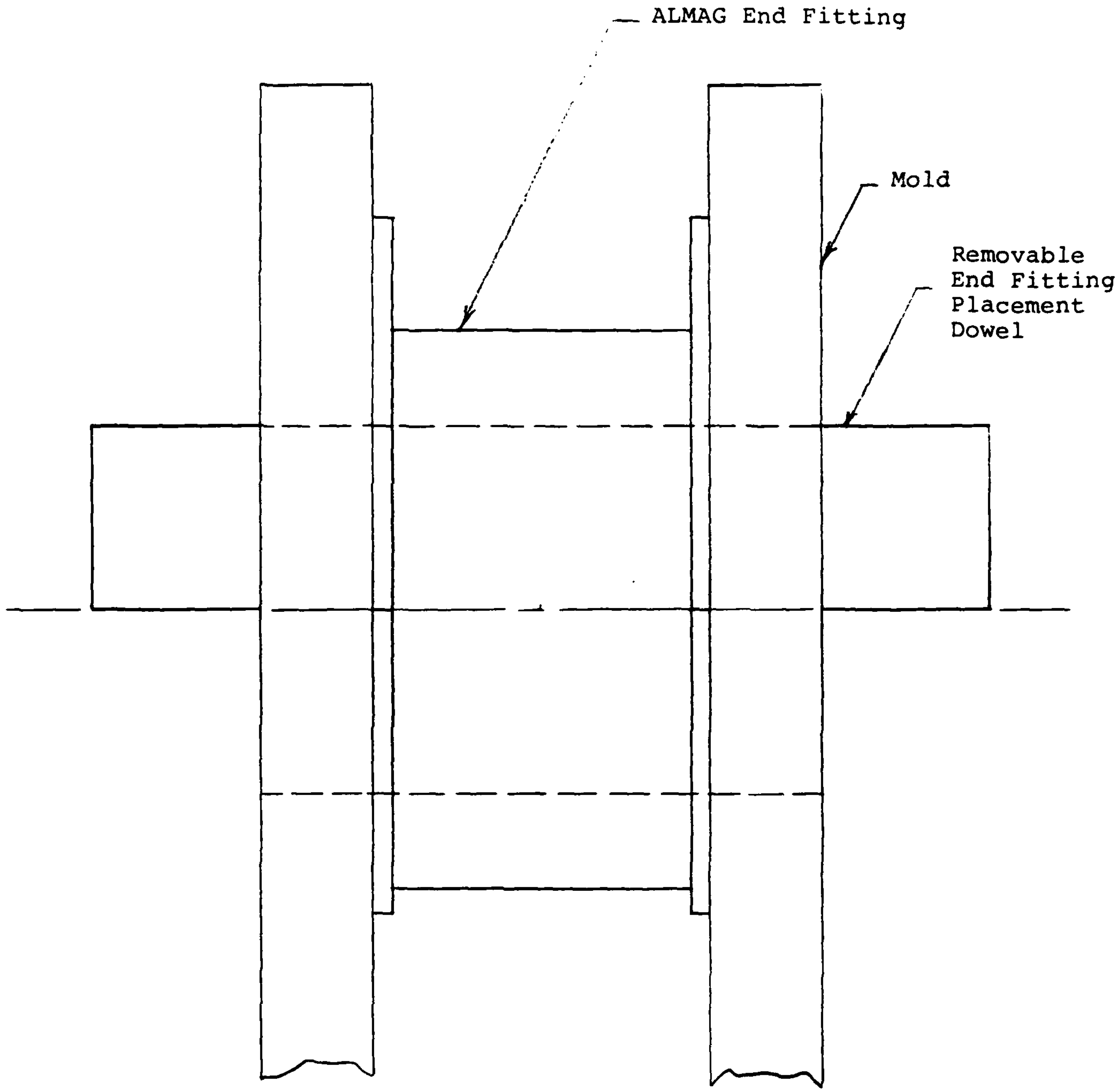

FIGURE 7: ALMAG End Fitting/Mold Detail

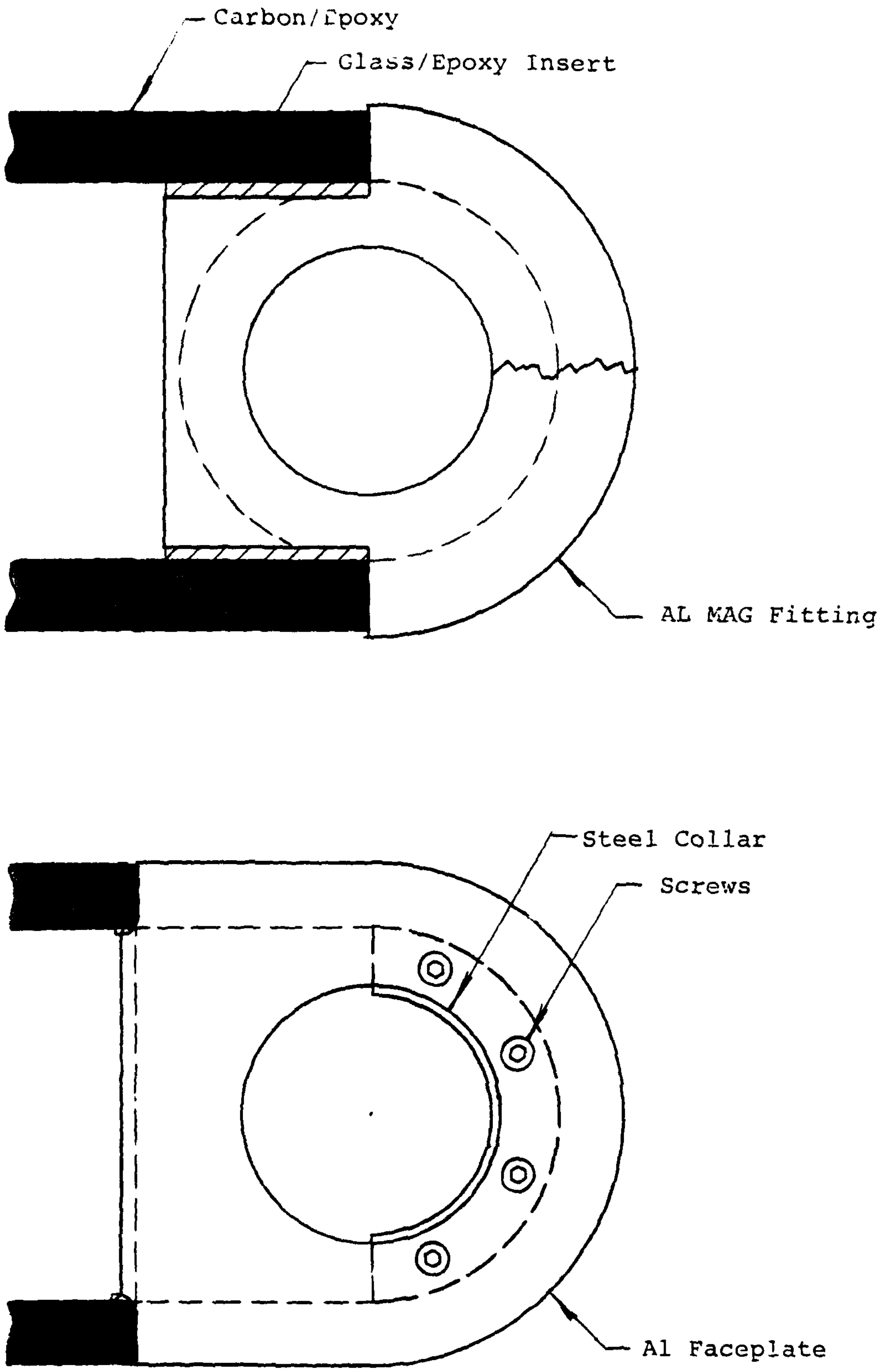

FIGURE 8: ALMAG and Revised Al/Steel Fitting

features. A comparison of the characteristics is as follows:

Aluminum Design	SS/Aluminum Design
o insufficient strength	o improved strength
o not replaceable	o capable of disassembly for inspection and/or replacement
o no inspection capability	o installed clean after curing the elements
o cleaning required after filament winding	o half round design simplified pin installation
o difficult to insert pins	o weight increase of 0.6 pounds per fitting

Proof testing of the elements with the SS/aluminum design was conducted without further problems.

4.4 Production Labor

Table 1 provides a breakdown of the labor for producing one tensile element.

4.5 Production Improvements

Each step in the production process was reviewed to determine what improvements were logical for a full production situation. The results in Table 1 are the values actually observed in the pilot production of the first 40 tensile elements. Suggested changes to the process and the resultant effects are as follows.

Step 1 (Set-up) Resin deispensing and mixing equipment would eliminate 40 minutes per day or 10 minutes per part. Redesign of the mold support system would eliminate 5 minutes per part.

Net Reduction = 15

TABLE 1 - PRODUCTION LABOR FOR ONE ELEMENT

	Production Operation	Man Minutes Per Part	Man Minutes Per Part
1.	Set-up	10	60
2.	Wind part	60	--
3.	Remove from winder	15	--
4.	Transfer to oven area	5	--
5.	Attach shafts & bearing caps	15	--
6.	Install caul plates (4)	40	--
7.	Attach chain between shafts	5	--
8.	Put in oven & attach drive chains	12	--
9.	Cure	5	--
10.	Remove drive chain & remove from oven	12	--
11.	Disconnect connecting chain & bearings	5	--
12.	Transfer to bench	10	--
13.	Remove caul plate	15	--
14.	Remove pins	20	--
15.	Remove side rails & end plates	15	--
16.	Demold	20	--
17.	Clean end fittings	40	--
18.	Remove sharp edges	15	--
19.	Cut foam	5	--
20.	Insert foam & wrap w/fabric	20	--
21.	Impregnate fabric	20	--
22.	Clean mold	20	--
23.	Prep end fittings	10	--
24.	Install side rails	10	--
25.	Install end fittings	5	--
26.	Install new roving & clean bath	--	60
27.	Clean area & equipment	--	60
		409	180

Total per element = 409 + 65

= 474 minutes (7.57 hrs.)

Adjustments for SS/Aluminum end fittings:

Delete #14, 17, 23, 25 & 1/3 of 15 = -80

Add fitting installation = +20

Revised Total = 474 - 60 = 414 minutes (6.9 hrs.)

Step 2 (Wind Part) The experience gained in making the first 40 parts had already reduced the labor to 40 minutes. This value is reasonable to project for future production.

Net Reduction - 20

Step 3 (Remove from Winder) Quick release bearing caps plus an overhead rail system would reduce this operation by 10 minutes. The system used required unbolting the bearing caps and attaching a four part sling to a mobile crane.

Net Reduction = 10

Step 4 (Transfer to Oven Area) Use of overhead rails would speed up this operation and change it from a two to one man task.

Net Reduction = 3

Step 5 (Attach Shafts & Bearing Caps) Use of an open top bushing will eliminate the bolting requirement and save 6 minutes. A side-by-side rather than over and under arrangement will enable the molds to be placed with less maneuvering for about 4 minutes saving.

Net Reduction = 10

Step 6 (Install Caul Plates) A reduction of 25 minutes can be achieved by increasing the height of the side rails and adding spring loaded clamps for the caul plates. The existing design was based on using a 360° wrap to apply pressure to the plates. The operation required two men and can be reduced to one man.

Net Reduction = 25

Step 8 (Put in Oven & Attach Chain Drive) The drive mechanism should be modified to eliminate the requirement to connect the drive chain each time. The system used was selected to avoid modifying the oven;

however, a production run would justify the modification and save 10 minutes.

Net Reduction = 10

Step 10 (Remove the Drive Chain & Remove from Oven) As in Step 8, the operation can be eliminated.

Net Reduction = 10

Step 11 (Discount Connecting Chain & Bearings) Use of open top bushing eliminates 2 minutes from the operation.

Net Reduction = 2

Step 12 (Transfer to Bench) Use of an overhead rail system and a quick connect lifting sling would simplify the procedure and change it from a two to one man operation.

Net Reduction = 7

Step 15 (Remove Side Rails & End Plates) The end plate removal operation was eliminated when the end fittings were redesigned. Removal of the side rails can be simplified by eliminating the attachment screws in favor of quick release clamps.

Net Reduction = 5

Step 16 (Demold) Demolding time can be cut in half by installing knock-out pins in the permanently attached side rails.

Net Reduction = 10

Step 20 (Insert Foam & Wrap W/Fabric) The method used for wrapping the 40 elements was a manual operation with the element in a fixed position. By rotating the element and applying a pre-impregnated fabric from a traversing carriage, a higher quality wrap can be applied in half the time.

Net Reduction = 10

Step 21 (Impregnating the Fabric) By using the process noted for Step 20, this operation becomes a matter of maintaining the winder.

Net Reduction = 10

Step 24 (Install Side Rails) As in Step 15, quick release clamps would cut this step in half.

Net Reduction = 5

The total possible reduction based on preceding improvements is 142 minutes per part or 34%. Increasing the production rate from 4 parts per day to in excess of 12 would reduce the set-up and clean-up labor by 45 minutes per part. The combined effect of increasing the production rate and reducing the labor for the operations noted is:

- o Original Labor = 414 minutes (6.9 hours)
- o Projected Labor = 227 minutes (3.8 hours)

4.6 Estimated Production Costs

Production costs for 200, 1000 and 5000 sets of tensile elements were estimated based on the following rationale:

- o No quantity discounts on materials
- o The labor savings noted in Section 4.4 would be achieved on the 5000 unit run.
- o The 1000 unit run would achieve 90% of the projected savings in Section 4.4
- o The 200 unit run would achieve 1/2 of the savings projected in Section 4.4.
- o Labor rate of $7/hour overhead rate of 100% on labor, G&A of 30% on labor and material.

Material Costs:

T300 carbon, 12.1 pounds @ $18/lb.	=	$217.80
Epoxy (DER 324/NMA/BDMA), 12.5 lb. @ $2.40/lb.	=	30.00
Glass Fabric Tape, 2 lbs. @ $3.10/lb.	=	6.20
Toughened Epoxy, 3 lbs. @ $2.75/lb.	=	8.25
Foam, 8 bd. foot @ $1/board foot	=	8.00
S.S. end fittings (2) @ $20.03	=	40.05
Aluminum end plates (4) @ $32.36	=	64.72
		$375.02
X 2 elements per set	=	$750.04

Labor Costs:

For 200 sets = 200 x $7/hr X 5.34 hrs/element x 2 elements/set
= $14,952 Direct Labor

For 1000 sets = 1000 x $7/hr x 4.1 hrs/element x 2 elements/set
= $57,400 Direct Labor

For 5000 sets = 5000 x $7/hr x 3.8 hrs/element x 2 elements/set
= $266,000

Cost Summaries

200 Sets:	Material	= $150,008
	Direct Labor	= 14,952
	Overhead	= 14,952
	G&A	= 53,974
	Cost Per Set	= $233,886
1000 Sets:	Material	= $750,040
	Direct Labor	= 57,400
	Overhead	= 57,400
	G&A	= 259,452
	Cost Per Set	= $1,124,292

Cost Summaries (Cont.)

5000 Sets:	Material	=	$3,750,200
	Direct Labor	=	266,000
	Overhead	=	266,000
	G&A	=	1,284,660
	Cost Per Set	=	$5,556,860

4.7 Weights

The weights of the finished elements varied from 23.9 pounds to 27.3 pounds. This variation was a result of developing the techniques to control the resin in the carbon and in the overwrap with the lower figure occurring near the end of the production run. This figure should be considered typical of what can be expected in future production.

5.0 CONCLUSIONS

The design developed under this program met the static, fatigue and elongation requirements specified in the contract. A pilot production line was established to demonstrate the production feasibility and to optimize the production procedures. These objectives were achieved and twenty sets of elements were produced for further evaluation by the Army.

6.0 RECOMMENDATIONS

The design of the tensile elements developed during this program is satisfactory as it presently exists and need not undergo further development. The production process demonstrated and evaluated in Phase III of the program resulted in the identification of further improvements that could be made. Development and verification of these improvements prior to full-scale production would be warranted due to the significant impact on the labor cost of the elements.

The projected labor cost reductions relative to the pilot production run amount to $564,000 for a run of 5000 sets of elements. This savings is due both to modification of equipment peculiar to the elements and to equipment at FMI such as handling and curing equipment. The most significant changes are those directly related to the mold design.

The primary modifications to be made are:

- Redesign of the ends of the mold to account for the new end fitting design.
- Redesign of the side rails to reduce labor and to improve the consistency of installation of the caul plates.
- Development of a basic apparatus to continuously wrap and impregnate the fabric to improve the quality and consistency of the overwrap.

APPENDIX A:

INTERIM REPORT

BRIDGE REINFORCEMENT SYSTEM

INTERIM REPORT

CONTRACT NO: DAAK 70-81-C-0228

FEBRUARY 2, 1983

PREPARED FOR:

U.S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT
COMMAND PROCUREMENT AND
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1.0 PROGRAM OVERVIEW

The overall program objective is to develop two continuously wound tensile element concepts. Simplicity of the tensile element end connection for hand assembly is a primary goal. An emphasis is also being put on the reduction of both weight and numbers of components. The tensile members developed under the contract are applicable to any Army modular bridge reinforcement system. This program has been divided into 3 specific phases.

Phase I - This phase involved subscale testing and manufacturing and cost analysis of the 2 basic element types. The results of this phase were used to select a tensile element concept for full scale testing in Phase II.

Phase II - During this phase full scale testing was performed on 2 tensile element types. A fiber link element and 2 racetrack elements (See Appendix A). The results of this testing and the weight and manufacturing analysis have been used to select a final element type for Phase II pilot production.

Phase III - During this phase a pilot production facility will be developed and 20 tensile element sets fabricated.

At the present time, Phase I and Phase II of this program have been completed. This report will summarize the results of Phase I and II and outline the plans for Phase III pilot production work.

2.0 PHASE I - SUBSCALE DEVELOPMENT

The results of the subscale testing program were as follows:

SUBSCALE TEST SPECIMEN DATA

SPECIMEN	SPECIMEN TYPE	FAIL LOAD	TOTAL ELONGATION
1	.15" Kevlar/.05" Hybrid/ .3" VSB	45,500 lbs.	.23"
2	.5" T300	55,000 lbs.	.21"
3	.15" T300/.05" Hybrid/ .3" VSB	52,000 lbs.	.165"
4	.5" VSB	31,500 lbs.	.87"
5	.15" T300/.05" Hybrid/ .24" VSB	32,000 lbs.	.105"
6	.10" T300/.05" Hybrid/ .24" VSB	27,500 lbs.	.098"
7	.10" T300/.05" Hybrid/ .30" VSB	30,000 lbs.	.090"
8	20" Long .1" T300/.05" Hybrid/ .4 VSB	30,000 lbs.	.135"
9	40" Long .1" T300/.05 Hybrid/ .4 VSB	28,500 lbs.	.195"
10	.1" Prepreg Coupon HY-E 1648 AD	12,000 lbs.	.241"
11	.5" Prepreg Specimen HY-E 1648 AD (vacuum molded)	50,000 lbs.	.219"
12	.25" T300 30K Coupon (improved tension type)	35,000 lbs.	.25"
13	.15" T300 30K .55" VSB	36,000 lbs.	.125"
14	.2" T300/.05 Hybrid/ .35" VSB Tape Wound (with vacuum)	33,000 lbs.	.126"

SUBSCALE TEST SPECIMEN DATA

(CONT.)

15	.6" T300 Tape Wound (no vacuum)	41,000 lbs.	.23"
16	.56 T300 Filament Wound (vacuum)	51,000 lbs.	.21"
17	.2 T300/.05 Hybrid/ .35 VSB Filament Wound (vacuum)	28,500 lbs.	.12"
18	.6 T300 Tape Wound (vacuum)	48,500 lbs.	.18"

The specimen geometry and testing set up is shown in Figure 2.0-1. All subscale specimens were ½ inch wide and 20 inches long. A large number of tests were run using several different fibers and curing techniques. The materials selected for subscale testing work were: (See Appendix B)

Kevlar 49 - 2130 denier

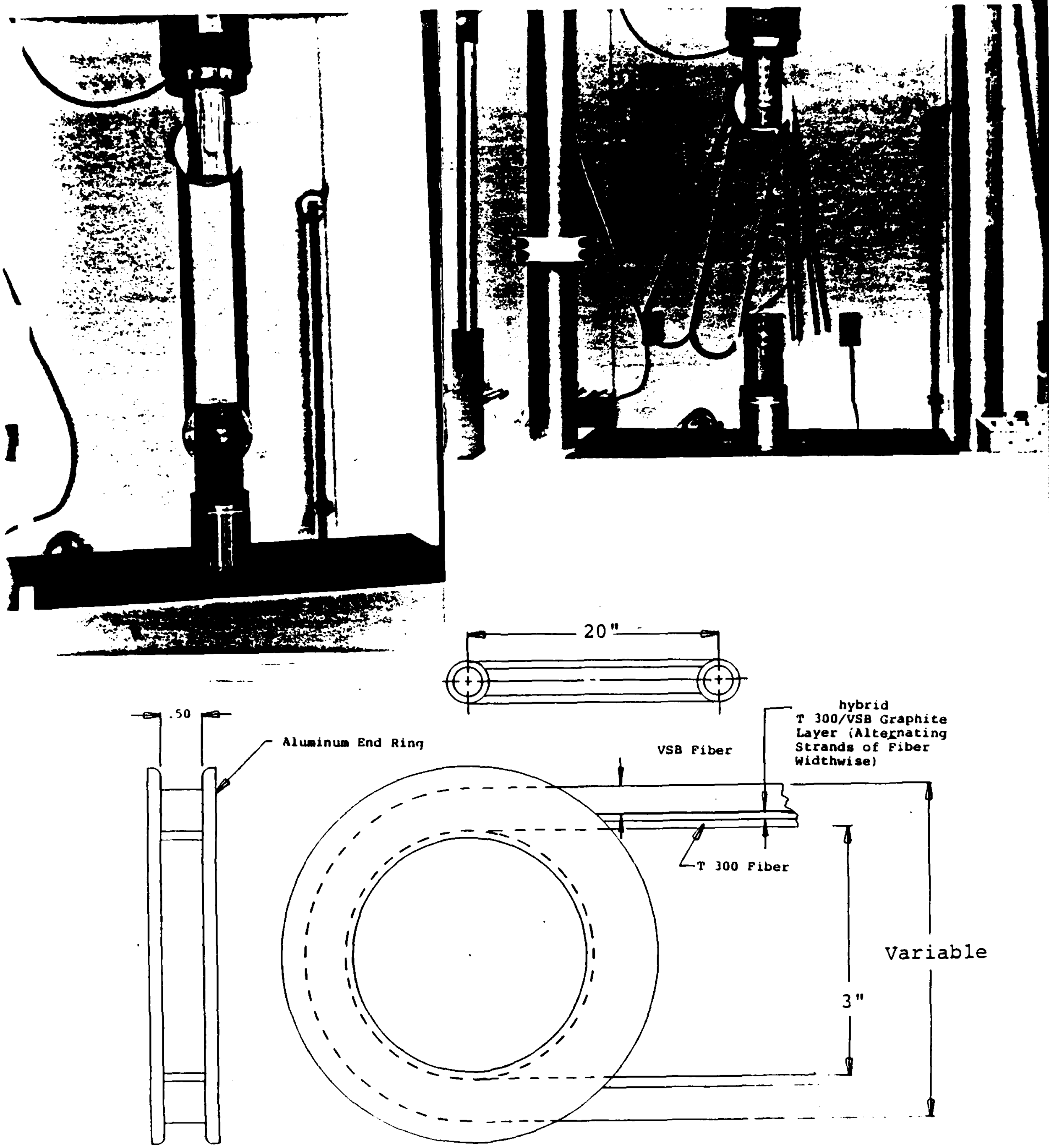
VSB-16 - 55 million modulus fiber

T300-30K - High strength fiber

DER 324/NMA/BDMA epoxy resin system

These fibers were selected because they are large tows and offer the lowest price. The resin system selected was DER 324/NMA/BDMA due to the long pot life available for filament winding and low temperature (250°F) cure capability.

The original plan was to hybridize the tensile specimens with a high strain fiber as an inner layer and a high modulus outer layer fiber. Initial results with Kevlar and high modulus graphite (VSB) showed that the strength and stiffness were low. Hybridization with T300 fiber on the inner layer replacing the



SUBSCALE TEST SPECIMEN
GEOMETRY AND TEST SET UP

FIGURE 2.0-1

Kevlar, improved the stiffness but was still low on required strength. Several types of molding techniques with and without pressure were also investigated. The highest strengths were obtained with specimens cured under some pressure. Due to the low strength of the hybrid specimens using VSB fiber, it was decided to test several specimens with all high strength fiber (T300). The reason for the lower strength of the VSB hybrid specimens is that the stiffer VSB fiber picked up most of the load requiring additional fiber to meet the strength requirements. These results showed that a marginal weight savings would be achieved through use of a hybrid system. The results of the testing with all high strength fiber indicated that a specimen with .61" thickness of T300 fiber would meet the required stiffness and have more than adequate strength. The use of high strength fiber with more than adequate strength will ensure that failure occurs through excessive elongation rather than breaking of the tensile member.

3.0 PHASE II - FULL SCALE PROTOTYPE FABRICATION AND TESTING

Using the results of the subscale testing, a final design was developed for both the racetrack and fiber link elements. Because of the difference in fabrication requirements, it was decided to fabricate full scale prototypes of both element types to compare fabrication time and mechanical properties. The final design of the racetrack and fiber link elements is shown in Appendix C. The required composite area to meet the 70 million EA value is 4.88 square inches. This area was determined based on the subscale test results which include the effect of additional elongation in the attachment area. The final part dimensions are .61 inches thick and 4 inches wide. Analysis of the hoop area of the racetrack element using orthotropic ring analysis results in a maximum stress at the inner radius of:

STRESS ANALYSIS FOR 2 CONCENTRIC RINGS WITH CYLINDRICAL ANISOTROPY.
INTERNAL PREASURE OF 30560.00 PSI.
EXTERNAL PREASURE OF .00 PSI.

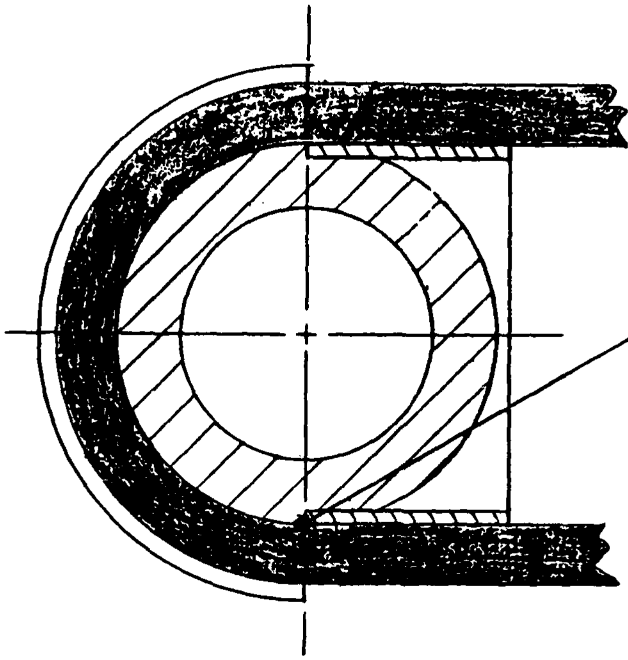
RING #	I.D. (INCHES)	O.D. (INCHES)
1	3.7500	4.2500
2	4.2500	4.9700

ANALYSIS FOR RING # 1
RADIAL MODULUS (PSI) .300E 06
TANGENTIAL MODULUS (PSI) .170E 08
TANGENTIAL POISSONS RATIO .2500

TEST POINT	INITIAL RADIAL POSITION (IN)	TAN STRESS (PSI)	RAD STRESS (PSI)	RAD DISPLACEMENT (INCHES)
1	1.8750	164080.6000	-30657.0200	.0189
2	1.9028	152620.2000	-27902.0000	.0179
3	1.9306	142284.2000	-25380.2400	.0169
4	1.9583	132969.0000	-23069.1700	.0160
5	1.9861	124573.1000	-20946.5900	.0152
6	2.0139	117005.6000	-18992.5200	.0144
7	2.0417	110137.1000	-17189.4500	.0137
8	2.0694	104046.0000	-15521.6600	.0131
9	2.0972	98519.1900	-13975.1500	.0126
10	2.1250	93556.5600	-12539.1600	.0121

ANALYSIS FOR RING # 2
RADIAL MODULUS (PSI) .300E 06
TANGENTIAL MODULUS (PSI) .170E 08
TANGENTIAL POISSONS RATIO .2500

TEST POINT	INITIAL RADIAL POSITION (IN)	TAN STRESS (PSI)	RAD STRESS (PSI)	RAD DISPLACEMENT (INCHES)
1	2.1250	93545.1900	-12535.7200	.0121
2	2.1650	87230.0300	-10637.3000	.0115
3	2.2050	81934.3100	-8910.5430	.0109
4	2.2450	77403.8100	-7333.4490	.0105
5	2.2850	73593.6900	-5884.3790	.0101
6	2.3250	70424.3700	-4545.1950	.0098
7	2.3650	67826.0000	-3299.9340	.0096
8	2.4050	65739.6900	-2134.9810	.0094
9	2.4450	64114.4600	-1038.4450	.0093
10	2.4850	62907.3200	-.9826	.0092



These results were obtained from the FMI hoop stress program (see Appendix D).

3.1 Racetrack Element Fabrication

The racetrack element was fabricated using a split aluminum tool. This tooling was rotated vertically as shown on the schematic in Figure 4.1-1. Ten ends of T300-30K yarn were wound on the tooling at one time. A magnetic particle clutch creel was used to tension the yarns (see Figure 3.1-1). The DER 324/NMA/BDMA resin system was metered on with a dip tank and roller set up, using a 50 percent volume fraction (Figure 3.1-2). The part was roller compacted during winding and then vacuum bagged for final cure (see Figure 3.1-3). Curing was performed in the oven extension shown in Figure 3.1-4 using the following cure cycle:

- o 2-5°F/min. heat up to 225°F
- o Hold at 225°F for 3 hours

FIGURE 3.1-1 - Magnetic Particle Clutch Creel

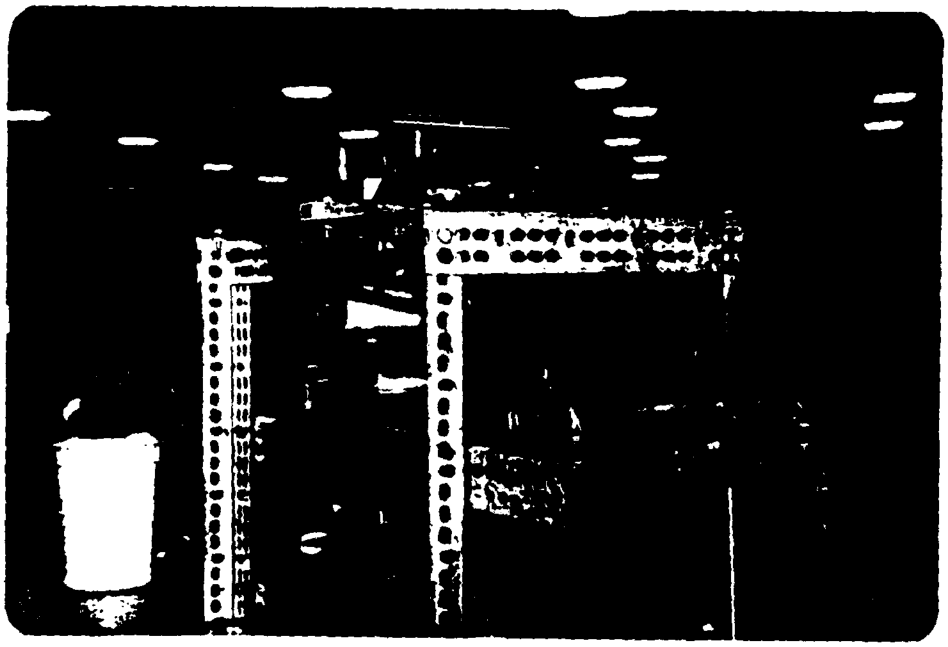


FIGURE 3.1-2 - Dip Tank Set Up

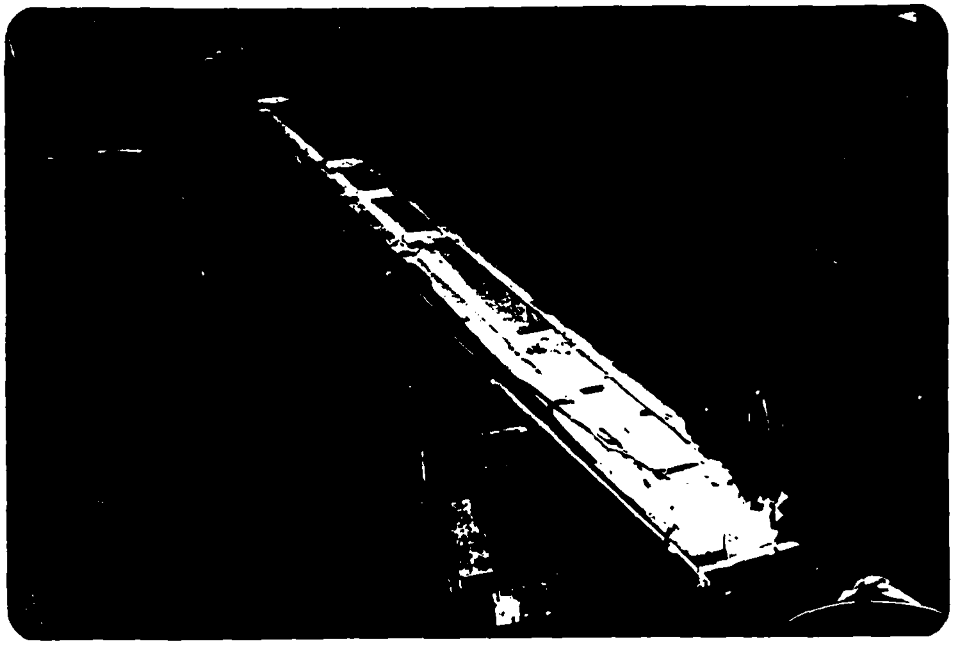


FIGURE 3.1-3 - Racetrack Element With Vacuum Bag

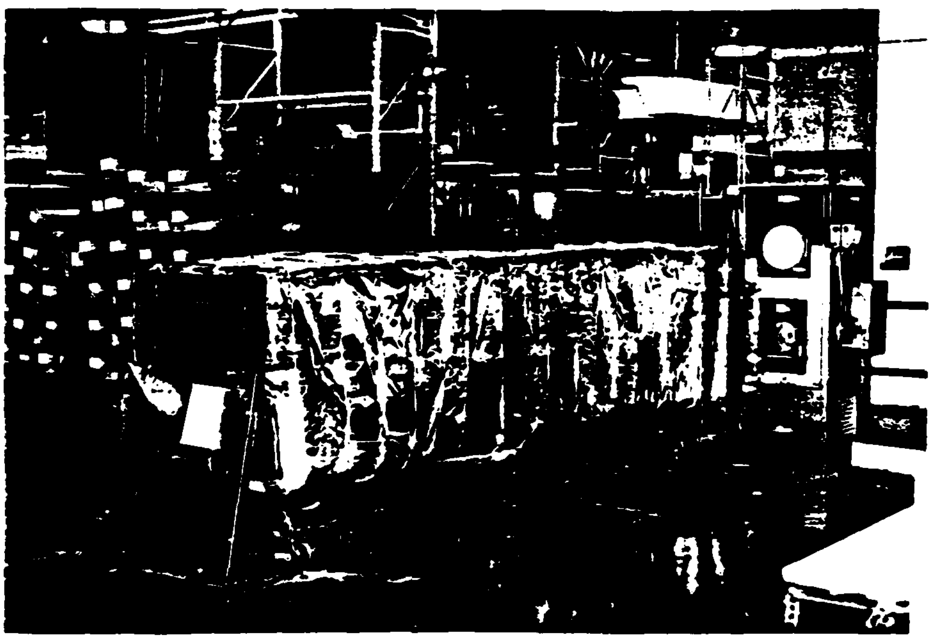


FIGURE 3.1-4 - Curing Oven

- o 2-5°F/min. heat up to 250°F
- o Hold at 250°F for 16 hours
- o Cool down at 2-5°F/min. to below 100°F

Two parts were fabricated using the same technique.

3.2 Fiber Link Element Fabrication

The fiber link was fabricated on the Entec 800 filament winder using the tooling shown in Figure 3.2-1. Winding of the part was accomplished using a single end of graphite yarn which was placed by hand around the end fittings. The filament winding carriage was used to move the yarn horizontally. The tooling was rotated 180° and the yarn position widthwise by hand during each pass of the carriage. Curing of the fiber link was accomplished by shrink taping the part lengthwise and widthwise and rotating it in the oven during cure.

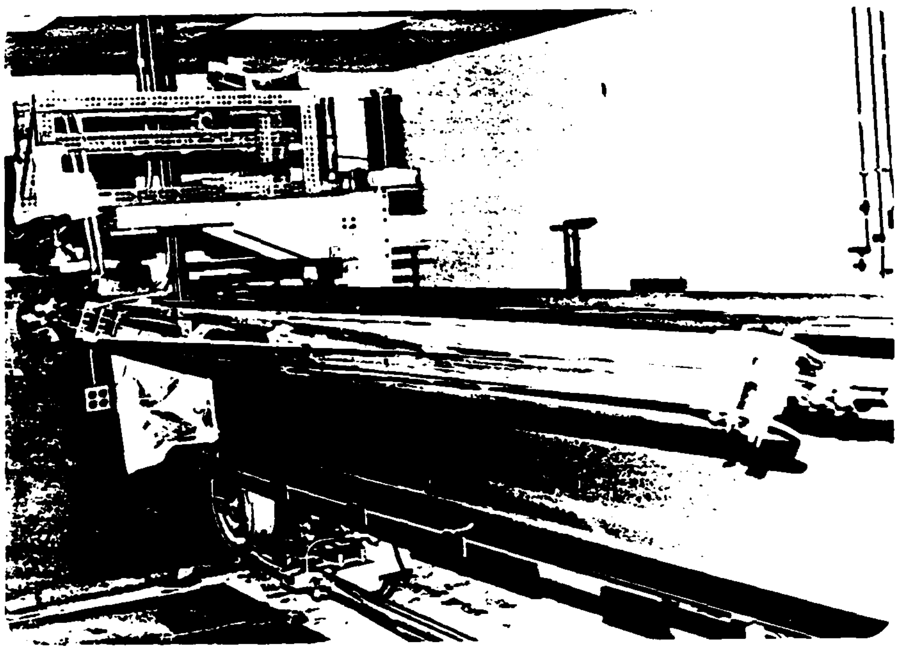


FIGURE 3.2-1 - Fiber Link Tooling

3.3 Full Scale Testing

Two full scale racetrack elements and one full scale fiber link element were tested during Phase II of this program. Fatigue testing was performed on the racetrack specimens only since this was the design of choice from a fabrication point of view. The results of the full scale testing were as follows: (pictures of the test set up and tested parts are in Appendix A.)

Static Loading

	Actual Load	Goal
Fiber Link	250,000	250,000
Race Track 1	125,000	125,000
Race Track 2	125,000	125,000

Static Elongation (at 230,000 lbs. for fiber link/115,000 lbs. for racetrack)

	Actual Elongation	Goal
Fiber Link	.477	.46 (average for 3 proof tests)
Race Track 1	.459	.46 (average for 3 proof tests)
Race Track 2	.466	.46 (average for 3 proof tests)

Fatigue Test (Race Track) 500 lbs. to 115,000 lbs.

Race Track 1	Survived	(Final elongation .47)
Race Track 2 (Residual ultimate strength 230,000 lbs.)	Survived	(Final elongation .47)

This testing was performed on Tension Member Technology's (TMT) 400,000 lb. machine. The fiber link was statically tested, only using a special clevis and cable attachment to accommodate the 90° rotation of the end fittings on the member. The race track elements were tested statically and cycled to 27,000 cycles each without a failure. The cycle tension test was performed at .25 cycles per second from 500 pounds to 115,000 pounds.

The testing report by TMT is attached in Appendix E. The fiber link was not quite as stiff as the racetrack elements due to some misalignment of the fibers during winding and curing. The residual strength of the racetrack element tested to failure was 2 times the design limit load. This large margin indicates that some long term degradation can be sustained without affecting the performance of these elements. This high margin of safety on strength will ensure a soft type of failure mode through excessive elongation rather than failure of the elements.

3.4 Attachment Fittings

The final design for the racetrack attachment fittings is shown in Appendix F. The attachment consists of a 4340 heat treated pin with 2 washers which is used to pin 4 links together. The previously designed bridge and king post attachment fittings will not be fabricated since the racetrack elements will be used on another bridging system.

4.0 PHASE III - PILOT PRODUCTION

4.1 Final Design

The results of the Phase II fabrication development work illustrated that much more complex winding machinery would be required to wind the fiber link in an automated mode. Results of the full scale testing indicated that either vacuum bag or shrink tape molding can be used to obtain good quality parts. The final design recommended for Phase III pilot production is the racetrack element. This design was selected primarily due to the fabrication advantages over the fiber link. This type of element is easier to fabricate since winding takes place in one plane. Production of the racetrack element is easy to scale up without the need for very expensive dedicated equipment. The winding time required to fabricate a racetrack element is much shorter than for the fiber link.

A shrink tape cure process similar to the technique used to cure the fiber link will be used to fabricate the racetrack elements. This process is much quicker than vacuum bagging and does not require vacuum pump equipment. The final design of the end fitting and assembled racetrack element is shown in Appendix C. The end fitting will be an Al-Mag 35 aluminum casting, anodized and dicromate sealed to reduce wear and eliminate corrosion with the graphite epoxy. A foam insert will be placed in the center of the element and the entire tensile member wrapped with a rubber modified epoxy/glass layer. This layer will protect against impact and abrasion damage. Pilot production winding of the racetrack elements will be performed utilizing a setup similar to the schematic in Figure 4.1-1. While one part is being wound, another part will be prepared for curing in the oven. All parts will go through a separate 3 hour cure on a rotating fixture in the oven, and then a final post cure overnight. The preliminary racetrack tooling drawings have been enclosed in Appendix G.

4.2 Production Weight Estimate

The final weight of one set of elements and one pin connector is estimated to be:

End Fittings	.94 lbs.
Composite Element	37.06 lbs.
Fiberglass Covering and Foam Insert	8.355 lbs.
1 Pin With 2 Washers and 2 Cap Screws	14.82 lbs.
TOTAL WEIGHT	61.17 lbs.

4.3 Production Cost Estimate

The estimated cost to produce the racetrack element in quantities of 200, 1000, and 5000 is:

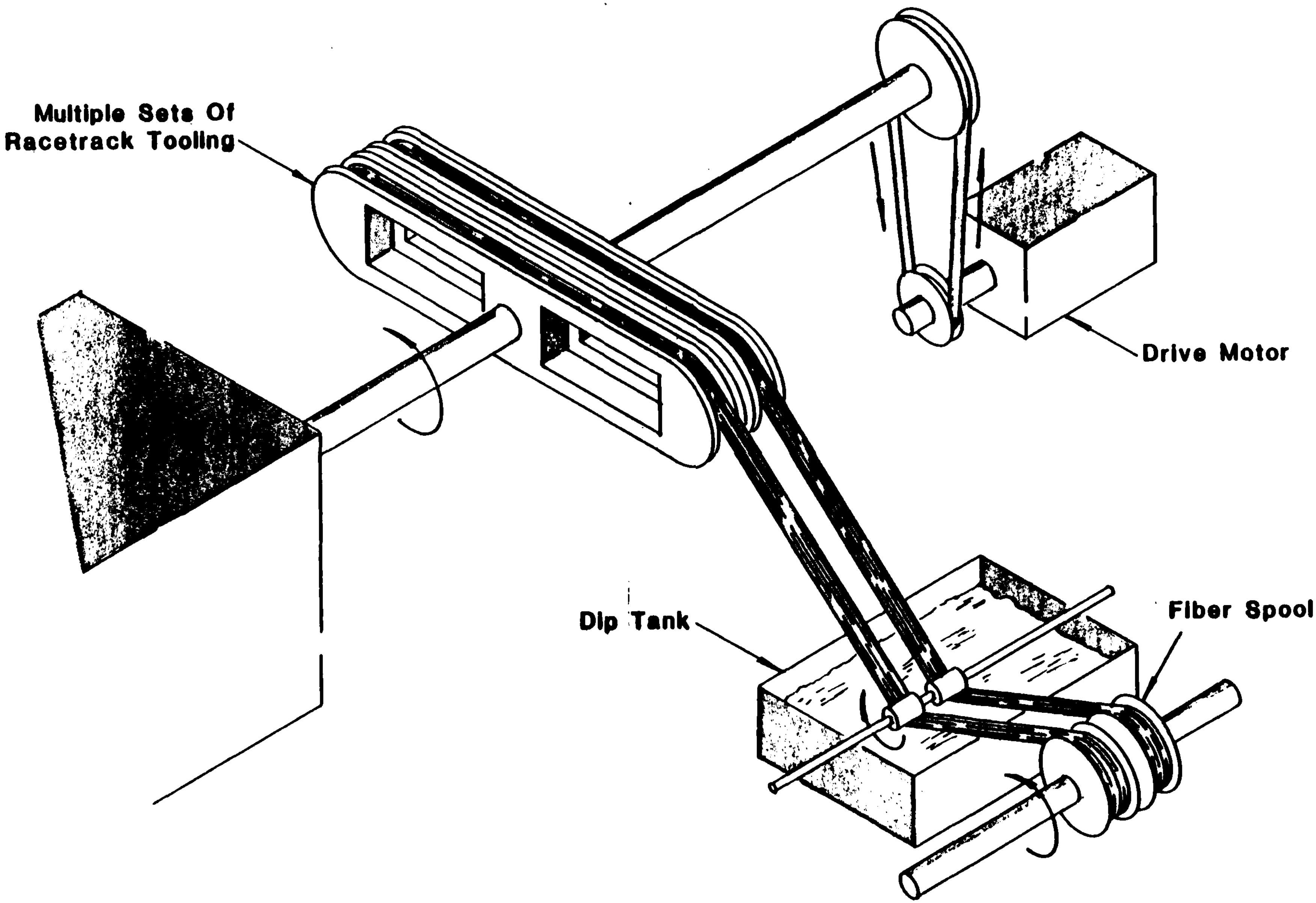
QUANTITY	COST/SET
200	1664
1000	1404
5000	1352

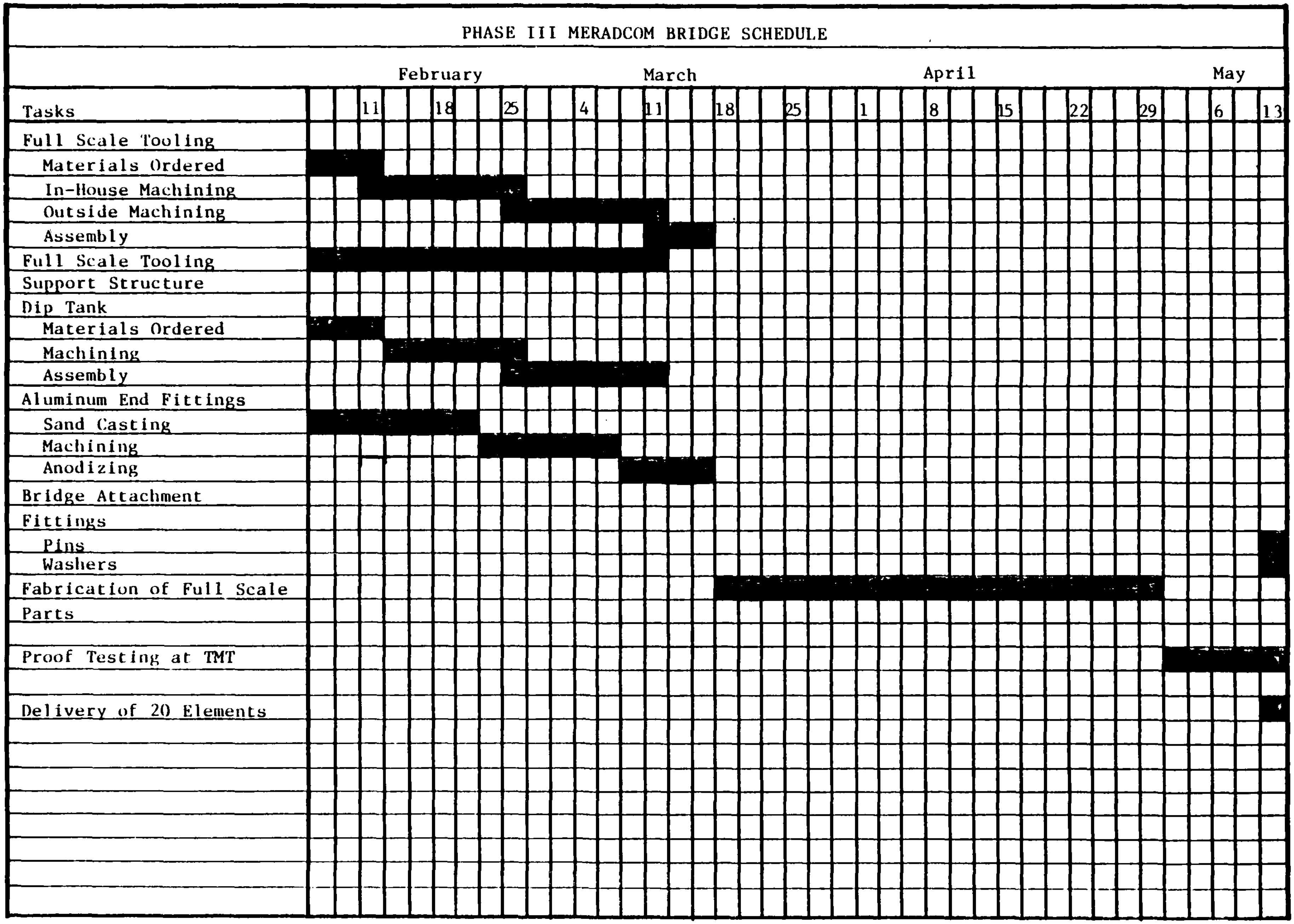
4.4 Program Schedule

The planned schedule for completion of the Phase III pilot production work is shown on the attached page. Expected completion date is May 15.

FIGURE 4.1-1

AUTOMATED RACETRACK WINDING

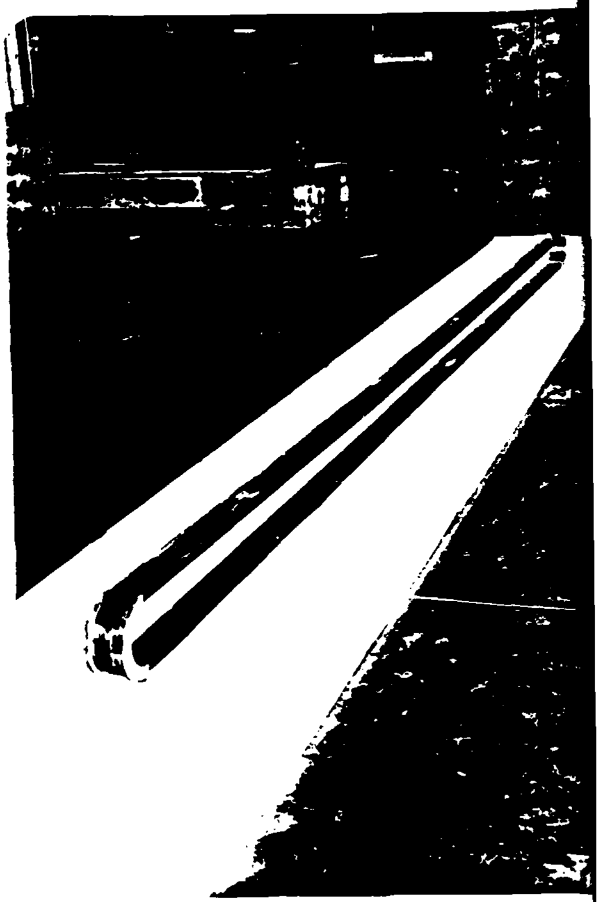



PHASE III MERADCOM BRIDGE SCHEDULE
February
March
April
May
Tasks
11
18
25
4
11
18
25
1
8
15
22
29
6
13
Full Scale Tooling
Materials Ordered
In-House Machining
Outside Machining
Assembly
Full Scale Tooling
Support Structure
Dip Tank
Materials Ordered
Machining
Assembly
Aluminum End Fittings
Sand Casting
Machining
Anodizing
Bridge Attachment
Fittings
Pins
Washers
Fabrication of Full Scale
Parts
Proof Testing at TMT
Delivery of 20 Elements

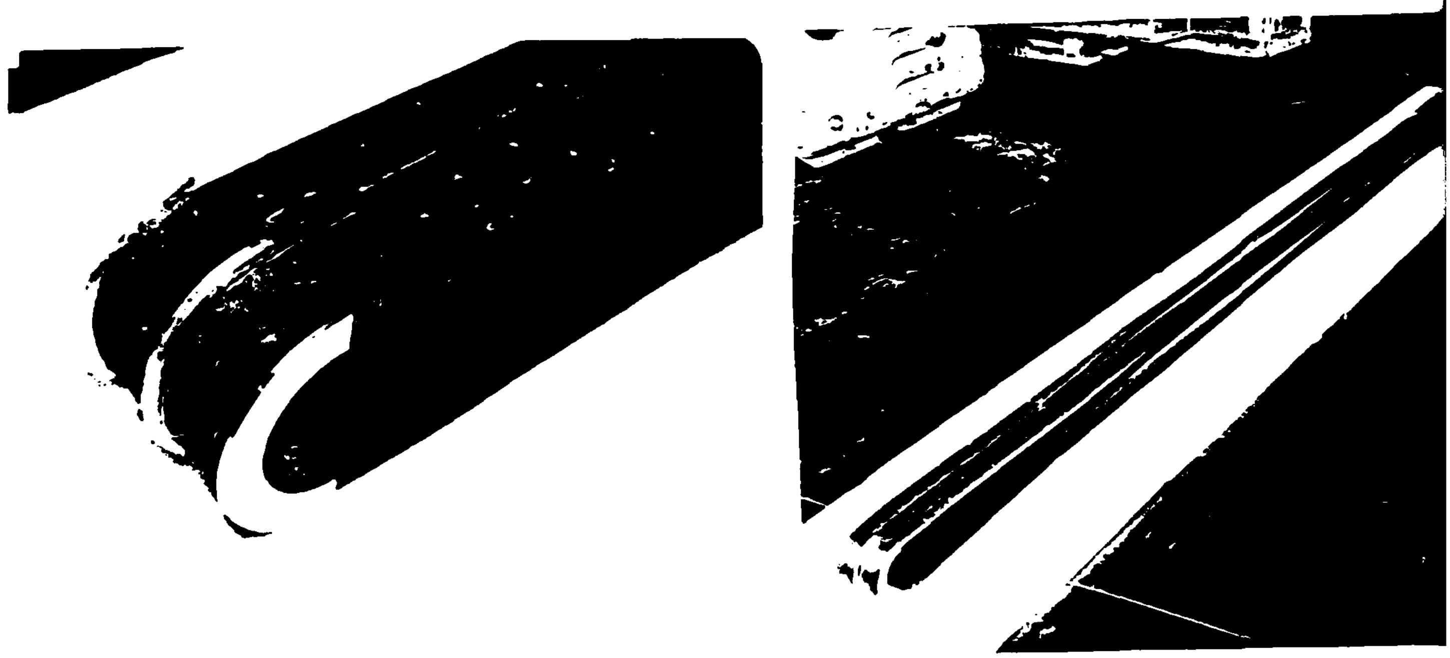
APPENDIX A

RACETRACK AND FIBER LINK ELEMENT TESTING SET UP

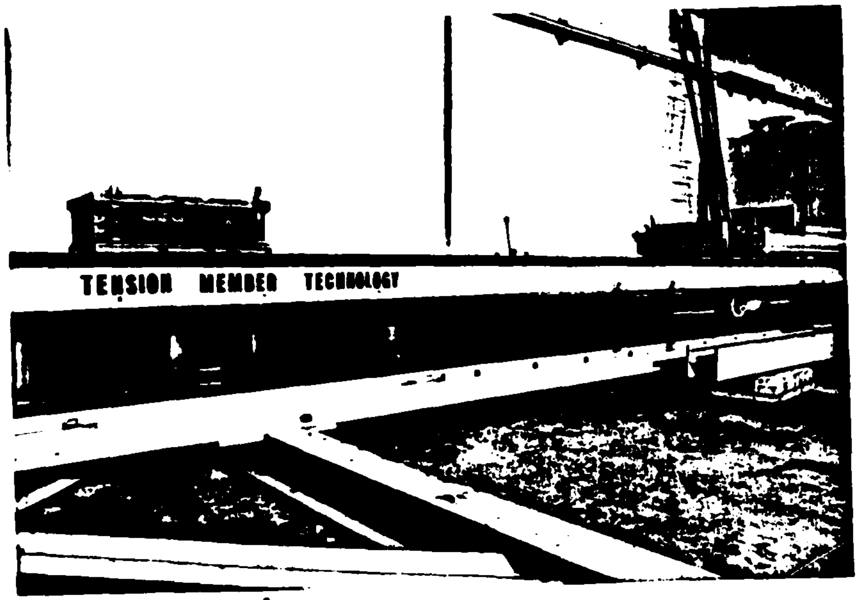
RACETRACK TEST SPECIMENS

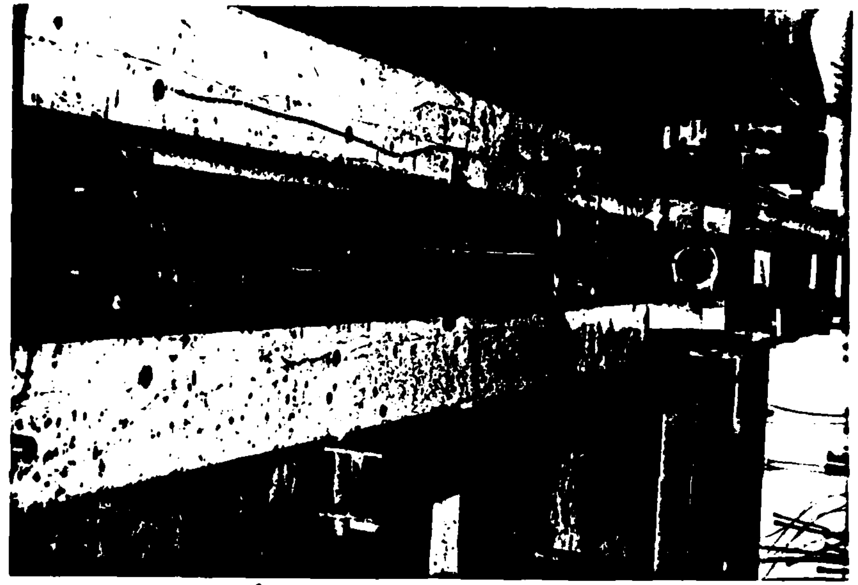


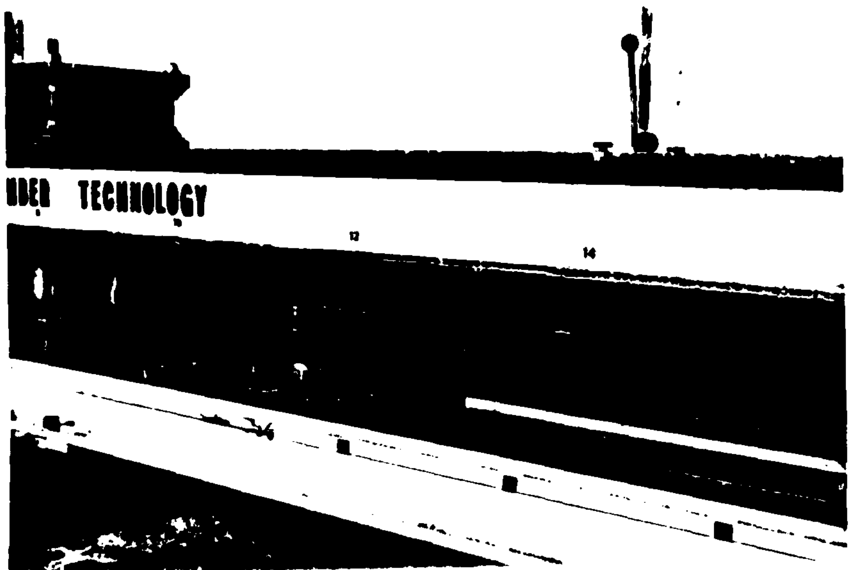
FIBER LINK SPECIMENS

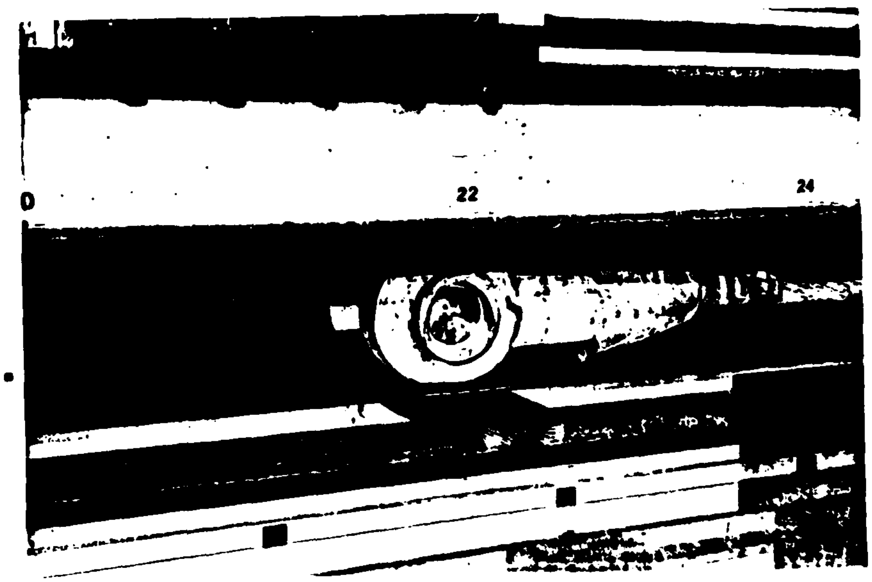


FULL SCALE TEST SET UP









APPENDIX B

MATERIAL DATA SHEETS

TECHNICAL INFORMATION

UNION CARBIDE CORPORATION
CARBON PRODUCTS DIVISION
Old Ridgebury Road, Danbury, CT 06817

BULLETIN NO. 465-248

"THORNEL" P-55 CARBON FIBER GRADE VSB-16

DESCRIPTION

"Thornel" P-55 Carbon Fiber Grade VSB-16 is a 4000 filament, continuous length, high modulus fiber from a pitch precursor. Grade VSB-16 fiber is designed for use in stiffness-critical applications.

TYPICAL PROPERTIES AND CHARACTERISTICS "THORNEL" P-55 CARBON FIBER GRADE VSB-16

PROPERTY	U.S. CUSTOMARY UNITS	VALUE	S.I. UNITS	VALUE
Tensile Strength	lb/in² x 10³	300	GPa	2.10
Tensile Modulus	lb/in² x 10⁶	55	GPa	380
Density	lb/in³	0.072	Mg/m³	2.0
Filament Diameter	μ	10	μ	10
Elongation at Break	%	0.5	%	0.5
Elastic Recovery	%	100	%	100
Carbon Assay	%	99 +	%	99 +
Surface Area	m²/g	1	m²g	1
Thermal Conductivity	BTU-ft/hr (ft²) (°F)	58	W/m K	100
Electrical Resistivity	Ohm-cm x 10⁻⁴	7.5	μohm-m	7.5
Longitudinal CTE at 70 °F (21 °C)	PPM/ °F	− 0.5	PPM/K	− 0.9
Specific Heat at 70 °F (21 °C)	BTU/lb °F	0.22	j/kg K	925

TYPICAL STRAND PROPERTIES "THORNEL" P-55 CARBON FIBER GRADE VSB-16

PROPERTY	U.S. CUSTOMARY UNITS	VALUE	S.I. UNITS	VALUE
Yield	yd/lb	800	m/g	1.6
Denier	g/9000m	5600	g/9000m	5600
Dry Pull Strength	lb	30	N	130
*Twist	tpi	0	tpm	0
Filaments/Strand	—	4000	—	4000
Fiber Area in Yarn Cross Section	in² x 10⁻⁵	48	mm²	310

*Also available with a twist of 0.4 TPI (16 TPM)

THORNEL is a registered trademark of Union Carbide Corporation.

For further information contact **UNION CARBIDE CORPORATION**
CARBON PRODUCTS DIVISION, 120 E. Riverside Plaza, Chicago, IL 60606

Export: CARBON PRODUCTS DIVISION, EXPORT SALES OFFICE, Danbury
In Canada: UNION CARBIDE CANADA LIMITED, Toronto

CP-5870
3M182

Litho in U.S.A.

TECHNICAL INFORMATION

UNION CARBIDE CORPORATION
CARBON PRODUCTS DIVISION
Old Ridgebury Road, Danbury, CT 06817

BULLETIN NO. 465-244

"THORNEL" 300 COMMERCIAL GRADE CARBON FIBER WYP 3 1/0

DESCRIPTION

"Thornel" 300 Carbon Fiber Grade WYP 3 1/0 is a continuous length, high strength, high modulus fiber consisting of 30,000 filaments in a one-ply construction. The fiber surface has been treated to increase the interlaminar shear strength in a resin matrix composite. "Thornel" 300 fiber, coated with a resin-compatible sizing, produces composites with typical shear strength in excess of 13,000 lb/in² (89.6 MPa).

TYPICAL PROPERTIES AND CHARACTERISTICS "THORNEL" FIBER GRADE WYP 3 1/0

PROPERTY	U.S. CUSTOMARY UNITS	VALUE	S.I. UNITS	VALUE
Tensile Strength	$lb/in^2 \times 10^3$	390	GPa	2.69
Tensile Modulus	$lb/in^2 \times 10^6$	31.5	GPa	217
Density	lb/in^3	0.064	Mg/m^3	1.78
Filament Diameter	μ	7	μm	7
Elongation at Break	%	1.2	%	1.2
Elastic Recovery	%	100	%	100
Carbon Assay	%	92	%	92
Surface Area	m^2/g	1	m^2/g	1
Thermal Conductivity	BTU-ft/hr(ft²)(°F)	5	W/m K	8.5
Electrical Resistivity	$Ohm\text{-}cm \times 10^{-4}$	18	μohm-m	18
Longitudinal CTE at 70°F (21°C)	PPM/°F	−0.3	PPM/K	−0.5
Specific Heat at 70°F (21°C)	BTU/lb °F	0.23	j/kg K	950

TYPICAL STRAND PROPERTIES "THORNEL" FIBER GRADE WYP 3 1/0

PROPERTY	U.S. CUSTOMARY UNITS	VALUE	S.I. UNITS	VALUE
Yield	yd/lb	275	m/g	0.55
Denier	g/9000m	16,240	g/9000m	16,240
Twist	tpi	0	tpm	0
Filaments/Strand	—	30,000	—	30,000
Fiber Area in Yarn Cross Section	$in^2 \times 10^{-5}$	158	mm^2	1.02

For further information contact UNION CARBIDE CORPORATION
CARBON PRODUCTS DIVISION, 120 S. Riverside Plaza, Chicago, IL 60606

Export: CARBON PRODUCTS DIVISION, EXPORT SALES OFFICE, Danbury
In Canada: UNION CARBIDE CANADA LIMITED, Toronto

CP-5868 Rev. 1
3M182

Litho in U.S.A.

D.E.R. 317 Epoxy Resin

A high viscosity, fast reacting (20% faster than D.E.R. 331) liquid epoxy resin designed for adhesive applications requiring quick gelling with amine curing agents.

D.E.R. 330 Epoxy Resin

A low epoxide equivalent weight liquid resin processed to give very low viscosity without the use of a reactive diluent.

D.E.R. 331 Epoxy Resin

A general purpose, widely used liquid resin. It is recognized as a standard from which variations have been developed.

D.E.R. 332 Epoxy Resin

The uniqueness of D.E.R. 332 epoxy resin is reflected in its maximum epoxide equivalent weight of 178 (chemically pure diglycidyl ether of bisphenol-A would have an epoxide equivalent weight of 170). Because of its high purity and lack of polymer fractions, D.E.R. 332 resin assures uniform performance and exceptionally low viscosity and color. Under some conditions of cure, as illustrated in the cure schedule and property data (pages 19-29), it gives improved elevated temperature properties.

D.E.R. 332 resin frequently crystallizes at room temperature. The pure diglycidyl ether of bisphenol-A is a solid with a melting point of approximately 42°C (108°F). Crystallization may be induced by chilling, seeding by dust particles, or incorporation of filler. Warming to 50-55°C (122-131°F) restores the resin to a liquid state. Long term warm storage may result in slight discoloration but does not affect resin usefulness.

D.E.R. 333 Epoxy Resin

A precatalyzed liquid resin designed to have selective reactivity with bisphenol-A to permit practical manufacture of typical solid resins used in the coatings industry. Resins prepared from D.E.R. 333 have excellent stability, color, pigment wetting, and other physical and chemical properties typical of the best solid epoxy resins commercially available. D.E.R. 333 resin offers the resin chemist an opportunity to develop specific resins for specific end uses.

D.E.R. 337 Epoxy Resin

An intermediate epoxide equivalent weight bisphenol-A semi-solid epoxy resin. Used in adhesives and coatings, or as a modifier for other epoxy resins to improve impact strength, extensibility, and adhesion.

TABLE 1—Typical Properties of Dow Liquid Epoxy Resins

D.E.R. 317	192-203	16,000-25,000	5	310	1.16	9.7
D.E.R. 330	177-188	7,000-10,000	3	270	1.16	9.7
D.E.R. 331	182-190	11,000-14,000	3	275	1.16	9.7
D.E.R. 332	172-176	4,000-6,000	1	340	1.16	9.7
D.E.R. 333	192-197	2,300-4,600	3	136	1.15	9.6
D.E.R. 337	230-250	400-800[2]	3	290	1.16	9.7

[1] Typical properties; not to be construed as specifications.
[2] 70% non-volatile in DOWANOL* DB solvent.
[3] Pensky-Martin, ASTM D-93.
* Trademark of The Dow Chemical Company.

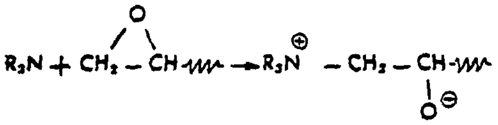
TABLE 4 — Anhydrides

NADIC Methyl Anhydride (NMA)	60-90[1]	2 hrs at 90°C + 4 hrs at 165°C + 16 hrs at 200°C	National Aniline Div. Allied Chemical Co.	Liquid anhydride having long pot life at room temp. Excellent elevated temp. properties
Hexahydrophthalic anhydride (HHPA)	60-75[1]	2 hrs at 100°C + 2-6 hrs at 150°C	National Aniline	Low melting point solid, approx. 35°C, soluble in liquid resin at room temp. Used in potting, filament windings, and clear castings.
HET anhydride	90-110	24 hrs at 150-180°C	Hooker Chemical Corp.	High melting point, 239°C solid anhydride containing chlorine. Short pot life at solution temp. Used in laminates, etc. for fire retardance. Eutectic mixtures can be made with HHPA.
Dodecenyl succinic anhydride (DDSA)	95-130[1]	2 hrs at 100°C + 4-6 hrs at 150°C	National Aniline	Liquid anhydride. Imparts flexibility to cured composition.
Phthalic anhydride (PA)	40-65	24 hrs at 120°C or 8 hrs at 150°C	Many	Solid anhydride with melting point 128°C. Low exotherm and long pot life. Used in large encapsulations.
Alkendic anhydride	95-115[1]	3 hrs at 100°C + 6 hrs at 140°C	Amchem Products, Inc.	Liquid anhydride with low vapor pressure and minimum fuming. Good elevated temperature properties.
Tetrahydrophthalic anhydride (THPA)	60-75[1]	24 hrs at 120°C or 8 hrs at 150°C	National Aniline	Solid anhydride with melting point of 100°C. Similar to hexahydrophthalic anhydride in cured resin properties. Used in pottings and encapsulations.

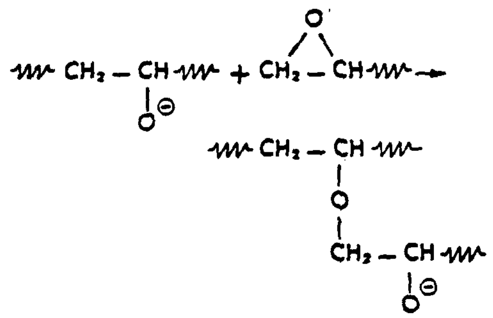
[1] Plus suitable accelerator.

Catalytic curing agents are those compounds that *promote epoxy-to-epoxy* or epoxy-to-hydroxyl reactions and do not themselves serve as direct crosslinking agents. Tertiary amines, amine salts, boron trifluoride complexes, and amine borates are in this class. The mechanism of epoxy-to-epoxy polymerization using a tertiary amine catalyst (or other catalytic curing agent) theoretically takes place as follows:

1. Opening of the epoxy group:



2. *The ion thus formed is capable of* opening another epoxy group:



This continues until a dense cross-linked structure containing the stable ether linkages is formed.

This oversimplified explanation does not *consider the* hydroxyl groups either present in the higher weight resin homologs or introduced by resin modifiers and curing agents. While the steps of the epoxy-hydroxyl reaction differ, the end structure is very similar to that postulated for the epoxy-epoxy *reaction. Pot life is moderate* (2 to 24 hours) for tertiary amine and amine salts, and is very long, up to several months, for the latent catalysts such as BF_3• MEA complex or dicyandiamide. The latent catalysts depend on dissociation by heat with the dissociation products capable of initiating epoxy cures.

The amount of catalyst used may vary from 2 to 10 phr. The *specific amount for a given system should be determined experimentally to develop the optimum in properties desired.* Tertiary amine catalysts are used in small amounts to accelerate the cure of anhydride-epoxy or aromatic amine-epoxy combinations, and they are also used in conjunction with latent catalysts to attain various degrees of B-staging.

TABLE 6—Catalytic Curing Agents

Benzyldimethylamine (BDMA)	**Maumee Chemical Company**
BF_3 monoethylamine (BF_3 • MEA)	**Harshaw Chemical Company**
	General Chemicals Div., Allied Chemical Corporation
Dicyandimide (DICY)	**American Cyanamid Company**
Dimethyl aminomethyl phenol (DMP-10)	**Rohm & Haas Company**
Tridimethyl aminomethyl phenol (DMP-30)	**Rohm & Haas Company**
Alpha methylbenzyl dimethylamine	**Union Carbide Corporation**
DB VIII	**Argus Chemical Corporation**

prene), portable storage tanks (neoprene, HYPALON*), and nonstick conveyor belting (TEFLON, silicone). In the latter application, the greater durability of the fabric of KEVLAR* coated with TEFLON* TFE Fluorocarbon compared with the similarly-coated glass fabric (Table X) results in longer life belts, with less downtime for belt replacement.

PRODUCT FORMS

KEVLAR 49 aramid is supplied by Du Pont as yarns and rovings (Table XI), while a variety of balanced and unidirectional fabrics and woven roving are available from commercial weavers. Specific product descriptions are included in the current price list available on request. In addition, detailed information is available on the use of KEVLAR 49 in specific applications.

*Du Pont registered trademark

TABLE XI

YARNS† AND ROVINGS†† OF KEVLAR® 49 ARAMID

Denier	Decitex*	Yield (yd/lb)**	Yield m/kg	Filaments	Twist
195†	215	22.895	46 155	134	0
380†	420	11.749	23 684	267	0
1140†	1270	3.916	7895	768	0
1420†	1580	3.144	6338	1000	0
2130†	2370	2.096	4225	1000	0
4560††	5100	980	1973	3072	0
7100††	7900	630	1268	5000	0

*Values rounded by Du Pont Textile Fibers Standard Conversion Method
**Based on actual deniers

APPENDIX

REFERENCES

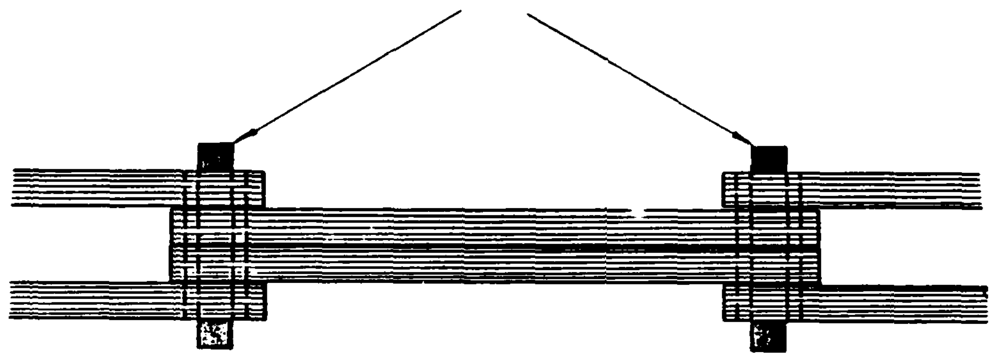
1. Moore, J. W., "Applications of PRD-49 Fibers", presented to the 27th Annual SPI Meeting, Washington, D.C., Feb. 8-11, 1972.
2. Sturgeon, D. L. G., "PRD-49 High Modulus Organic Fibers for Aluminum Replacement", presented to an Aerospace Industry Seminar in London, September 7, 1972.
3. Miner, L. H., et al., "Fatigue, Creep, and Impact Resistance of KEVLAR* 49 Reinforced Composites", presented at ASTM Composite Reliability Conference, Las Vegas, Nevada, April 15-16, 1974.
4. Wolffe, R. A., "PRD-49 Composites for Aerospace Applications", presented to an Aerospace Industry Seminar in London, September 7, 1972.
5. Sturgeon, D. L. G., et al., "KEVLAR* 49 Composites for Sporting Goods and Recreational Equipment", presented to the 29th Annual SPI meeting, Washington, D.C., February, 1974.
6. Chiao, T. T., et al., "Stress-Rupture Behavior of Strands of an Organic Fiber Epoxy Matrix", presented to the American Society of Testing and Materials Third Symposium on Composite Materials, Williamsburg, Virginia, March, 1973.

*Du Pont registered trademark

APPENDIX C

RACETRACK AND FIBER LINK ELEMENT DESIGN DRAWINGS

See Drawings, Engineering and Associated Lists for Racetrack and Fiber Link Element Design Drawings.

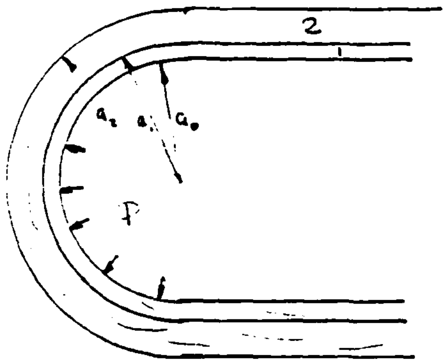


ASSEMBLY OF RACETRACK TENSILE MEMBER

APPENDIX D

HOOP STRESS PROGRAM

EQUATIONS USED TO LOOK AT HOOP STRESSES IN THE ATTACHMENT LOOP OF THE COMPOSITE TENSILE MEMBER



(1) low modulus graphite

(2) high modulus graphite

Assume the pin reaction force acts as a distributed pressure on the internal surface of the loop and the loop itself behaves mechanically like two orthotropic rings, one inside the other. The equation for the hoop stress (σ_θ) in an orthotropic ring with an internal and an external pressure is given by:

$$\sigma_\theta = \frac{p c^{k+1} - q}{1 - c^{2k}} k \left(\frac{r}{b}\right)^{k-1} + \frac{p - q c^{k-1}}{1 - c^{2k}} k c^{k+1} \left(\frac{b}{r}\right)^{k+1} \quad (1)$$

where p = internal pressure

q = external pressure

c = inside radius ÷ outside radius

r = radius, independent variable

b = outside radius

$k = \sqrt{\frac{E_\theta}{E_R}}$

E_θ = hoop modulus

E_R = radial modulus

The equation for the radial displacement of a point on a orthotropic ring is given by,

$$u_r = \frac{b}{E_\theta (1 - c^{2k})} \left[(p c^{k+1} - q)(k - \nu_\theta)\left(\frac{r}{b}\right)^k + (p - q c^{k-1}) c^{k+1} (k + \nu_\theta)\left(\frac{b}{r}\right)^k \right]$$

where ν_θ is Poisson's ratio for a stress in the direction.

To solve the problem of concentric orthotropic rings, equation (2) is written at all interfaces for adjoining rings. Using the condition that one ring moves as much as the other at their interface, the radial pressure one ring exerts on the other at the interface can be determined by equating

$u_{r_1} = u_{r_2}$ for example

remembering to use the proper material constants (E_θ, k, ν) for each ring.

After the internal pressures are found at each interface, the stresses are obtained from equation (1).

We have used the attached Fortran program to solve up to four concentric rings. This model breaks down somewhat at the point of tangency to the straight portion due to shear stresses ($\tau_{r\theta}$) which exist there. For the ring model, $\tau_{r\theta} = 0$.

```
C  STRESS
C
C  MICHAEL J. EDWARDS          12/2/82
C
C  THIS PROGRAM ANALYSES THE STRESS DISTRIBUTION IN A COMPOSITE
C  CURVILINEAR ANISOTROPIC RING.  THIS PLATE IS MADE UP OF 2 TO 10 RINGS.
C  THE RINGS ARE RIGIDLY CONNECTED ALONG THIER CONTACT SURFACES.
C
C
      COMMON/DAT/NRINGS,ER,ET,V,SRAD,STAN,DRAD,P,RADIUS,PNT
      REAL MAT(10,10),B(10),ANS(10),PNT(10,10),ER(10),ET(10),V(10)
      REAL SRAD(10,10),STAN(10,10),DRAD(10,10),P(11),RADIUS(11)
      REAL TEMP2(10),ALPHA(10),BETA(10),C(10),K(10),TEMPA(10),TEMPB(10)
      INTEGER ERR
C
C INITIALIZE VARIABLES
C
200   DO 60 I=1,10
         DO 70 J=1,10
70          MAT(I,J)=0.
60       B(I)=0.
      CALL INDAT
C
C CALCULATE CONSTANTS
C
      DO 10 I=1,NRINGS
         C(I)=RADIUS(I)/RADIUS(I+1)
         K(I)=SQRT(ET(I)/ER(I))
         TEMP1=C(I)**(2.*K(I))
         TEMP2(I)=1.-TEMP1
         TEMP3=1.+TEMP1
         ALPHA(I)=2.*K(I)*C(I)**K(I)/(ET(I)*TEMP2(I))
         TEMPA(I)=(V(I)-K(I)*TEMP3/TEMP2(I))/ET(I)
10       TEMPB(I)=(V(I)+K(I)*TEMP3/TEMP2(I))/ET(I)
      DO 20 I=1,NRINGS-1
20       BETA(I)=TEMPA(I)-TEMPB(I+1)
C
C CHECK NUMBER OF RINGS FOR SPECIAL CASES
C
      IF(NRINGS-3)1,2,2
C
C CASE OF ONLY 2 RINGS.  (ONE EQUATION)
C
1     P(2)=(-RADIUS(1)*ALPHA(1)*P(1)-RADIUS(3)*ALPHA(2)*P(3))
     1     /(RADIUS(2)*BETA(1))
      GOTO 4
C
C CASE OF 3 OR MORE RINGS
C
2     MAT(1,NRINGS-1)=RADIUS(2)*BETA(1)
      MAT(1,NRINGS-2)=RADIUS(3)*ALPHA(2)
      IF(NRINGS.EQ.3)GOTO 3
      DO 30 I=2,NRINGS-2
         MAT(I,NRINGS-I+1)=RADIUS(I)*ALPHA(I)
         MAT(I,NRINGS-I)=RADIUS(I+1)*BETA(I)
30       MAT(I,NRINGS-I-1)=RADIUS(I+2)*ALPHA(I+1)
3     MAT(NRINGS-1,1)=RADIUS(NRINGS)*BETA(NRINGS-1)
      MAT(NRINGS-1,2)=RADIUS(NRINGS-1)*ALPHA(NRINGS-1)
      B(1)=-P(1)*RADIUS(1)*ALPHA(1)
      B(NRINGS-1)=-P(NRINGS+1)*RADIUS(NRINGS+1)*ALPHA(NRINGS)
C  ***********************************************************
```

```
C
      TYPE 'EQUATION AND VALUE BEING PASSED.'
      TYPE 'FORM OF X1 X2 X3 ... X(N-1) VALUE'
      DO 269 I=1,NRINGS-1
269      WRITE(10,369)(MAT(I,J),J=1,NRINGS-1),B(I)
369      FORMAT(8(E10.4))
      PAUSE 'PRESS CR TO CONTINUE.'
C
C  ************************************************************
      CALL SIMEQ(MAT,B,NRINGS-1,ANS,ERR)
      DO 30 I=1,NRINGS-1
30       P(I+1)=ANS(NRINGS-3)
C  ************************************************************
C
C  PRINT CALCULATED VALUES (THE P'S)
C
      DO 469 I=1,NRINGS+1
469      WRITE(10,569)I,P(I)
569      FORMAT('PRESSURE #',I2,' IS ',F9.2,' (PSI)')
      PAUSE 'PRESS CR KEY TO CONTINUE'
C
C  ************************************************************
      IF(ERR.NE.1)GOTO 4
      WRITE(10,102)
      WRITE(10,102)
      WRITE(10,100)
100   FORMAT('ERROR IN SOLUTION OF SIMULTANEOUS EQUATIONS.',
     1        '  GET HELP FAST.')
      WRITE(10,101)
101   FORMAT(' EXECUTION ENDS!!!')
      STOP
C
C  CALCULATE TEST POINTS.  (STRESS/DISPLACEMENT)
C
4     DO 40 I=1,NRINGS
         THICK=RADIUS(I+1)-RADIUS(I)
         SPACE=THICK/9.
         PNT(I,1)=RADIUS(I)+SPACE/1000.
         PNT(I,10)=RADIUS(I+1)-SPACE/1000.
         DO 40 J=2,9
40          PNT(I,J)=RADIUS(I)+(J-1.)*SPACE
C
C  CALCULATE STRESS/DISPLACEMENT
C
      DO 50 I=1,NRINGS
         T1=K(I)+1
         T2=K(I)-1
         T3=C(I)**(2.*K(I))
         T4=P(I)*C(I)**T1
         T5=T4*K(I)
         T8=K(I)-V(I)
         T9=K(I)+V(I)
         T12=RADIUS(I+1)/(ET(I)*TEMP2(I))
         DO 50 J=1,10
            T6=(PNT(I,J)/RADIUS(I+1))**T2
            T7=(RADIUS(I+1)/PNT(I,J))**T1
            SRAD(I,J)=T4/TEMP2(I)*(T6-T7)+P(I+1)/TEMP2(I)*(T3*T7-T6)
            STAN(I,J)=T4*K(I)/TEMP2(I)*(T6+T7)-P(I+1)*K(I)
     1               /TEMP2(I)*(T3*T7+T6)
            T10=(PNT(I,J)/RADIUS(I+1))**K(I)
            T11=(RADIUS(I+1)/PNT(I,J))**K(I)
```

```
300   CALL OUTDAT
9      WRITE(10,102)
102   FORMAT(' ')
      WRITE(10,102)
5     WRITE(10,103)
103   FORMAT(' SELECT OPTION (AS AN INTEGER).')
      WRITE(10,104)
104   FORMAT(' (1) ENTER NEW DATA AND RERUN PROGRAM.')
      WRITE(10,105)
105   FORMAT(' (2) VIEW PROGRAM RESULTS AGAIN.')
      WRITE(10,106)
106   FORMAT(' (3) PRINT PROGRAM RESULTS (HARD COPY).')
      WRITE(10,107)
107   FORMAT(' (4) QUIT PROGAM.')
      READ FREE(11,ERR=6) I
      IF(I.GE.1.AND.I.LE.4)GOTO 7
6     WRITE(10,102)
      WRITE(10,108)
108   FORMAT(' ERROR IN INPUT.  TRY AGAIN.')
      GOTO 5
7     GOTO (200,300,400,500),I
400   WRITE(10,102)
      WRITE(10,109)
109   FORMAT(' CALL THE COMPUTER ROOM (#369) AND',
     1       ' CHECK IF IT IS OK TO PRINT.')
      WRITE(10,110)
110   FORMAT(' PRESS THE CR KEY WHEN IT IS OK TO PRINT.')
      READ (11,69)I
69    FORMAT(A1)
      CALL PRINTDAT
      GOTO 9
500   STOP
      END
```

APPENDIX E

TEST REPORT

FINAL REPORT

on

TESTS OF FIBER COMPOSITE TENSILE ELEMENTS

to

FIBER MATERIALS INCORPORATED
Biddeford, Maine
Purchase Order 28120

December 30, 1982

Report No. 327

By

Philip T. Gibson

TENSION MEMBER TECHNOLOGY
15202 Pipeline Lane
Huntington Beach, CA 92649
(714) 898-5641

TESTS OF FIBER COMPOSITE TENSILE ELEMENTS

By

Philip T. Gibson
Tension Member Technology

INTRODUCTION

This report describes the results of a series of tensile tests conducted on one fiber link and two race-track elements provided to TMT by Fiber Materials Incorporated. The elongation versus tension characteristics of these specimens were measured both during static proof load tests and at predetermined intervals during cyclic-tension fatigue tests. Finally, one of the race-track elements was pulled to determine its maximum breaking load.

TEST APPARATUS AND PROCEDURES

All tests were conducted on a horizontal machine using a hydraulic tensioning ram and a strain gauge load cell having a calibration traceable to the National Bureau of Standards. This machine has a maximum load capacity of 400,000 pounds.

Each specimen was mounted in the machine using loading pins provided by FMI. The test fixture was configured so that these pins were loaded in double shear and experienced a minimum amount of bending.

Specimen elongation was monitored using a remote reading extensometer with the gauge points attached directly to the loading pins or, in the case of the fiber link element, to the aluminum insert at one end of the link. The outputs of the tension load cell and the extensometer were used to drive an X-Y plotter to provide a continuous trace of specimen elongation versus tension.

TESTS OF FIBER LINK

The fiber link was subjected to three proof load cycles to a maximum tension of 250,000 pounds. The elongation versus tension characteristics are presented in Figures 1, 2, and 3. In each case, the 250,000-pound proof load was maintained on the specimen for 10 minutes during each load cycle. This specimen exhibited no deterioration as a result of these proof load cycles.

TESTS OF RACE-TRACK ELEMENTS

Each of the two race-track elements was subjected to three proof load cycles to a maximum tension of 125,000 pounds. During each proof load cycle, the 125,000-pound tension load was held for a period of 10 minutes.

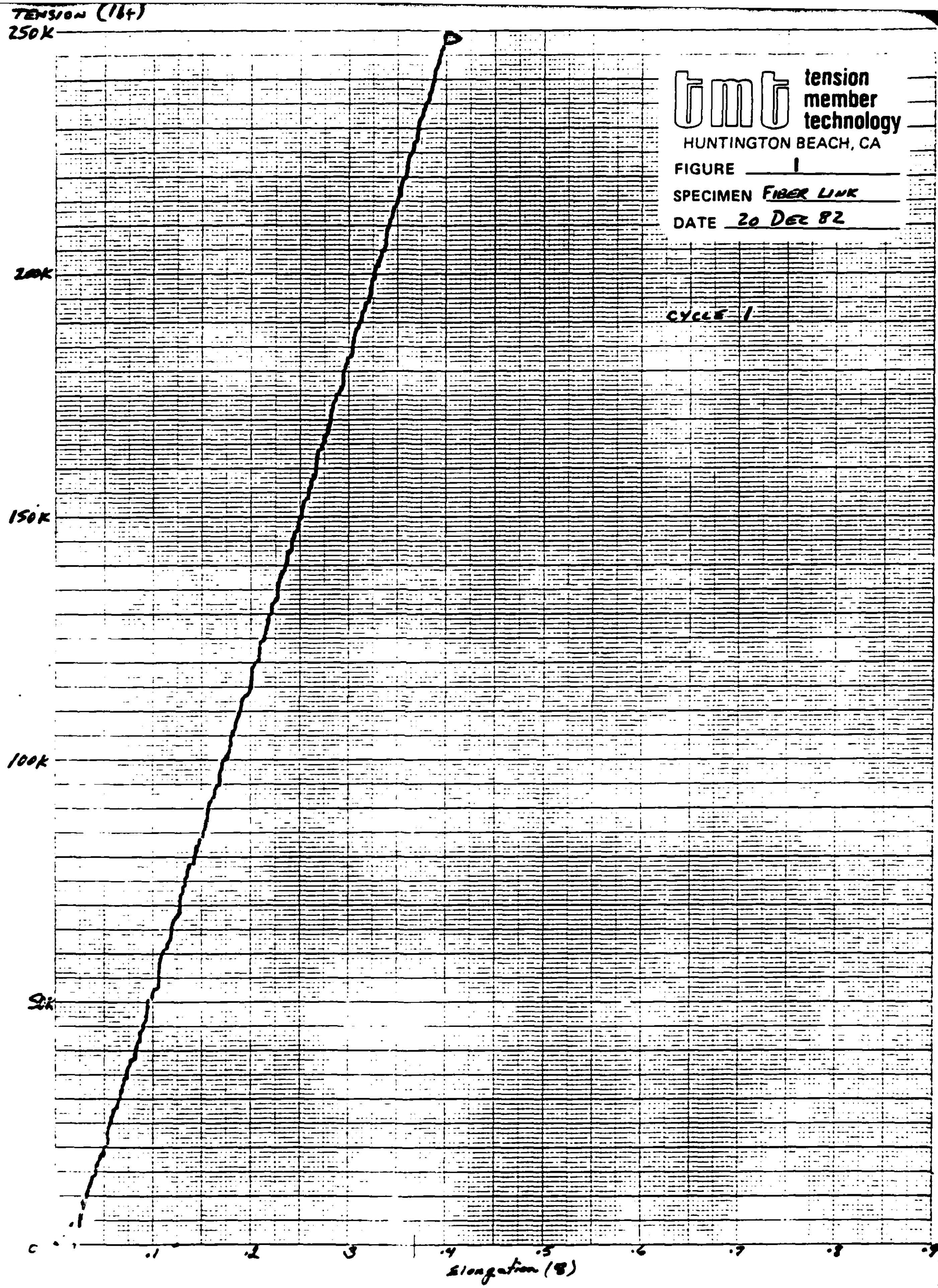
After the three proof load cycles, each specimen was subjected to 27,000 cyclic-tension fatigue cycles between a minimum tension of approximately 500 pounds and a maximum tension of 115,000 pounds. The elongation versus tension characteristics of these specimens were recorded periodically during the tests.

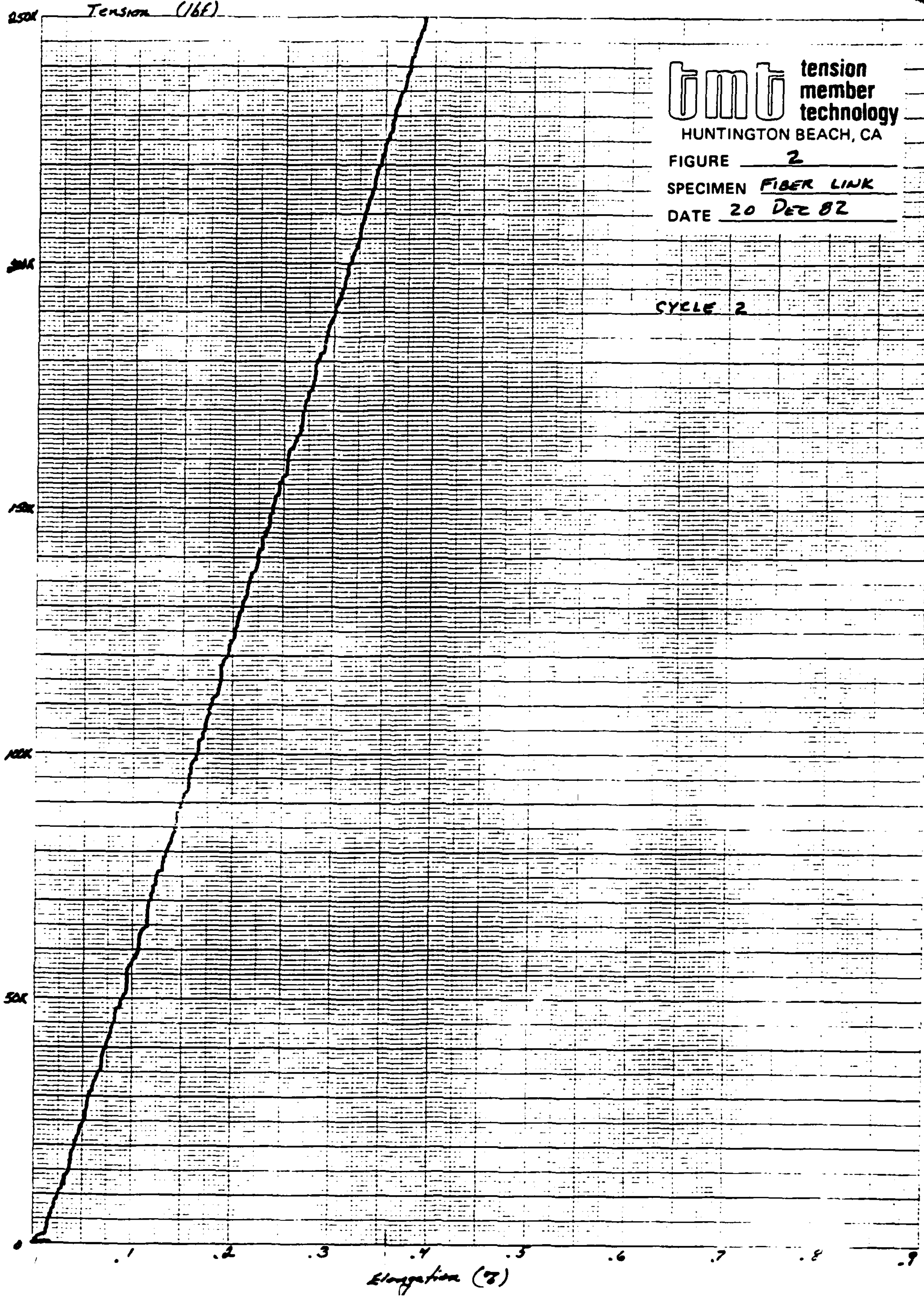
The test results for race-track specimen 1 are shown in Figures 4 through 10, and the test results for race-track specimen 2 are shown in Figures 11 through 14. Neither specimen exhibited any noticeable deterioration nor any change in the elongation versus tension characteristics.

Finally, race-trace specimen 2 was pulled to failure to determine the maximum breaking load. The elongation versus tension data recorded during this load cycle are shown in Figure 15. This specimen failed at a tension of 230,000 pounds and at a total elongation of 0.68 percent.

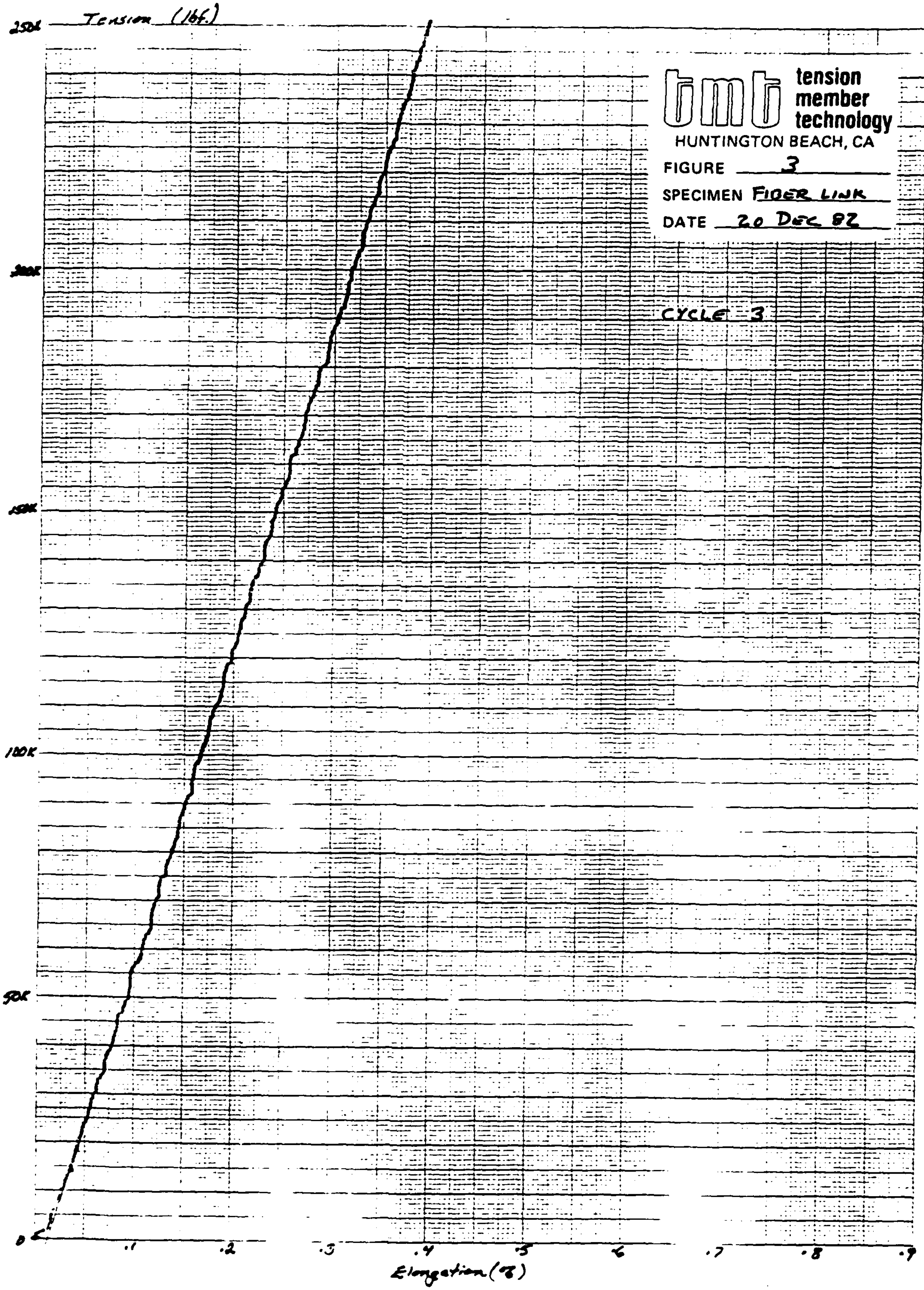
SUMMARY AND CONCLUSIONS

All three fiber composite tensile elements tested during this program survived the proof load and fatigue tests without apparent deterioration and without change in the elongation versus tension characteristics. The one race-track element which was pulled to failure exhibited a breaking load of 230,000 pounds after having been subjected to 27,000 tension fatigue cycles to a maximum tension of 115,000 pounds.

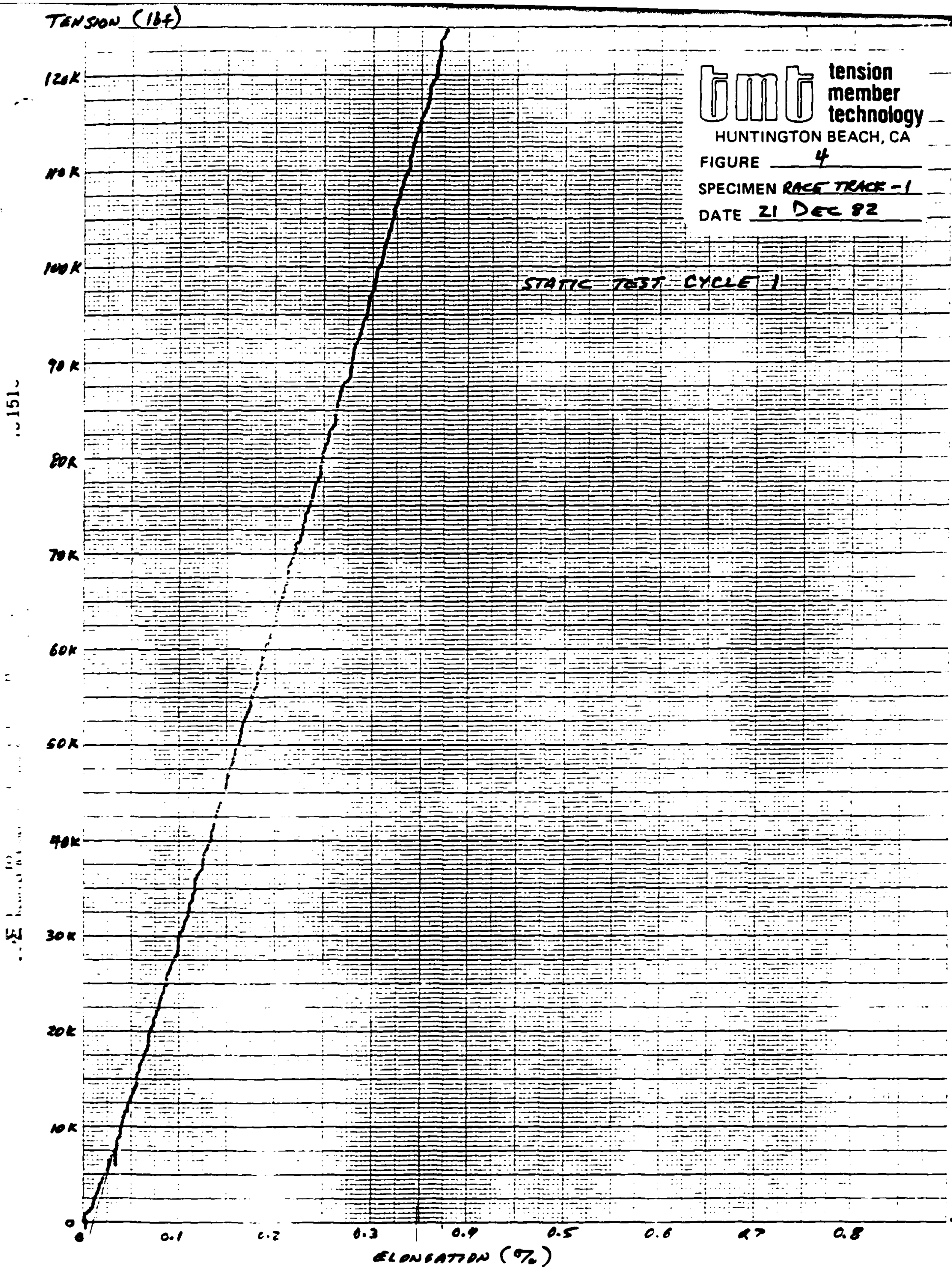

TENSION (lbf)
250K
200K
150K
100K
C
.1
.2
.3
.4
.5
.6
.7
.8
.9
Elongation (%)
tmt tension member technology
HUNTINGTON BEACH, CA
FIGURE 1
SPECIMEN FIBER LINK
DATE 20 DEC 82
CYCLE 1



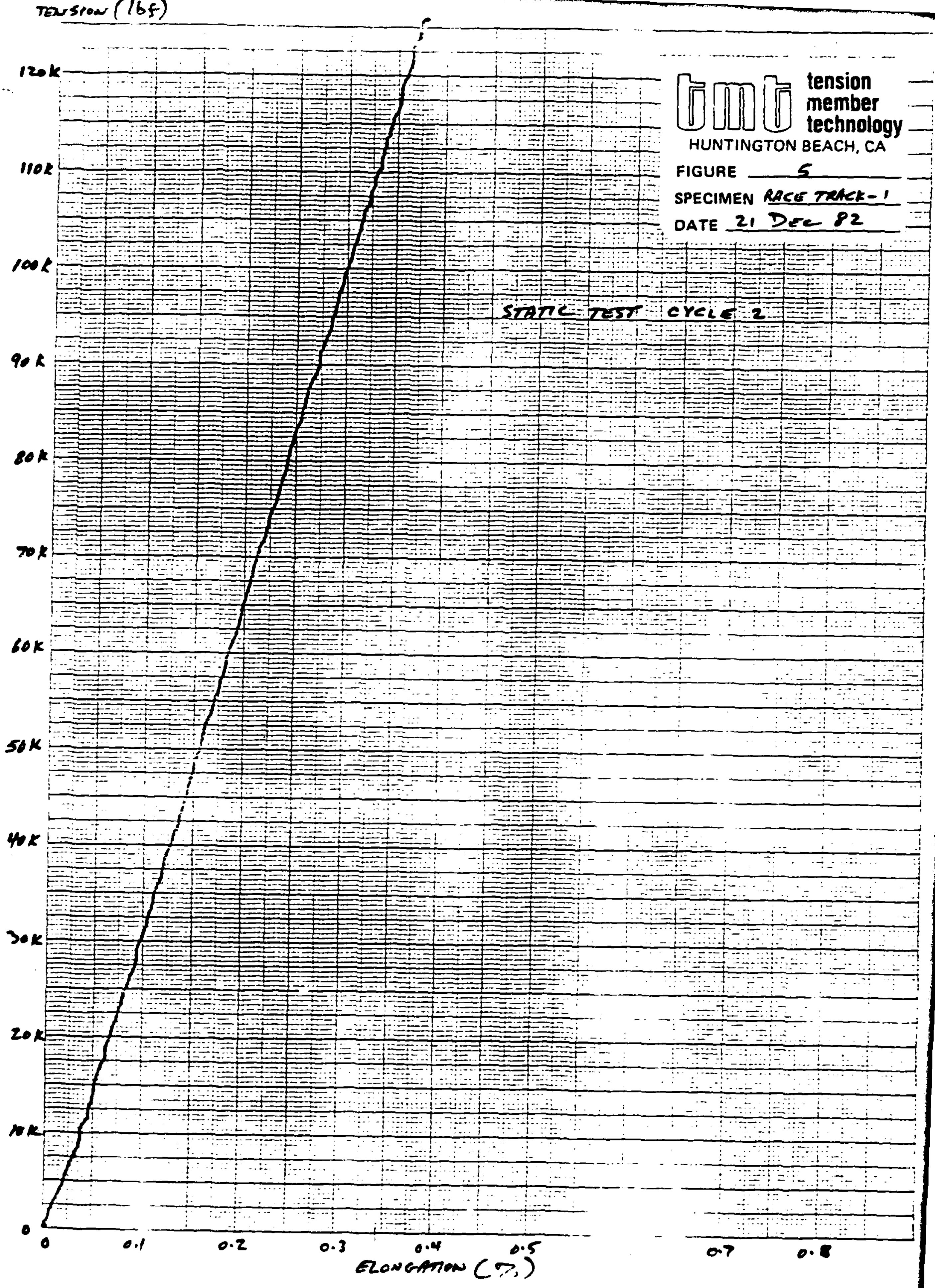
Tension (lbf)
250K
200K
150K
100K
50K
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
Elongation (%)
tmt tension member technology
HUNTINGTON BEACH, CA
FIGURE 2
SPECIMEN FIBER LINK
DATE 20 DEC 82
CYCLE 2



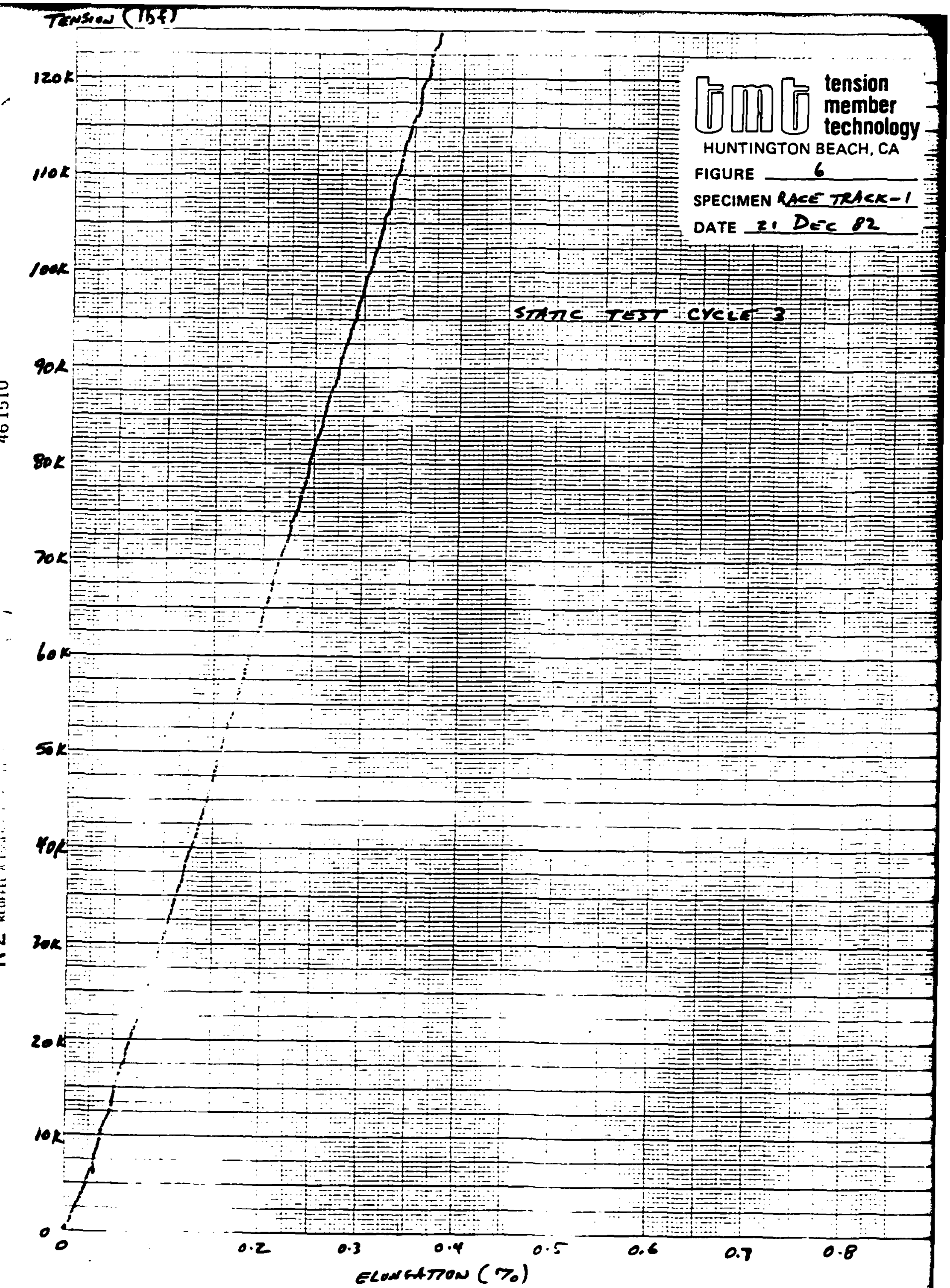
Tension (lbf)
250K
200K
150K
100K
50K
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
Elongation (%)
tension member technology
HUNTINGTON BEACH, CA
FIGURE 3
SPECIMEN FIBER LINK
DATE 20 DEC 82
CYCLE 3

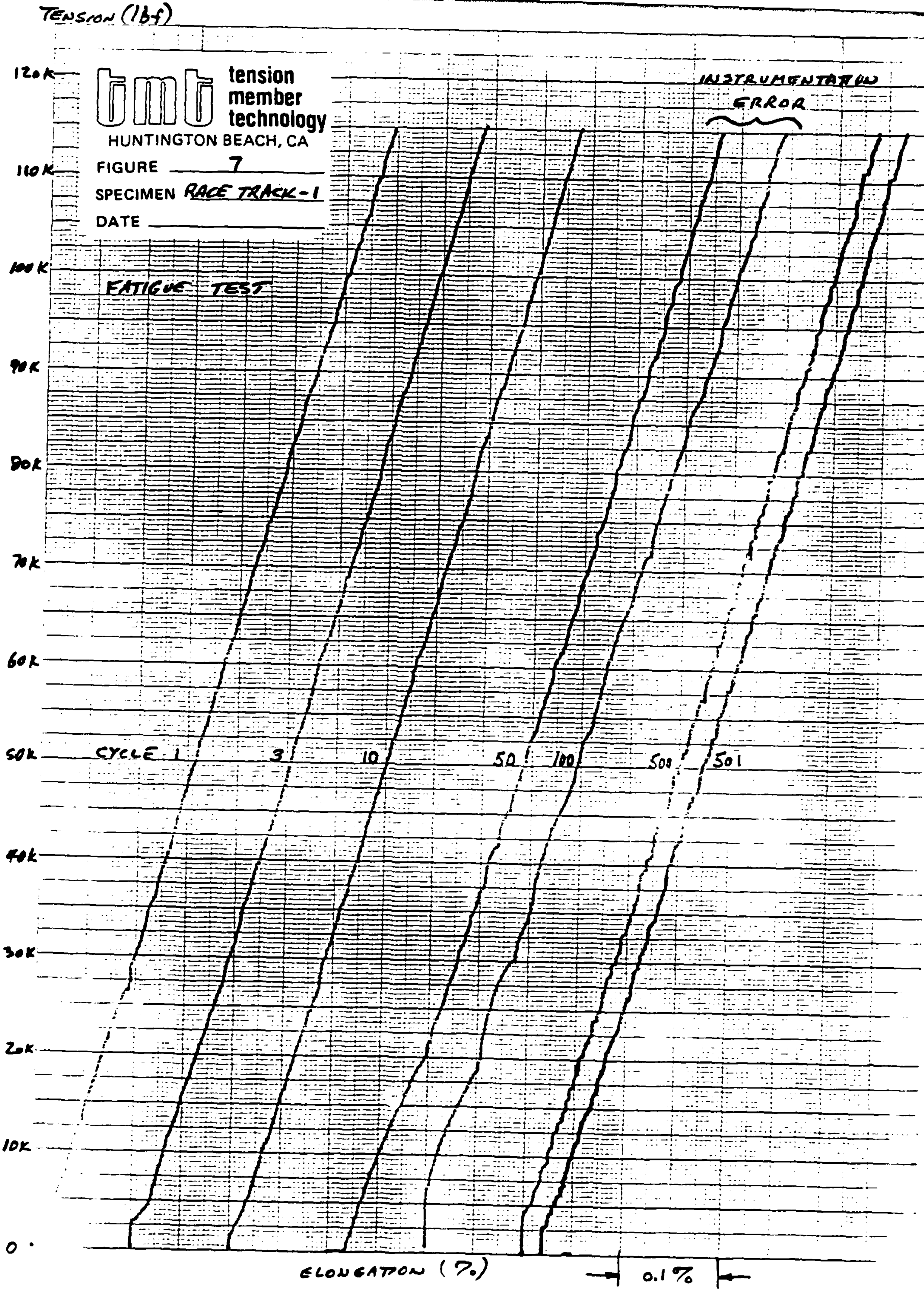


TENSION (lbf)
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
ELONGATION (%)
tmt tension member technology
HUNTINGTON BEACH, CA
FIGURE 4
SPECIMEN RACE TRACK - 1
DATE 21 DEC 82
STATIC TEST CYCLE 1

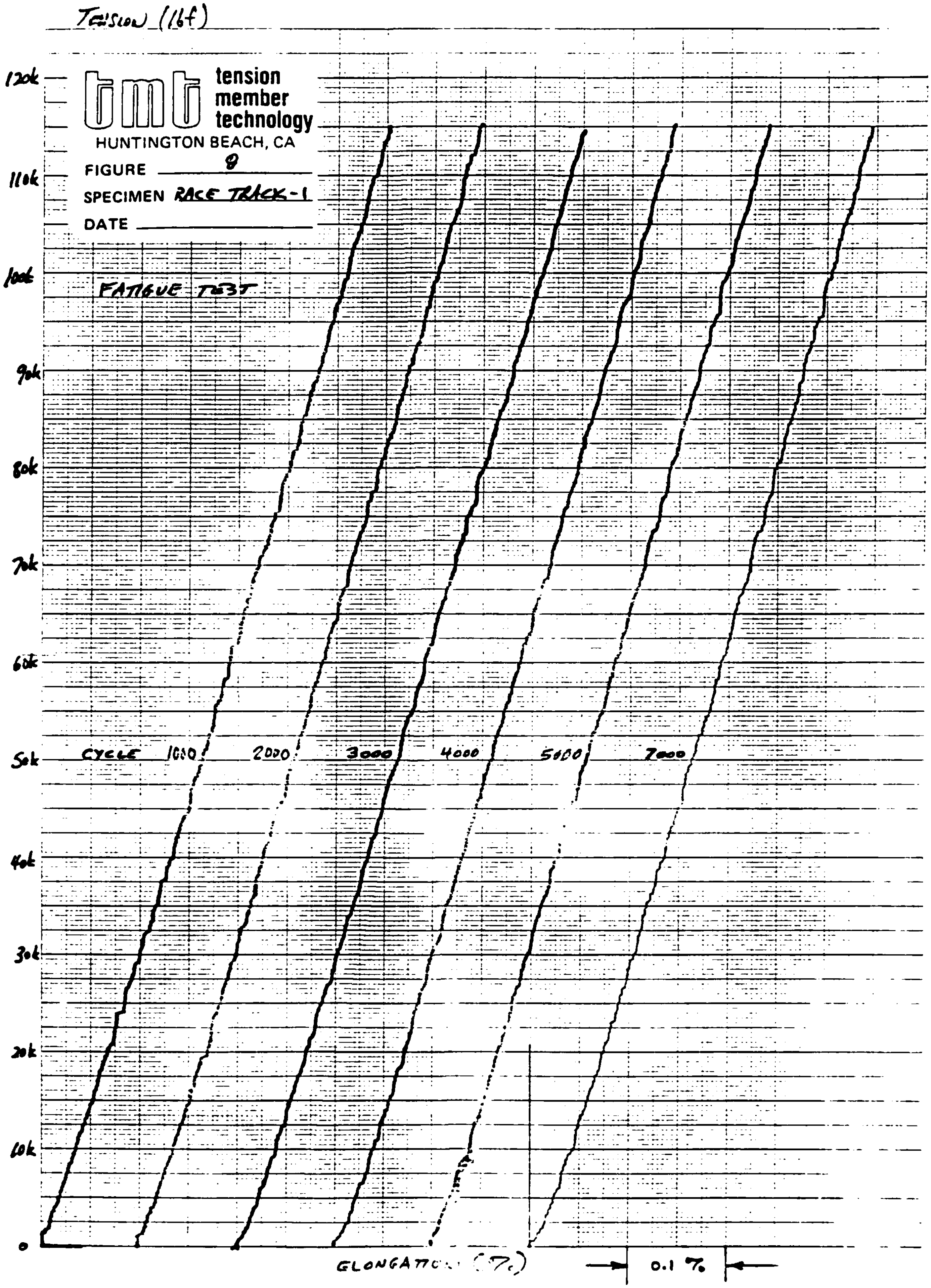

TENSION (lbf)
120k
110k
100k
90k
80k
70k
60K
50K
40K
30K
20K
10K
0
0
0.1
0.2
0.3
0.4
0.5
0.7
0.8
ELONGATION (%)
STATIC TEST CYCLE 2
tension member technology
HUNTINGTON BEACH, CA
FIGURE 5
SPECIMEN RACE TRACK-1
DATE 21 Dec 82

510

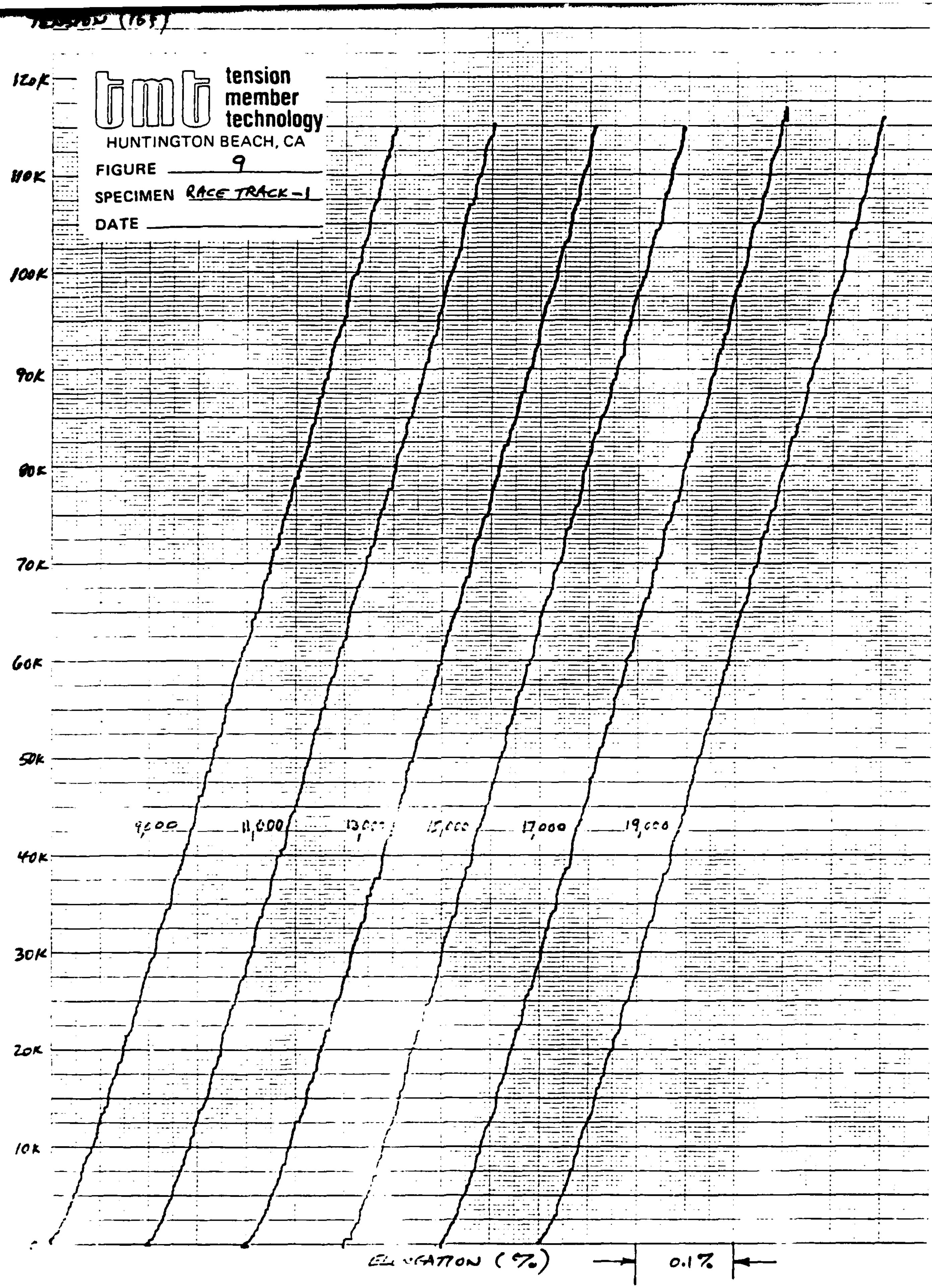

TENSION (lbf)
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
ELONGATION (%)
STATIC TEST CYCLE 3
tmt
tension member technology
HUNTINGTON BEACH, CA
FIGURE 6
SPECIMEN RACE TRACK-1
DATE 21 DEC 82

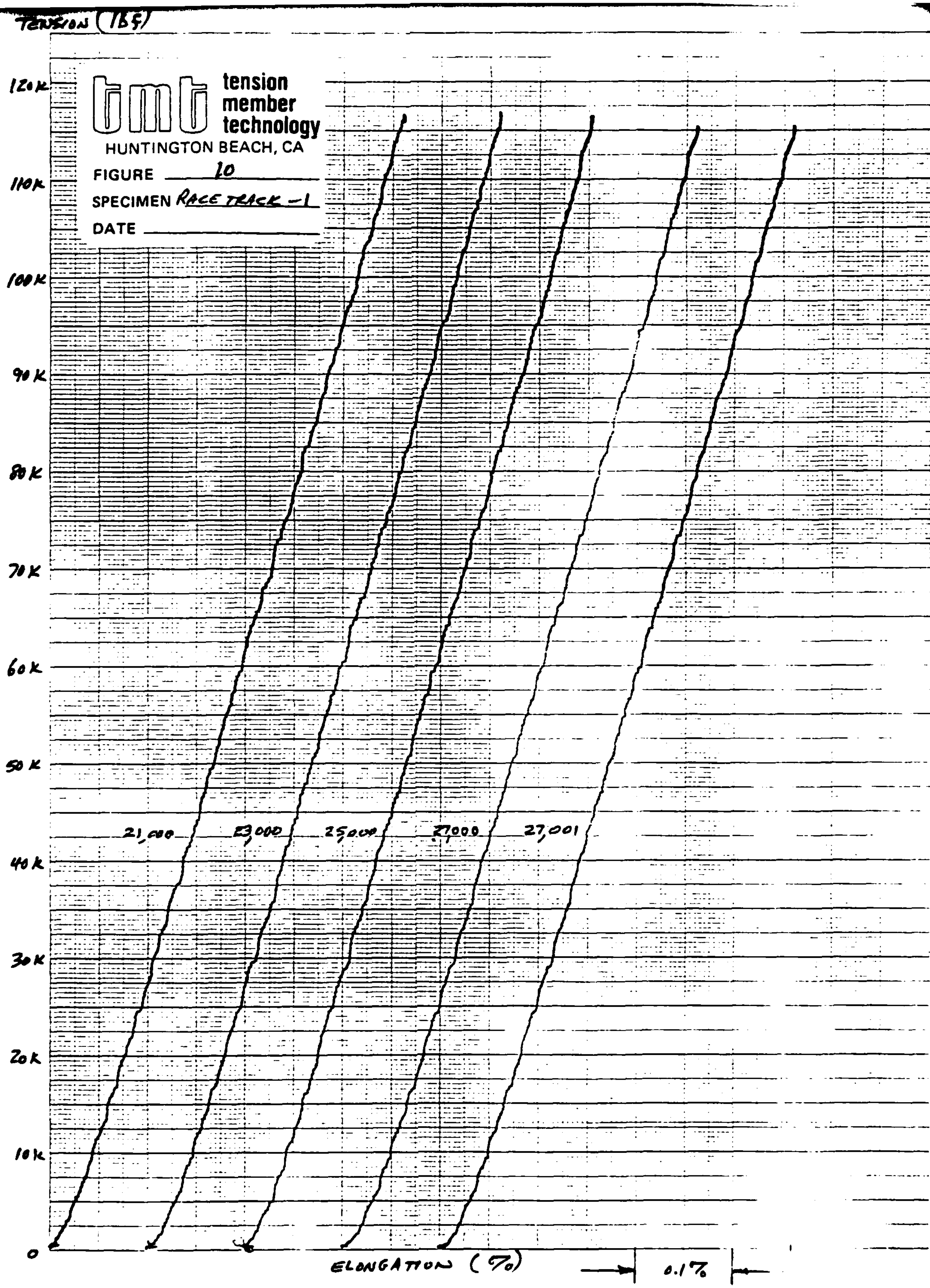


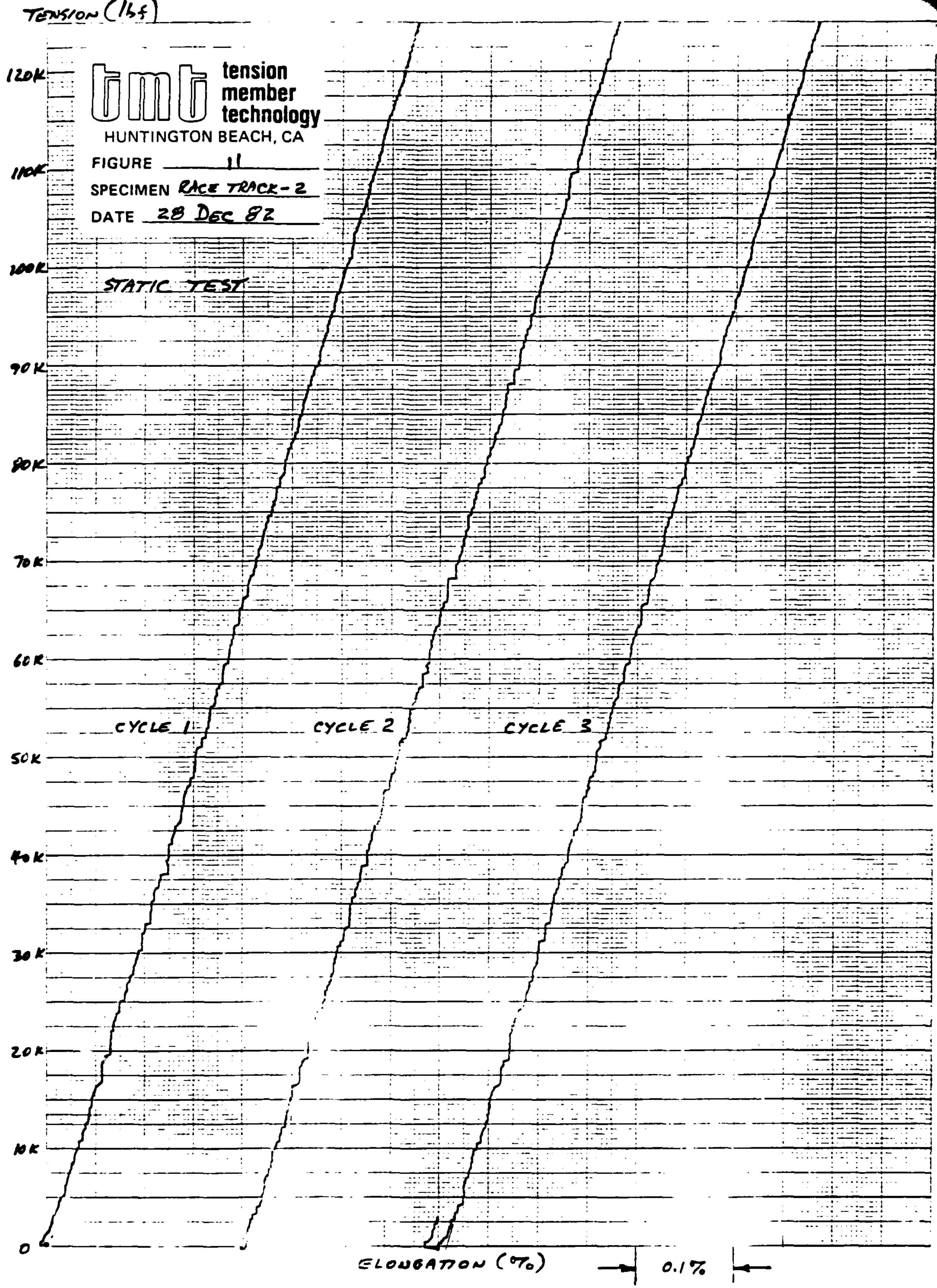
TENSION (lbf)
tension member technology
HUNTINGTON BEACH, CA
FIGURE 7
SPECIMEN RACE TRACK-1
DATE
FATIGUE TEST
INSTRUMENTATION ERROR
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
CYCLE 1
3
10
50
100
500
501
ELONGATION (%)
0.1%

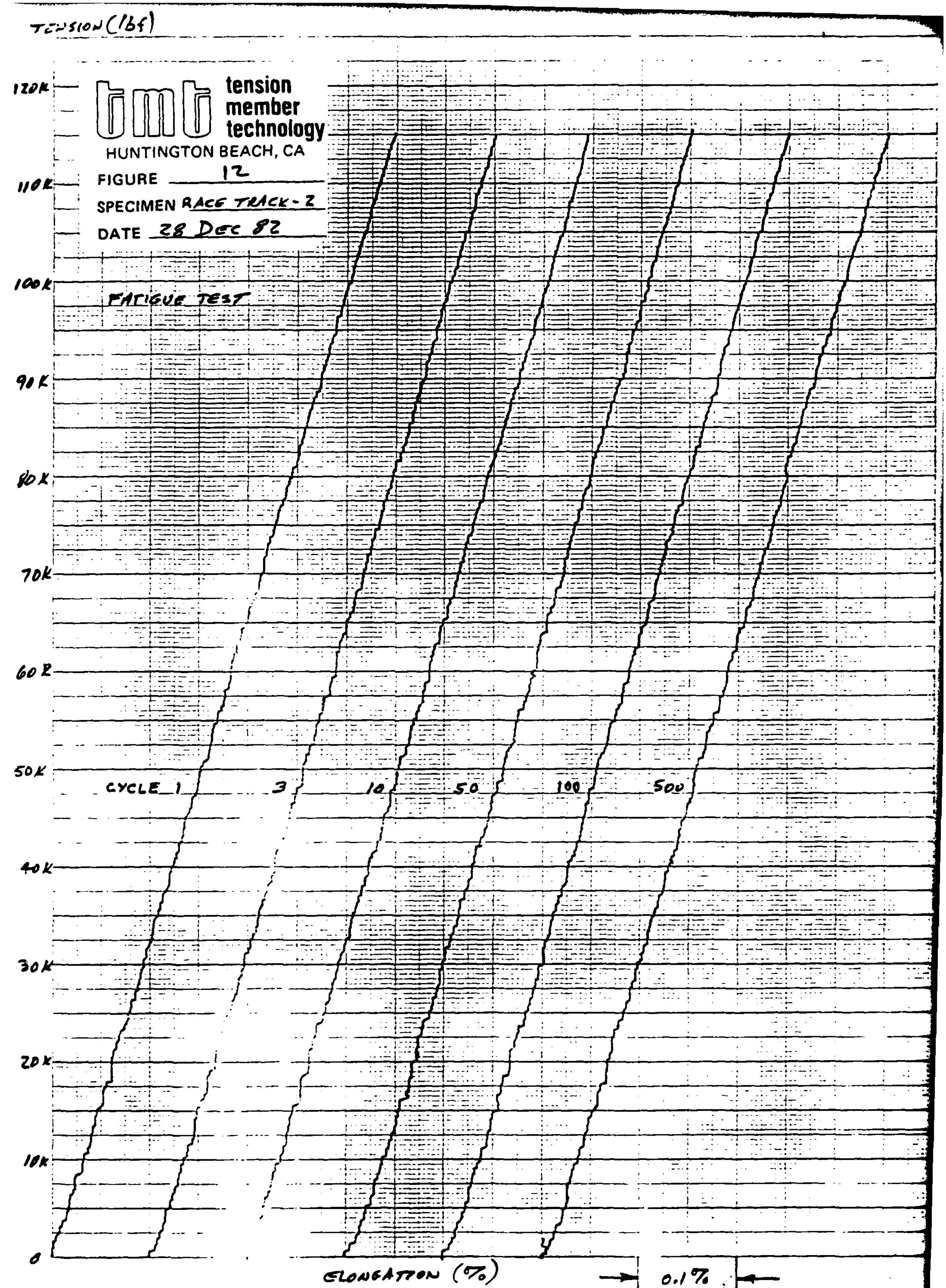


Tension (lbf)
tension
member
technology
HUNTINGTON BEACH, CA
FIGURE 8
SPECIMEN RACE TRACK-1
DATE
FATIGUE TEST
120k
110k
100k
90k
80k
70k
60k
50k
40k
30k
20k
10k
0
CYCLE 1000
2000
3000
4000
5000
7000
ELONGATION (%)
0.1 %

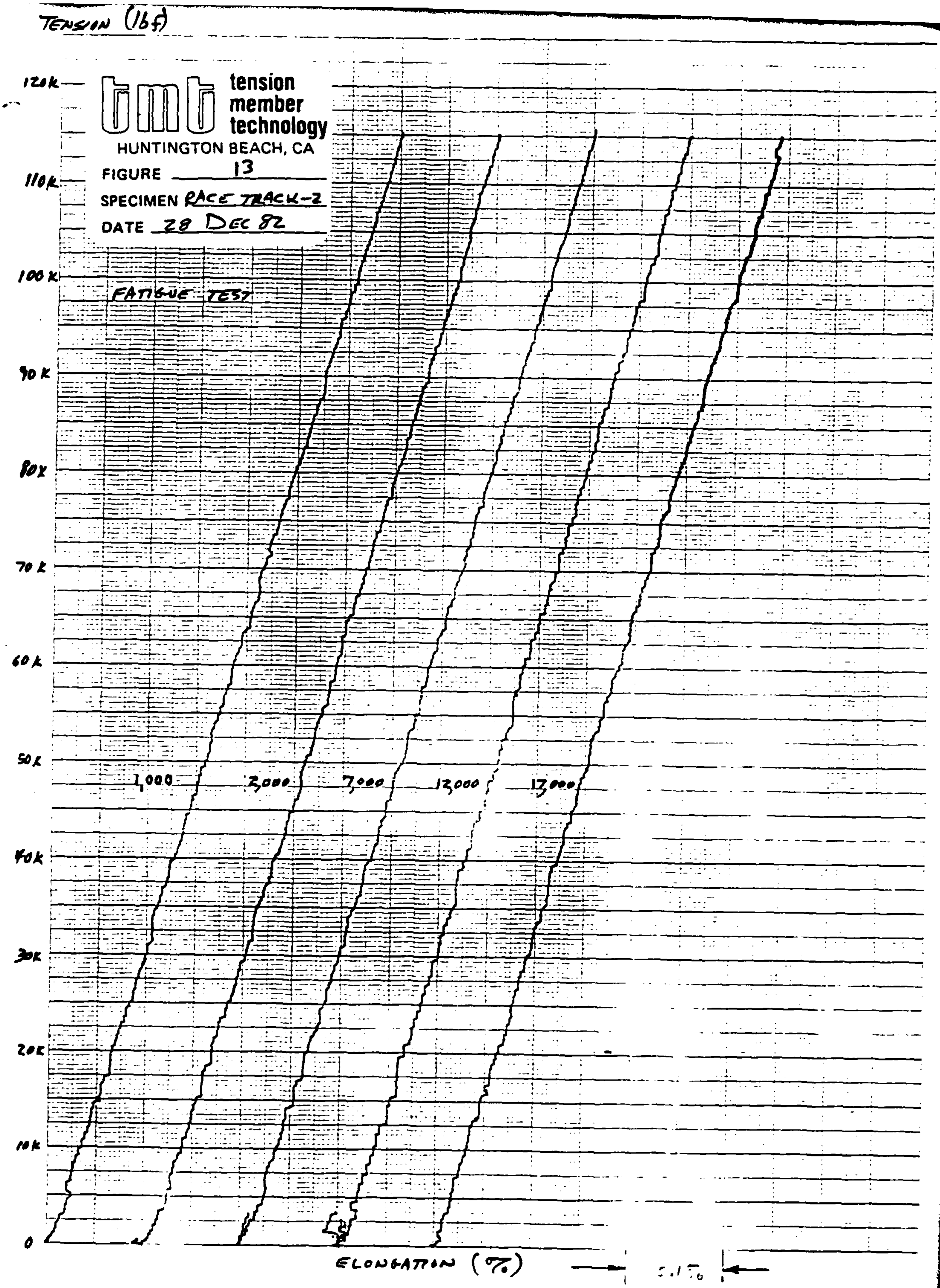

TENSION (lbs)
tension member technology
HUNTINGTON BEACH, CA
FIGURE 9
SPECIMEN RACE TRACK-1
DATE
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
9,000
11,000
13,000
15,000
17,000
19,000
ELONGATION (%)
0.1%


TENSION (LBS)
tension member technology
HUNTINGTON BEACH, CA
FIGURE 10
SPECIMEN RACE TRACK -1
DATE
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
21,000
23,000
25,000
27,000
27,001
ELONGATION (%)
0.1%

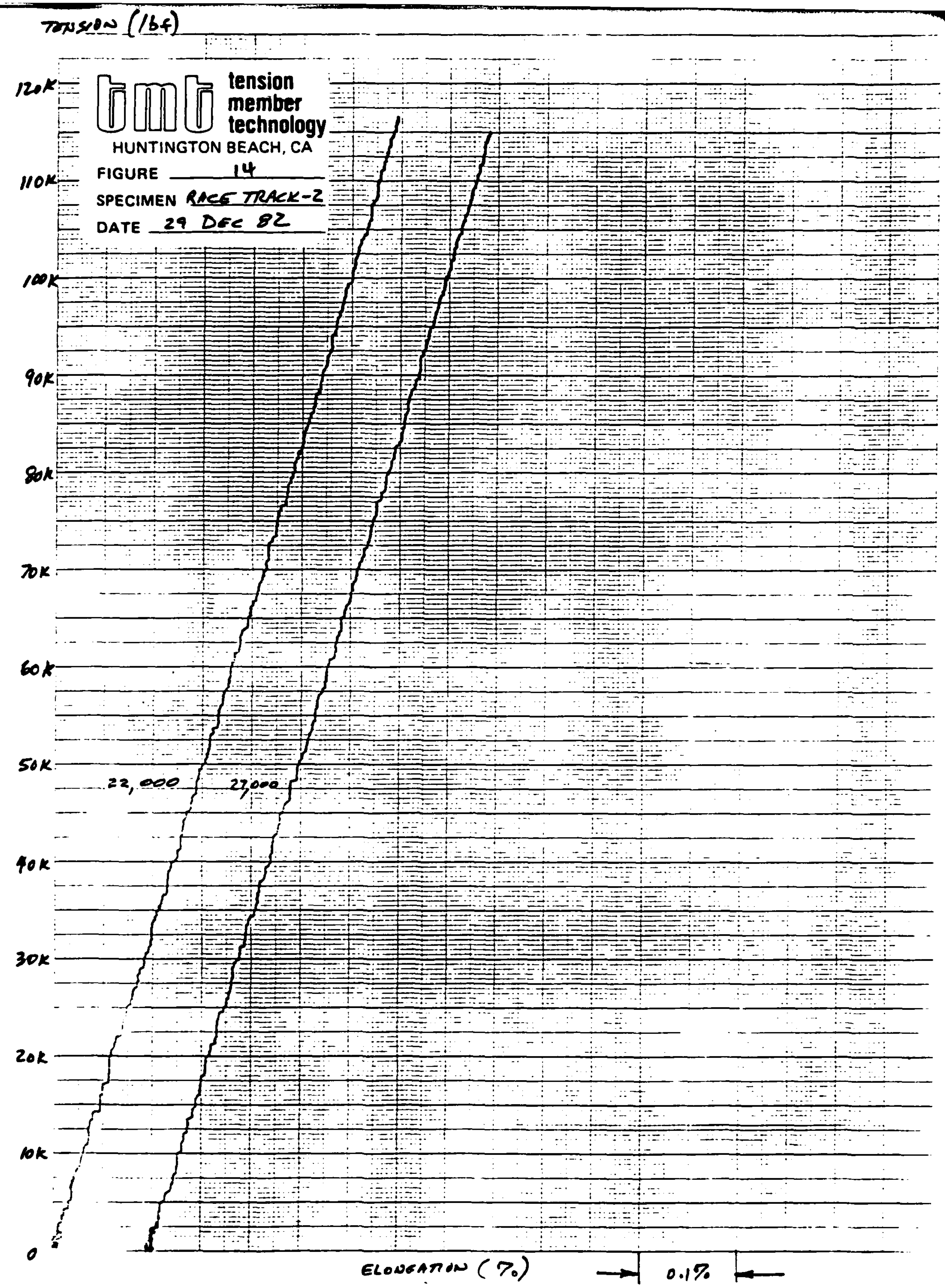

TENSION (lbf)
tmt
tension
member
technology
HUNTINGTON BEACH, CA
FIGURE 11
SPECIMEN RACE TRACK-2
DATE 28 DEC 82
STATIC TEST
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
CYCLE 1
CYCLE 2
CYCLE 3
ELONGATION (%)
0.1%

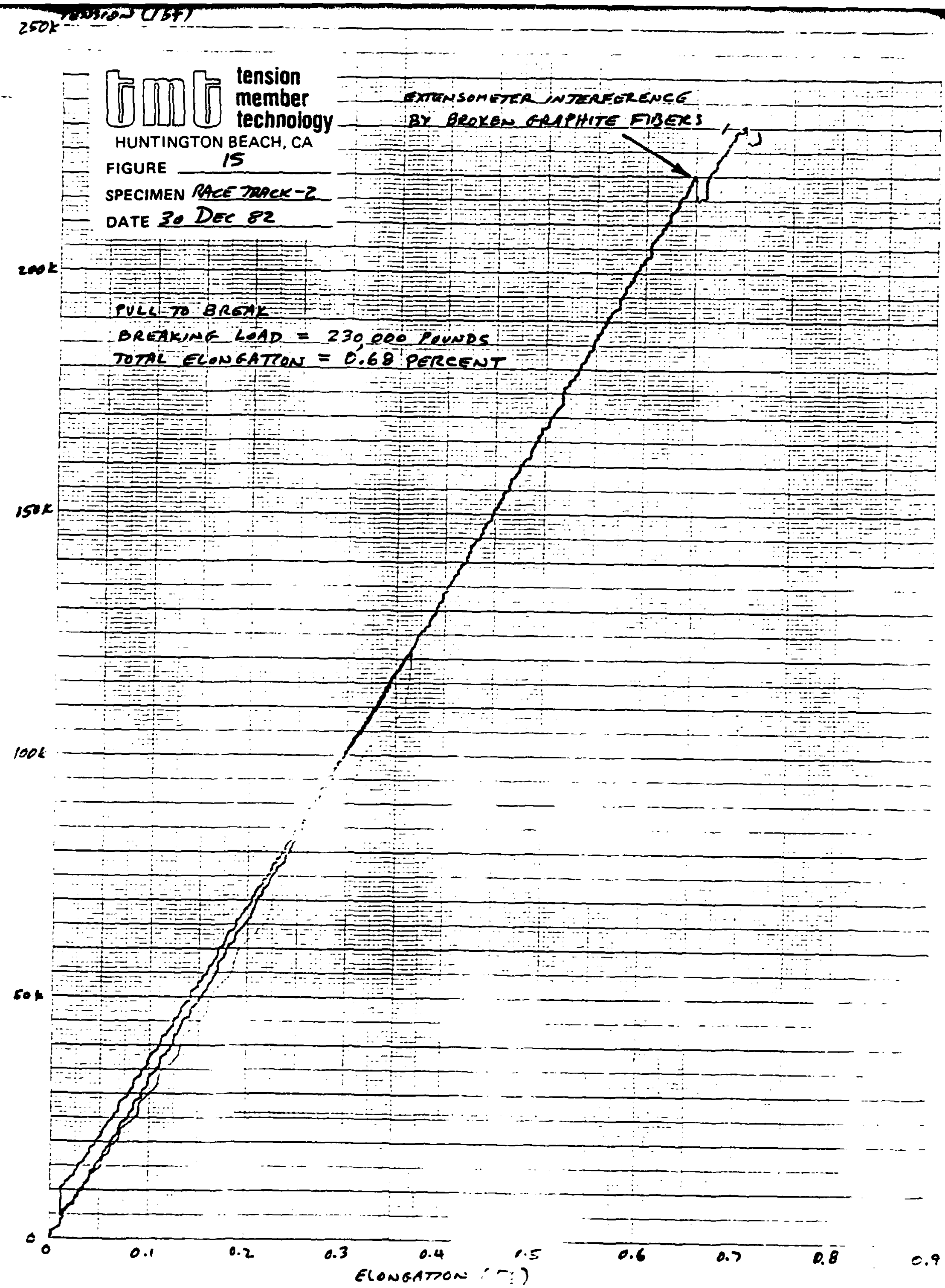

TENSION (lbf)
tmt tension member technology
HUNTINGTON BEACH, CA
FIGURE 12
SPECIMEN RACE TRACK-2
DATE 28 DEC 82
FATIGUE TEST
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
CYCLE 1
3
10
50
100
500
ELONGATION (%)
0.1%

- 510



TENSION (lbf)
tmt
tension member technology
HUNTINGTON BEACH, CA
FIGURE 13
SPECIMEN RACE TRACK-2
DATE 28 DEC 82
FATIGUE TEST
120k
110k
100k
90k
80k
70k
60k
50k
40k
30k
20k
10k
0
1,000
2,000
7,000
12,000
17,000
ELONGATION (%)
0.1%


TENSION (lbf)
tension member technology
HUNTINGTON BEACH, CA
FIGURE 14
SPECIMEN RACE TRACK-2
DATE 29 DEC 82
120K
110K
100K
90K
80K
70K
60K
50K
40K
30K
20K
10K
0
22,000
27,000
ELONGATION (%)
0.1%



TENSION (LBF)
250K
tmt tension member technology
HUNTINGTON BEACH, CA
FIGURE 15
SPECIMEN RACE TRACK-2
DATE 30 DEC 82
EXTENSOMETER INTERFERENCE
BY BROKEN GRAPHITE FIBERS
200K
PULL TO BREAK
BREAKING LOAD = 230,000 POUNDS
TOTAL ELONGATION = 0.68 PERCENT
150K
100K
50K
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
ELONGATION (%)

APPENDIX A

LABORATORY EQUIPMENT

APPENDIX A

LABORATORY EQUIPMENT

The following tables present a partial listing of equipment available in the Tension Member Technology Laboratory. Those items which were used during this test program are indicated with a check mark.

Current calibrations are maintained for all items of test equipment, and calibration records are available for inspection in TMT's instrumentation laboratory.

TABLE A-1. PARTIAL LISTING OF LABORATORY EQUIPMENT

Check	Instrument	Manufacturer	Model Number	Serial Number
___	100-lbf Load Cell	Interface	SSM-100-AJ	7658
___	1,000-lbf Load Cell	Ditto	SSM-AN-1000	5004
___	1,000-lbf Load Cell	"	1210 AF	17570
___	10,000-lbf Load Cell	"	1210 AF	9405
___	25,000-lbf Load Cell	"	1220 AF	9895
___	25,000-lbf Load Cell	"	1220 AF	12145
___	50,000-lbf Load Cell	Sensotec	41	55250
___	50,000-lbf Load Cell	Ditto	41	55251
___	50,000-lbf Load Cell	"	41	55252
___	50,000-lbf Load Cell	"	41	55253
___	100,000-lbf Load Cell	Interface	1232 AF	7057
___	200,000-lbf Load Cell	Sensotec	41	55589
___	350,000-lbf Load Cell	TMT	1635	128
X	500,000-lbf Load Cell	TMT	1650	135
X	Signal Conditioner	Himmelstein	6-269.3976	6-139
___	Load Indicator/Controller	Daytronic	3370	55
___	Load Indicator/Controller	Ditto	3370	56
___	Load Indicator/Controller	"	3370	61
___	Load Indicator/Controller	"	3370	276
X	Load Indicator/Controller	"	3370	277
___	Load Indicator/Controller	"	3370	289

TABLE A-2. PARTIAL LISTING OF LABORATORY EQUIPMENT

Check	Instrument	Manufacturer	Model Number	Serial Number
X	Elongation Sensor	TMT	TMT-2	1
	Elongation Sensor	TMT	TMT-3	3
	LVDT	Schaevitz	5000-HPD	106
	Rotation Sensor	TMT	FCS-40K	1
	Rotation Sensor	TMT	FCS-300K	3
	Corona Test Set	TMT	TMT-1A	100
	Hypot Test Set	Associated Research	5220	1065
	Milliohmmeter	TMT	TMT-2	10
	Capacitance Meter	ECD Corporation	100	15832
	Temperature Meter	Doric	430A	42976
	Continuity Meter	TMT	ACM-1	1
X	X-Y Recorder	Hewlett-Packard	7044 A	1605A01638
X	Chart Recorder	Hewlett-Packard	7132 A	1606A00613
	X-Y Recorder	Hewlett-Packard	7044 B	2047A00188
	Optical Multimeter	Photodyne	22XL	10425
	F/O Signal Source	Fotec	S210	S22202
	F/O Converter	Ditto	C200	C22202
	F/O Converter	"	C200	C22203
	F/O Converter	"	C200	C22204
	F/O Converter	"	C200	C22205
	Time Domain Reflectometer	Tektronix	1502	B113008

APPENDIX F

ATTACHMENT FITTINGS

See Drawings, Engineering and Associated Lists for Attachment Fitting Drawings.

APPENDIX G

PRELIMINARY RACETRACK TOOLING DRAWINGS

AD-A136 267 BRIDGE REINFORCEMENT SYSTEM PHASE III(U) FIBER MATERIALS INC BIDDEFORD ME 14 OCT 83 DAAK70-81-C-0228 2/2

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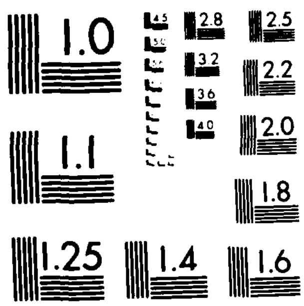

See Drawings, Engineering and Associated
Lists for Preliminary Racetrack
Tooling Drawings.

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