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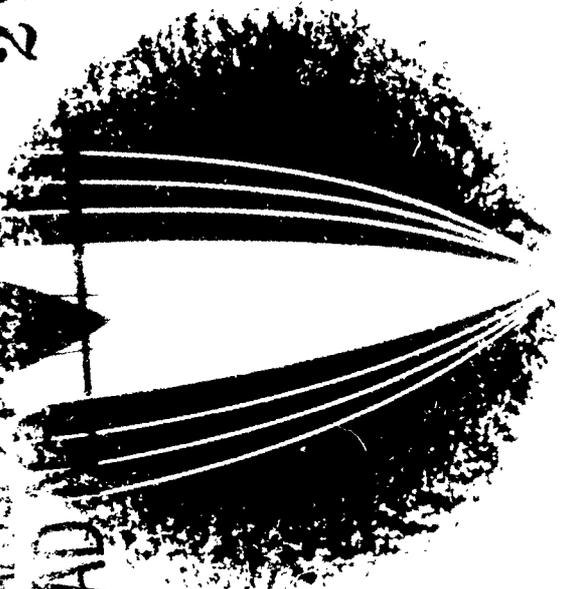
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STUDY OF THE EFFECTS OF THICKNESS ON THE PROPERTIES OF LAMINATES FOR UNDERWATER PRESSURE VESSELS

Contract NObs 86406



Structural Materials Division

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Report No. 0623-01-3
(Third Quarterly Report)

STUDY OF THE EFFECTS OF THICKNESS ON THE PROPERTIES OF
LAMINATES FOR UNDERWATER PRESSURE VESSELS

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Design Engineering Department
Structural Materials Division

AEROJET-GENERAL CORPORATION

Azusa, California

FOREWORD

This is the third quarterly report on Aerojet-General Corporation (AGC) Work Order 0623-01, covering the period 1 September through 30 November 1962 on Contract NObs 86406. This contract is under the direct supervision of the Materials Development and Application Branch, Code 634C, Bureau of Ships, with Mr. William Graner acting as technical monitor.

The program is being conducted by the Design Engineering Department of the Structural Materials Division at Aerojet-General Corporation, Azusa, California. Major responsibility for the program resides with R. D. Saunders and R. L. Smith. Other significant contributors to the program include T. R. Sakakura, T. E. Anvick, and F. E. Brown.



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ABSTRACT

A discussion of the program and a summary of the work conducted is presented. The basic program is to study the effects of thickness on the mechanical and physical properties of fiber-reinforced plastic laminates for deep submersible external pressure vessels. An analysis of fabrication methods and problems related to thick-walled cylinders is given. Methods of testing and test results of cylinders and rings are presented.

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I. SUMMARY

The purpose of this program is to determine the effects and relationship of thickness on the physical and mechanical properties of filament-wound underwater pressure vessels. This relationship is being determined by conducting analyses to determine design criteria and fabrication methods for thick-walled cylinders; by fabricating and testing small cylinders and test rings; and by comparing and correlating actual fabrication methods and test results with the analytical work.

The principal investigations during this quarter centered on fabrication methods for thick-walled cylinders and on improvement of the test base. Several significant improvements in the development of fabrication methods for thick-walled test cylinders have resulted in the attainment of composite stress levels of 116,000 psi.

Eleven cylinders were fabricated during this period with wall thicknesses up to 4-in. thick. These cylinders were fabricated using the standard U.S. Polymeric E787/HHS 20-E prepreg roving wound with both constant and programmed tension patterns and using both the bulk-cure and step-cure methods.

Ten of these cylinders were hydrostatically tested, including both test base cylinders (to more closely evaluate such parameters as ply dispersion and winding pattern), and thick cylinders which were machined into thinner cylinders representative of the inner and outer surfaces. No significant changes in mechanical or physical properties directly attributable to thickness have occurred, thus indicating that the analyses, designs, and fabrication processes selected are valid for the present material of construction. The yield strength or ultimate composite stress value for this material is established according to the present state of the art as between 95 and 120 psi, depending on the winding pattern selected and the accuracy of construction.

II. BACKGROUND

The U.S. Navy requires lightweight, high-strength structures such as buoys, mines, torpedoes, and submarines. Performance requirements of deep submergence vessels are exceeding the capabilities of conventional structures and fabrication methods. Glass filament winding, a process which provides the highest available strength-to-weight ratio has been steadily improved, and will continue to be improved, to meet the difficult hydrospace problems of strength, weight, corrosion resistance, impermeability, reliability, producibility, and low cost.

An important aspect of the development of hulls for deep-submergence vessels is the effect and relationship of thickness on the properties of filament-wound structures.

This program encompasses research and development in the areas of design theories, fabrication procedures, and evaluation methods for heavy-walled, filament-wound structures.

III. DESIGN ANALYSIS

A. FILAMENT TENSIONING

1. Circumferential

A theoretical method was derived during the first quarter of this thick-walled cylinder program for obtaining a uniformly stressed composite, when cylinders are uniformly loaded by external pressure, by using a programmed tension pattern.*

The attainment of an optimized pre-tension condition is elusive of attainment because of the many parameters and variables inherent in the fabrication process. Two test cylinders, TW-12 and TW-13, were fabricated during this period to evaluate one method of attaining a programmed tension pattern. The details of construction are given in Section IV,A. A comparison of the test results of these cylinders with cylinders wound, using a constant tension, showed a small increase (10%) in the composite stress of the programmed tension cylinder. However, positive conclusions regarding this parameter are considered premature at this time because of the limited number of test samples.

* See Quarterly Report No. 0623-01-1 for detailed circumferential pre-tension analysis.

A constant tension is considered most practical at present, in order to concentrate on the investigation of other problems associated with thick-walled cylinder design and fabrication. Five pounds constant tension/20E prepreg was selected as the standard tension pattern for current program phases because

a. Higher tensions have resulted in damaged, or resin-starved, inner plies (see Quarterly Report No. 0623-01-2).

b. The resolution of such problems as craze cracking, telescoping of the circumferential plies, circumferential ply wrinkling, and mandrel removal has dictated the use of a constant tension pattern to reduce the number of fabrication variables.

c. It is not desirable to use a programmed tension pattern in fabricating the thicker cylinders now being fabricated. Since these thick cylinders are machined into thinner, representative concentric cylinders for test, a programmed tension in these thick cylinders would not produce the same tension pattern in each machined cylinder.

2. Preheating

One of the variables affecting tension and the residual stress pattern in a composite is the amount of preheating applied to the prepreg immediately before payoff onto the part surface. Preheating the prepreg before, and during, payoff softens the resin and allows the tension, which is applied through the spool, to straighten out any kinks, birdseyes, or patterns inherent in the roving because it was helically wound onto a spool. Another variable inherent in prepreg roving is the degree of resin advancement. Advancement of the resin makes the prepreg stiffer and affects not only the amount of preheating required but makes a difference in the amount of tension required to produce a consistent, compact laminate.

One problem encountered with cylinders wound during this report period was the difficulty in removing parts from the mandrel. This difficulty was due to the higher effective roving tension resulting from prepreg preheating. Five pounds constant tension, when used without preheating, resulted in parts which would allow sufficient mandrel expansion to facilitate easy mandrel removal. Utilizing preheating, the same 5.0 lb/20-E tension results in an initial part grip to the mandrel requiring pressures on the order of 20 tons to break loose.

Preheating the prepreg before winding onto the mandrel is highly desirable because of the superior parts which are produced by this method. Tension patterns must be selected that will not cause mandrel removal problems. Possibilities include use of the lowest possible tension that will allow payoff of consistent straight fibers, and use of a programed tension with, say, a very low tension on the inner plies only.

Incorporating a programed tension pattern into a resin-glass filament composite is a complex problem. Some of the specific variables which must be evaluated in association with programed tension are (a) fabrication processes, (b) manufacturing practicality, (c) mandrel deflection, (d) resin percentage, and (e) the eventual effect on such design properties as short-term, long-term and cyclic external pressurization loading.

3. Mandrel Design Considerations

It has become apparent that mandrel design is a critical factor related to tension. The small cylinder sizes presently being fabricated present no problem but do serve to point out that for mandrel scale-up, such as for an 8-ft-dia or larger hull, present methods of fabrication may have to be modified to allow use of more realistic mandrels.

At present, 6.0-in. ID and 12.0-in. ID cylindrical parts are being fabricated on steel mandrels 0.62 and 1.25-in. thick, respectively. The thickness of mandrels was selected to withstand compressive loads due to winding tension. However, mandrel removal difficulty from these parts has been directly affected by the filament winding tension and part thickness. It would seem, therefore, that a large hull structure may have to be fabricated by some method other than bulk elevated temperature cure, possibly by an in-process room temperature cure system or by step elevated temperature cure. Both of these methods would provide additional strength to the composite during fabrication and thereby reduce requirements for mandrel strength.

B. WINDING PATTERN AND PLY DISPERSION - CIRCUMFERENTIAL FILAMENTS

A change in wrap pattern has been accomplished during this quarter. Each succeeding circumferential layer (4 plies) is now reverse wound (wound with the helix in the opposite direction) so that the stress pattern of all circumferential filaments after cure (and before loading) is geometrically in

equilibrium. This change was required because of the displacement noted in the longitudinal filaments of several thick-walled cylinders after cure. This displacement, visible through the outer surfaces of these cylinders after cure, was evident in Cylinder TW-15-2. It was concluded that this displacement was caused by an unbalanced winding due to winding the circumferential filaments in one direction only, resulting in an initial circumferential residual stress, before cure, directly proportional to the winding tension. This residual stress is released during the initial stages of cure when the resin viscosity is lowered, resulting in an "unwinding" of the cylinder and resulting in longitudinal fiber displacement.

Reverse winding, incorporated in chamber Nos. TW-17, TW-18, and TW-20 fabricated during this period, has eliminated all of the displacement of longitudinal fibers due to an unbalanced stress pattern.

It is possible that layer thickness (dispersion) may be a prime variable in the attainment of optimized filament-wound external pressure vessel mechanical properties. The standard dispersion used on all cylinders, except one, on this program has been four circumferential plies to two longitudinal plies. This dispersion was selected because it lends itself to present methods of manufacture (hand-layed-up longitudinals) as well as to the likely alternate of wound longitudinals in which a double ply must always be wrapped.

One cylinder, TW-17 (to evaluate the effect of maximum, or 2:1, dispersion) was built during this quarter. (See Section IV,A.)

The hydrotest of a 5-in. length of this fiber reinforced plastic cylinder resulted in the highest composite stress known at this time, 115,725 psi. It is notable that this cylinder would have attained a higher stress value except for a gage failure which occurred in the pressurization system at 16,000 psi.

This result indicates that the combination of reverse winding and the 2:1 dispersion has produced an increase of approximately 20% in the composite stress over previously fabricated single direction winding and 4:2 dispersion cylinders. Subsequent tests of reverse wound cylinders not fabricated with a 2:1 dispersion will be compared with values obtained with this cylinder to evaluate the effects of each major variable.

C. FABRICATION METHODS

Fabrication methods evaluated during this period were based on the winding of progressively thicker cylinders and the attendant problems of obtaining precise filament placement, and uniform layer buildup and of minimizing fiber movement during cure.

1. Materials of Construction

U.S. Polymeric E787/HTS 20-E with 20% $\pm 1\%$ resin, has been used for all cylinders fabricated during this report period. This preimpregnated material has been subjected to stringent quality-control procedures and acceptance tests. Consistent results indicate that this material is a good selection as the current standard material of construction.

Two problem areas associated with the use of this type of prepreg material are the variation in material strength and the material softening characteristics due to the degree of resin advancement, and the "memory" of the roving of the lay of the helically wound bundle. The degree of resin advancement may well be an important factor in obtaining consistent physical and mechanical properties. It has been found, on other programs at Aerojet, that the degree of resin advancement, as determined by the number of days at room temperature, can grossly affect resin interlaminar shear strength. (Since this program is currently in the laboratory evaluation stage, results are not yet available for publication.)

Degree of resin advancement is a definite factor in cylinder fabrication techniques. Since some rolls of roving are more advanced than others, more heat is required to soften the roving before winding, and additional heat has to be applied to the part surface.

Because of the wide helical pattern in which prepreg roving is currently wound on the storage spools, proper preheating and tensioning are required to make the roving lie flat on the part mandrel. In addition, because of the variation in prepreg roving width, the forming of a tape from several rovings involves exact payoff roller adjustment and considerable care in winding. It is expected that improvement in this area will evolve with improved heated payoff roller designs, and more experience in pre-impregnating by suppliers. A major

improvement is expected with Aerojet's in situ process preimpregnated roving whereby the roving is vacuum impregnated without removing the material from the spool. The capacity of this laboratory process which, from all indications, will produce a superior prepreg, is expected to be expanded soon.

Roving aging (the amount of time prepreg material on the spool or after winding onto a mandrel can sit at room temperature before cure) is an important parameter of prepreg efficiency. Additional cylinders should be fabricated and tested to evaluate the effect of this aging.

2. Fabrication Methods

The methods used and evaluated for the winding of all cylinders during this report period are discussed below.

a. General Approach

All cylinders were wound on 6.0-in.-OD steel mandrels (except for TW-20) with removable end dams to prevent "telescoping" of the circumferential plies. All circumferential plies were paid off, either 2 plies or 4 plies at a time, similar to the method shown in Figure 1, utilizing tension noted in sections on cylinder fabrication. Unidirectional tape, made of E787 prepreg roving was layed-in by hand parallel to the mandrel axis for the longitudinal elements. A shrink tape overwrap was utilized on all cylinders. The standard cure was monitored and controlled by thermocouples.

b. Longitudinal Plies

Unidirectional tape is fabricated of E787 prepreg by winding onto a plastic-film-covered 12-in.-dia aluminum mandrel heated to approximately 150°F. Two E787 prepreg 20-E rovings, tensioned at the spool, are wound at one pass using a lead which will give the desired layer thickness which has been calculated to obtain the desired finished composite thickness ratio of two circumferentials to one longitudinal. The finished thickness of each ply is approximately 0.016 in. After winding a length sufficient to wrap the circumference of the test cylinder, the windings are cut through, parallel to the mandrel axis, and removed from the mandrel as a flat sheet.

c. Winding

Recently, cylinder fabrication on this program was transferred from a cam-hydraulic controlled winding machine to a new machine having a lead screw controlled carriage and roving payoff head. Improved roving application for linear patterns is possible with the new machine. In both machines, tensioning of the circumferential filaments is applied at the roving spool.

d. Cure

Both bulk and step cures were evaluated and used for cylinder fabrication during this period. In both cases the final cure of the entire composite thickness is as follows:

2 hours at 200°F
15 min at 225°F
15 min at 250°F
15 min at 300°F
8 hours at 325°F

For the step-cured cylinders, this standard cure cycle was followed for the first step except that the time at 325°F was reduced to one hour so that the final cure of the entire thickness would result in a uniform time at temperature relationship. All temperatures given are part temperatures controlled by thermocouples which are wound in close to the inner surface at part mid-length. After completion of the cure cycle, the part is slowly cooled to room temperature. For thick, step-cured parts (TW-16 and TW-18), the first step, after cure, is machined to obtain a smooth surface and concentric diameter before the second stage is wound on.

A significant improvement was achieved during this report period by placing the thermocouples close to the inner surface. None of the craze-cracking experienced during the previous quarter has occurred during this period, indicating that the cure is now more uniform and comparatively stress-free.

e. Mandrel Removal

Preheating the prepreg roving before winding has resulted in much more compact windings which have, in turn, made mandrel removal more difficult. Mandrel removal is more fully detailed in Section III,A,2.

D. TESTING

1. Test Methods

Biaxial hydrotest has been the primary method of test for all cylinders on this program.

The test cylinders are mounted on end closure holding plates as is shown in Figure 2. These plates are stepped to provide a 0.400 minimum wide support on the internal surface at each end of the cylinder.

Significant strain data is recorded at specific increments during test on a Consolidated Electrodynamics Corporation oscilloscope. Strains are recorded from six circumferential gages 60° apart and two axial gages 180° apart at mid-length on the inside diameter of the part. Budd Metalfilm HE-181-E strain gages are used. All strain gages are waterproofed.

Pressurization is accomplished by a standard sprague pump system. The pressure vessel used for all tests has been the Aerojet 17,500 psi chamber which can test parts up to 14 in. dia and 35 in. long. The top head of this pressure chamber is shown above the end closure and cylinder assembly in Figure 2. The pressure medium used has been fresh water.

The test cylinder is filled with distilled water and vented during test, to reduce implosion and prevent complete destruction when collapse occurs. No malfunction of the waterproofed strain gages has occurred to date.

2. Data Reduction

Strain and pressure data obtained during hydrotest are converted into significant mechanical values using the following formulas, identified by \triangle , for reference in Section IV,A.

Per Lamé's formulas,

\triangle Maximum circumferential stress, inner surface $\sigma_{\phi i}$

$$\sigma_{\phi i} = -P \frac{2 R_o^2}{R_o^2 - R_i^2}$$

2 Maximum circumferential stress, outer surface $\sigma_{\phi\sigma}$

$$\sigma_{\phi\sigma} = -P \frac{R_o^2 + R_i^2}{R_o^2 - R_i^2}$$

3 Axial (longitudinal) stress σ_{X1}

$$\sigma_{X1} = -P \frac{R_o^2}{R_o^2 - R_i^2}$$

4 Circumferential Modulus ϵ_{ϕ}

$$\epsilon_{\phi} = \frac{\sigma_{\phi i 2} (1 - \mu_1, \mu_2)}{\epsilon_{\phi i} + \mu_2 \epsilon_{X1}}$$

5 Axial (longitudinal) modulus ϵ_X

$$\epsilon_X = \frac{\sigma_{X i 2} (1 - \mu_1, \mu_2)}{\epsilon_{X i} + \mu_1 \epsilon_{\phi i}}$$

6 Effective Modulus E_{eff}

$$E_{\text{eff}} = 2\epsilon_{\phi} \frac{K}{1+K}, \quad K = \frac{\epsilon_X}{\epsilon_{\phi}}$$

7 Critical instability pressure, P_c (Trilling Eq. 9)

$$P_c = \frac{2.42 E_{\text{eff}}}{(1 - \mu^2)^{3/4}} \frac{(t/D)^{5/2}}{L/D - 0.45 (t/D)^{1/2}}$$

μ assumed = 0.25

where

P_c = Critical instability pressure, psi

-P = Pressure, psi

R_o = Radius, outer surface, in.

R_i = Radius, inner surface, in.

$\epsilon_{\phi i}$ = Midlength hoop strain, inner surface at specified pressure (approx 60% of $-P_c$), micro in./in.

- ϵ_{X1} = Midlength axial strain, inner surface at specified pressure (approx. 60% of P_c), micro in./in.
 μ_1 = Hoop Poisson's ratio
 μ_2 = Axial Poisson's ratio
 $\sigma_{\phi 12}$ = Midlength hoop stress, inner surface midlength at specified pressure (approx. 60% of P_c), psi
 σ_{X12} = Midlength axial stress, inner surface midlength at specified pressure (approx. 60% of P_c), psi
 t = Cylinder thickness, in.
 D = Mean diameter, in.
 L = Effective test length, in.

Circumferential modulus, axial modulus, and effective modulus are calculated using the stress, strain, and Poisson's ratios at approx 60% of ultimate failure stress. At this stress level, no major deviation or indication of instability is present, thus allowing calculation of true modulus values.

3. Test-Specimen Geometry

Specimen geometry (i.e., thickness and length) has been varied during this period. Cylinders having a geometry which predicts failure by instability and also cylinders with geometry predicting failure by yield have been tested. These tests have indicated strengths which are independent of the mechanism of failure, and have helped to more accurately determine the ultimate yield strength of the material. The conclusion drawn from these tests is that the standard geometry for all remaining cylinders on the program will be a configuration with an L/D of less than 1.0. All 6.0-in. ID cylinders furnished to DTMB will be 11.40 in. long.

An analysis of the primary methods of failure (material yield and instability) indicates that test cylinders 6.0-in. ID x 0.60 thick x 11.4 long will probably fail by material yield. Shortening the cylinder length, therefore, should theoretically produce the same stress values as the 11.4 length. Since this program is based on a comparison of stress values of representative concentric cylinders machined from thicker cylinders, specimen cost for thick cylinders would be prohibitive if geometry were kept at the 11.4-in. test base length. This is especially true of the larger cylinders being fabricated to check scale effect.

For the above reasons, test cylinder length for most of the future parts will have a length-to-diameter ratio of less than one ($L/D < 1$). Six inch diameter parts will be 5.0 in. long, 12 in. diameter parts will be 10.0 in. long.

E. TOOLING AND TEST EQUIPMENT

1. Mandrels

Three new mandrels were designed and fabrication was completed during the quarter. They included

a. A 6.0-in.-dia x 45.0-in. long steel mandrel, which was required because of an expedited schedule and to fabricate longer cylinders from which can be machined several shorter cylinders

b. A 12.0-in.-dia x 30.0-in. long steel mandrel, which was required for fabrication of test cylinders to check scale effect and is shown with end dams attached in Figure 1.

A 24-in.-dia steel mandrel is in fabrication and will be completed during December.

2. Test Fixtures

a. End Closure Plate Fixtures

New end closure plate fixtures for holding cylinders up to 10 in. in diameter during hydrotest were completed and used for most of the tests during this period. This fixture is shown in Figure 2.

b. Ring Compression Fixture

This fixture was completed and satisfactorily tested. A leak developed in the hydraulic bag during calibration, and the bag is being repaired.

c. Creep and Fatigue Test Facility

The first three units of this facility, utilizing the 16-in.-dia projectiles (Mark 13 Mod 2) obtained from the Naval Weapons Depot are in process of fabrication. The first chamber is almost completed, and will be

tested during December. Two of the original units will be for long-term creep tests and the third for cyclic fatigue testing.

NOTE: All tooling, tool design, test equipment, and facilities used on this contract are supplied by the Aerojet-General Corporation, and are noted here only to indicate project progress.

IV. FABRICATION AND TESTING

A. CYLINDERS

Cumulative data for all cylinders fabricated and tested, to date, are summarized in Table 1.

Eleven cylinders were fabricated during this period with wall thicknesses up to 1.250 in. These cylinders were fabricated to determine the limitations and effectiveness of such techniques as programed tension, bulk cure, step cure, etc., dispersion, reverse winding, and the general techniques of prepreg winding.

All cylinders were fabricated on a 6.0-in.-dia x 30.0-in. long steel mandrel with end dams.

A 12.0-in. ID x 4.0-in. thick x 30.0-in. long part is at present being fabricated by the step-cure method. This cylinder is being wound in four 1-in.-thick steps. Each step is cured and machined before the succeeding stage is wound on. This cylinder will be fully reported in the next report period.

All cylinders fabricated during this report period were wound using U.S. Polymeric E787/HTS 20-E prepreg roving, with a 20% resin content. All plies were dispersed in a ratio of four circumferential plies to two longitudinal plies unless otherwise noted. Longitudinal plies were laid in by hand using tape fabricated of E787/HTS 20-E roving. Additional information on these cylinders follows.

1. Cylinder TW 10

Specifications for this cylinder were as follows: 0.402 in. thick, 7 circumferential layers (28 plies) and 6 longitudinal layers (14 plies)

giving a ratio of two circumferentials to one longitudinal. Two of the longitudinal plies were three plies thick, and four were two plies thick. Tension on the circumferential was 5 lb/20-E constant.

The mandrel slid freely out of this cylinder indicating that some mandrel expansion took place. Visual inspection of this cylinder, after mandrel removal, showed the same type of crazing or resin cracking on the inner surface as was evidenced on cylinders fabricated during the previous period. Evidence of this crazing is shown in Figure 3. It is concluded that this crazing is indicative of an insufficient or improper resin cure. Thermocouples were placed close to the inner surface of succeeding cylinders to obtain more positive control of laminate temperature through the entire thickness.

This cylinder was machined into three shorter lengths and tested as follows: Cylinders were mounted on end closure plates, and pressurized to 8,000 psi at 500 psi/min. From 8,000 psi to cylinder failure, loading was reduced to 50 psi increments held for two minutes.

<u>Cylinder No.</u>	<u>Thick-ness in.</u>	<u>ID in.</u>	<u>Overall Length in.</u>	<u>P_c psi</u>	<u>$\sigma_{\phi 1}$ psi</u>	<u>Density lb/in.³</u>	<u>Weight/Displacement</u>
TW-10-1	0.402	6.000	11.4	8,700	78,087	0.076	0.454
TW-10-2	0.407	6.000	7.2	9,500	85,500	0.076	0.454
TW-10-3	0.402	6.000	4.13	9,800	88,200	0.076	0.454

This series of tests was run to determine for this t/d relationship the effect test specimen length has on collapse pressure and on the circumferential composite stress at the inner surface. This test also serves as a good comparison with future cylinders not having craze cracking.

2. Cylinder TW-11

Specifications of this part were as follows: 0.750-in. thick, 15 circumferential layers (60 plies) and 14 longitudinal layers (30 plies). Winding tension was maintained at a constant 5.0 lb per 20-E roving on the circumferential layers. The standard cure was controlled by thermocouples wound into part inner surface at cylinder midlength.

Several significant areas of interest related to thick-walled cylinder fabrication became apparent.

a. Smoothness of circumferentials was hard to control because of twists, variations in the prepreg band width and thickness, and slight errors in the winding machine lead. The outer surface, therefore, becomes progressively more irregular with each ply. A heated roller will be tried later on for thick-walled parts to smooth the circumferential windings.

b. The mandrel, after removal of end dams, slid freely out of the part indicating that using 5.0 lb tension and the above-mentioned fabrication process allowed some mandrel expansion. Figure 4 shows this mandrel and part after removal.

c. There was no craze-cracking on the inner surface indicating that the longer cure cycle, controlled by the deeply embedded thermocouples, was a decided improvement.

d. Examination of polished rings, shown in Figures 5 and 6, cut from sections of this cylinder showed some wrinkling of two plies near the outer surface. This wrinkling was probably due to lowered resin viscosity during cure which, with the filament tensioning, resulted in filament movement. This wrinkling indicates the need for further investigations of step cure and bulk curing, as well as other fabrication improvements for thick-walled cylinder fabrication.

The part was machined into two cylinders, representative of the inner and outer surfaces, and rings for test as shown in Figure 7.

The hydrotest procedure for these two cylinders was as follows:

Cylinders were pressurized to 60% of their predicted failure pressures at 500 psi per min in 500 psi increments. Each increment was held for 1 min. Strain readings were recorded at each increment.

From 6,000 psi to test cylinder collapse, pressure was increased in 250 psi increments. Each increment was held 1 min.

Both cylinders failed by instability as is evidenced by the reversal of the strain-pressure curves shown on Figures 8 and 9. A summary of physical and mechanical values follows:

<u>Physical</u>						
<u>Cylinder No.</u>	<u>ID in.</u>	<u>Thick-ness in.</u>	<u>Overall Length in.</u>	<u>Weight lb</u>	<u>Density lb/in.</u>	<u>Weight/Displace-ment</u>
TW-11-1	6.000	0.444	11.405	7.692	0.075	0.489
TW-11-2	6.623	0.440	11.409	8.372	0.075	0.448

<u>Mechanical</u>							
<u>Cylinder No.</u>	$\epsilon_{\phi i}$ <u>X10⁶ psi</u>	$\epsilon_{X i}$ <u>X10⁶ psi</u>	E_{eff} <u>X10⁶ psi</u>	P_c  <u>psi</u>	P_c <u>psi</u>	$\sigma_{\phi i}$ <u>psi</u>	$\sigma_{X i}$ <u>psi</u>
TW-11-1	6.17	4.64	5.29	11,191	10,750	89,139	44,570
TW-11-2	5.79	4.41	5.00	9,079	8,500	76,908	38,454

Conclusions drawn from this cylinder indicate that a more comprehensive comparison of inner and outer surfaces could have been obtained by using a specimen geometry that would preclude instability type failures; and the fact that the outer surface test results were not as good as inner surface confirms the effect of movement during cure as shown in Figure 6.

3. Cylinder TW-12

Specifications for this part were as follows: 0.380 (0.400) in. thick x 6.0-in. ID x 30.0-in. long, 8 circumferential layers (32 plies), and 7 longitudinal layers (16 plies).

This cylinder was wound utilizing a programmed tension pattern designed so that thermal mandrel expansion would provide part of the final tension on the inner plies. Previous attempts at incorporating a programmed tension pattern into several cylinders used 12 or 8 lb tension on the inner plies and resulted in delaminations or resin-starved inner surfaces. The initial circumferential layer on this cylinder was wound using 5.0 lb tension per 20E Roving. The second circumferential layer was applied at 8.0 lb tension and each succeeding layer was decreased until 4.0 lb tension was attained at the outer surface.

A damaged cam on the winding machine caused an instantaneous dwell at one point in the cylinder length. An initial defect was, therefore, built into the cylinder. Mandrel removal was somewhat more difficult than for the parts utilizing 5.0 lb constant tension, indicating, as predicted, that the higher tension still restricted mandrel thermal expansion. An Arbor press was required to break the initial grip of the part on mandrel. The inner surface of this part revealed no damage due to winding tension, and no crazing. Indications are that this method of obtaining a programmed tension pattern is satisfactory and that thermocouples near the inner surface assure a uniform cure of the resin.

This 30-in. long cylinder was machined into two 11.4-in. long cylinders and representative test rings. The cylinder containing the initial imperfection, caused by the nicked cam, was designated as TW-12-2.

The hydrotest procedure for TW-12-1 was as follows:

The cylinder was pressurized to 6,000 psig in 500 psi increments, for obtaining strain data. After venting to zero, the cylinder was again pressurized in 500 psi increments to 8,000 psi, and strain readings were recorded at each increment. From 8,000 psi to cylinder failure, increments were reduced to 200 psi. Duration at each increment was 1 min. Views of the cylinder after failure are presented in Figure 10.

Strain gage data obtained during the second cycle is shown in Figure 11. This data shows that deviation began at approximately 8,000 psig and indicated instability failure. Test results for this cylinder are as follows:

<u>Physical</u>					
<u>ID</u> <u>in.</u>	<u>Thickness</u> <u>in.</u>	<u>Overall</u> <u>Length</u> <u>in.</u>	<u>Weight</u> <u>lb</u>	<u>Density</u> <u>lb/in.³</u>	<u>Weight/</u> <u>Displacement</u>
6.000	0.400	11.410	6.960	0.0758	0.454

Mechanical

$\epsilon_{\phi 1}$ <u>X10⁶ psi</u>	ϵ_{X1} <u>X10⁶ psi</u>	E_{eff} <u>X10⁶ psi</u>	P_c  <u>psi</u>	P_c <u>psi</u>	$\sigma_{\phi 1}$ <u>psi</u>	σ_{X1} <u>psi</u>
6.30	4.93	5.53	9,064	9,225	83,320	41,660

The second cylinder, TW-12-2 was tested (without strain gages) to determine any significant reduction in composite stress due to the wound-in initial defect. Significant test results are

Physical

ID <u>in.</u>	Thickness <u>in.</u>	Overall Length <u>in.</u>	Weight <u>lb</u>	Density <u>lb/in.³</u>
6.000	0.400	11.402	6.985	0.076

Mechanical

P_c <u>psi</u>	$\sigma_{\phi 1}$ <u>psi</u>	σ_{X1} <u>psi</u>	Weight/ <u>Displacement</u>
7,950	71,804	35,902	0.456

Preliminary conclusions drawn at this time indicate that (a) composite stress values at failure for cylinder No. TW-12-1 are higher than previous cylinders having the same geometry, indicating that properly programed tension patterns can achieve a more efficient stress distribution and higher pressures; and (b) initial defects such as occurred in TW-12-2 can substantially reduce the composite stress.

4. Cylinder TW-13

Specifications for this part are the same as for TW-12. This 30-in.-long cylinder has been machined into shorter lengths and is currently undergoing diffusion and permeability tests. The cylinder was machined into two

sections, 3-in. long and four sections, 4-in. long. One section of each length is used as a control cylinder. The remaining cylinders were weighed, and are being subjected to varying time periods of exposure to 5000 psi pressure in simulated sea water. After this exposure, the cylinders will again be weighed and then biaxially hydrotested. These tests will then be compared with the hydrotest results of the control cylinders. Results of these tests will be reported during the next report period.

5. Cylinder TW-14

Specifications for this part were as follows: 0.50-in. thick x 6.0-in. ID x 30-in. long, 10 circumferential layers (40 plies) and 9 longitudinal layers (20 plies). The circumferential windings used 5.0 lb/20E roving constant tension. The outer surface was overwrapped with shrink tape to eliminate the overwrap used on previous cylinders. The standard cure was controlled by thermocouples wound into the inner surface.

The part was consistent in diameter except for a 4-in. long area at one end, which was a maximum of 0.60 in. smaller than the rest of the cylinder. This change in diameter is believed to be caused by the cam-hydraulic system in the machine on which this part was wound.

This cylinder has been machined into cylinders 5 in. long for initial creep and fatigue tests. One cylinder will be hydrotested as a control. The results of these tests will be reported in the next Quarterly.

6. Cylinder TW-15

Specifications for this part were as follows: 1.250-in. thick, 25 circumferential layers (100 plies) and 24 longitudinal layers (50 plies). The circumferential plies were wound using 5 lb constant tension.

a. Winding

The cylinder was wound utilizing a heat gun to continually heat the part surface in the area of the prepreg application. In addition, the roving was passed over a heated payoff roller to pre-soften and size the prepreg before it was wound onto the part surface. A Teflon-faced roller was used to smooth the circumferential plies before applying the longitudinals.

During the final stage of winding this part, local longitudinal wrinkles appeared in the circumferential plies. Apparently these wrinkles occurred between the hours of 12:00 PM and 8:00 AM while winding was not taking place, and may be attributed to both temperature and volumetric changes. A gradual redistribution of stresses may have been taking place in the part during this time. Upon warming the part, in preparation for the continuation of winding operations, the wrinkles disappeared. Winding was completed without further difficulty

b. Machining

Observations during the machining of the OD and after parting of the test rings revealed the following conditions:

(1) The wall cross section is extremely dense and well-packed throughout. Polished rings cut from the center and end sections show uniform and concentric layers without wrinkling. This uniform cross section, as shown in Figures 5 and 6, indicates that winding (using a heat-softened prepreg) and applying heat and a pressure roller to the part surface help to produce a densely packed cross section in which circumferential filament movement is minimized during cure.

(2) Some movement of the longitudinal plies was apparent on this cylinder. This condition was discernible by observation of the cured cylinder's surface. A tentative analysis indicates that this slippage of the longitudinal elements may be caused by winding the circumferential plies in one direction only. Winding in one direction builds in a unidirectional residual circumferential stress directly proportional to the winding tension. It is likely that these circumferential windings, during cure, tend to return to their untensioned length carrying the longitudinal plies with them in the process.

The cylinder was machined into two cylinders representative of the inner and outer surfaces for test.

c. Testing

Both cylinders were hydrotested as follows:

(1) First cycle: Cylinder was pressurized to 10,000 psig at 500 psig/min in 1,000 psig increments. Strain gage data was recorded at each increment. Each increment was held 1 min. Pressure was reduced to zero.

(2) Second cycle: Cylinder was pressurized to failure as follows: Pressure was increased from 0 to 5,000 psi at 500 psi per minute, from 5,000 psi to 10,000 psi in 1,000 psi increments, and from 10,000 psi to cylinder failure in 200 psi increments. Strain data was recorded at each increment. Views of the cylinder before and after testing are shown in Figure 12.

Significant test results for these cylinders are as follows:

Cylinder No.	ID in.	Thickness in.	<u>Physical</u>			
			Length in.	Weight lb	Density lb/in. ³	Weight/Displacement
TW-15-1	6.000	0.602	10.019	9.441	0.0757	0.625
TW-15-2	7.032	0.750	9.992	13.74	0.0750	0.650

Cylinder No.	<u>Mechanical</u>					
	$\epsilon_{\phi 1}$ X10 ⁶ psi	ϵ_{X1} X10 ⁶ psi	E_{eff} X10 ⁶ psi	P_c psi	$\sigma_{\phi 1}$ psi	σ_{X1} psi
TW-15-1	5.95	4.50	5.13	14,000	91,476	45,738
TW-15-2	6.05	4.82	5.37	14,900	92,976	46,488

Both cylinders probably failed by material yield stress as shown in curves in Figures 13 and 14. Other conclusions drawn from this cylinder indicated that

The application of heat during winding eliminated most of the fiber wrinkling experienced on TW-11.

Winding the circumferentials in one direction only resulted in an unbalanced stress pattern causing visible angular displacement of the longitudinal elements during the cure cycle.

There is no decrease in the mechanical properties of composites up to 1.250 in. thick.

The method of testing concentric cylinders representative of inner and outer surfaces provides an excellent method of evaluation. This comparison would not be available if full thickness cylinders were tested since the inner surface is more highly stressed than the outer surface.

7. Cylinder TW-16

Specifications for this part were as follows: 0.750-in. thick x 6.0-in. ID with 15 circumferential layers (60 plies) and 14 longitudinal layers (30 plies). This part was wound and cured in two steps. The first step involved applying 8 circumferential layers and 7 longitudinal layers, followed by curing, and the machining of the OD. The final stage was then wound onto this cylinder and a standard final cure was accomplished. This part has been machined into two 6.0-in. ID x 11.4-in. long x 0.750-in. thick cylinders for test. Fabrication methods were the same as for TW-15.

Longitudinal elements on this cylinder were also slightly displaced because of the unwinding action of the circumferential plies during cure. These cylinders will be tested during the next period in Aerojet's new 30,000 psi hydrotest facility. This facility utilizes three 16-in.-dia projectile shells (Mark 13, Mod 2). Use of this projectile facility will eliminate the necessity for machining parts up to 1.250 in. thick into thinner cylinders for test, except those required to compare the two extreme surfaces.

The appearance of the joint area (or cure line) between the two stages shows no visible line or difference between the two sections. Practicality of the step cure approach will be evaluated by hydrotests, mechanical tests, and photomicrographic analysis.

8. Cylinder TW-17

Specifications for this cylinder were as follows: 0.50-in. thick x 6.00-in. ID with 20 circumferential layers (40 plies) and 19 longitudinal layers (19 plies). Ratio of circumferentials to longitudinals was 2:1, fully dispersed. Each succeeding circumferential layer (2 plies) was reverse wound (helix was wound in the opposite direction) to attempt elimination of the displacement of longitudinal layers experienced on previous cylinders. Circumferentials were wound using 5.0 lb/20E prepreg constant tension. No indication of movement of the longitudinal plies was evident in the cured cylinder, indicating that reverse-wound cylinders have less movement during cure than cylinders wound by previous methods.

This cylinder was wound to also determine the effect of ply dispersion on the properties of filament-wound reinforced plastic external pressure vessels. A 5.0-in. length of this cylinder has been hydrotested and sustained 16,000 psi without failure. The test was suspended at this time because of a gage failure in the pressurization system. An 11.40-in. long cylinder (TW-17) will be furnished to David Taylor Model Basin (DTMB) for evaluation.

A summary of significant values relative to Cylinder TW-17-2 follows:

<u>ID</u> <u>in.</u>	<u>Thickness</u> <u>in.</u>	<u>Length</u> <u>in.</u>	<u>Density</u> <u>lb/in.³</u>	<u>P_c</u> [*] <u>psi</u>	<u>$\sigma_{\phi 1}$</u> <u>psi</u>	<u>σ_{X1}</u> <u>psi</u>	<u>Weight/</u> <u>Displacement</u>
6.001	0.526	5.00	0.076	16,000	115,725	57,865	0.567

* Test suspended before specimen failure because of a broken gage.

9. Cylinder TW-18

Specifications for this part are as follows: 1.250-in. thick x 6.0-in. ID step-cured part. This cylinder was fabricated in two steps. The first step was 0.6 in. thick, 12 circumferential layers (48 plies), and 11 longitudinal layers (24 plies). The second step was 0.650 in. thick, 13 circumferential layers (52 plies), and 12 longitudinal layers (26 plies). The standard cure was followed for each section except that the time at 325°F was reduced from 8 hours to 1 hour for the initial cure. Final cure was controlled by thermocouples wound into the first stage to guarantee an even cure. Each succeeding circumferential was reverse wound. Five pounds constant tension was used throughout for the circumferential plies.

There was no movement of the longitudinal plies indicating that reverse winding to obtain a balanced winding is helpful. Figure 15 shows this part before any machining. This cylinder has been machined into thinner cylinders representative of the inner, outer, and step-cure line areas for test and will be reported in the following quarter.

The maximum variation in the outside diameter of this part was 0.008 in. over a 28-in. length, indicating precise circumferential prepreg placement.

Significance of the tests on this cylinder is the determination of

- a. Physical and mechanical properties of step-cured cylinders.
- b. Efficiency of cure-line between steps.
- c. Comparison of the physical and mechanical properties of cylinders representative of the inner, middle, and outer surfaces with the whole thickness cylinder. (The 1.250-in. thick part will be hydrotested in Aerojet's new 30,000 psi test facility.)
- d. Any significant increase to reverse winding only.

Test results will be compared with the high stress level attained on the reverse wound, 2:1 dispersion TW-17 cylinder.

10. Cylinder TW-20

Specifications of this part are as follows: 4.0-in. thick x 12.0-in. ID x 30.0-in. long. This part is currently in-process and is shown in Figure 1. Objectives for the fabrication and testing of this part are to determine any significant change in the mechanical or physical properties of filament-wound external pressure vessels due to scale-up.

This cylinder is being fabricated in four 1-in. thick steps. Each step is cured and machined before the succeeding stage is wound on.

After fabrication, this cylinder will be machined into representative concentric cylinders for test, and test results will be reported during the next report period.

11. Conclusions

- a. Thicknesses in excess of the presently wound 1-1/4-in. thickness appear feasible in one step by maintaining precise control of filament placement.

b. A means of positively sizing the prepreg before application to the cylinder is desirable.

c. Pre-sizing the prepreg by preheating increases the resultant tension or residual stress pattern wound into the part. Pre-sizing and winding with a lower roving tension is being tried on the 4-in. thick part to reduce residual stress and facilitate mandrel removal.

d. Step cures are extremely interesting from both a quality-control and fabrication standpoint. By this method one step can be wound, inspected, and reworked if necessary by machining, before winding the next step. This method should also allow the use of thinner mandrels as the cured first stage becomes a mandrel for the second stage. If prepreg is used, step curing may also be of decided advantage to accomplish a cure after elapse of allowed time of prepreg at room temperature.

e. Thermocouples for thick-walled parts must definitely be placed close to the inner surface to obtain a proper and even cure.

f. The effect of initial imperfections should be more closely determined (Reference TW-12-1).

g. Programed tension shows promise but, because of the insufficient number of tests conducted to date, no significant conclusions can be stated.

h. Maximum dispersion of all longitudinal and circumferential plies appears to have resulted in cylinders having a significant increase in composite stress levels. However, fabrication cost of maximum dispersion cylinders is much greater than for the standard 4:2 dispersion cylinders because handling of thinner layers is more difficult and the number of layers is doubled.

i. Reverse winding each successive circumferential layer results in a balanced winding pattern with no filament crossovers as the longitudinal layer forms a separating element. Reverse winding results in considerably less movement of the longitudinal plies, and appears to result in cylinders having an increase in composite stress level.

j. Test cylinder 40 (length/diameter) ratio was reduced from the standard 11.4-in. length for 6.0 ID cylinders to an L/D of less than 1.0 to simplify the evaluation of the laminate by obtaining a yield failure, and to maintain the costs of the thicker and larger diameter cylinders within the working budget.

k. Composite stress values obtained in wall thicknesses up to 1-1/4 in. have not only been maintained but consistently improved.

B. MECHANICAL TESTING OF RINGS AND RING SEGMENTS

Rings or ring segments from all test cylinders fabricated during this period were mechanically tested for horizontal and axial shear and for compressive modulus. These tests were conducted to not only verify the fabrication processes but to determine any possible correlation between specific mechanical and physical properties and the properties indicated by cylinder hydrotest results.

The ring bending test is now being used to obtain the compressive modulus of rings of different diameters. This type of test has been substituted for the hydraulic ring compression test since the ring compressive fixture will accept rings of up to 6.625 in. maximum diameter only.

Values for ultimate compressive yield stress have not been attained because of difficulties with the hydraulic bag of the compression test fixture. This fixture was "proofed" on several rings and worked satisfactorily. A leak developed in the hydraulic bag during calibration and the bag is being repaired.

Cylinder rings and segments tested during this period were as follows:

Cylinder No.	t Thickness in.	b Width in.	Horizontal Shear σ psi*	Axial Shear Stress σ psi**	Compressive Modulus $\times 10^6$ psi***	Resin %
TW-10	0.402	0.251	9,770	7,356	2.9	19.78
TW-11-1	0.443	0.253	10,412	7,206	2.8	21.04
TW-11-2	0.437	0.255	--	--	2.7	21.04
TW-12	0.404	0.248	9,458	7,038	2.9	19.16
TW-13	0.381	0.253	10,103	8,904	3.3	19.6
TW-14	0.496	0.249	11,458	7,654	3.1	20.5
TW-15-1	0.601	0.252	10,793	7,869	3.1	20.7
TW-15-2	0.750	0.252	--	--	3.1	20.7

* Horizontal interlaminar shear stress = $\frac{3}{4} \frac{P_u}{bt}$
(Specimen length = 1.0 in.)

** Axial interlaminar shear stress = $\frac{P_u}{D_s b}$

*** Compressive modulus = $E_c = \frac{1.786 r^3 \text{ avg}}{bt^3} \cdot \frac{P}{\Delta}$

where

P_u = ultimate pressure at failure, lb

P = pressure, lb

b = width, in., t = thickness, in.

D_s = diameter of sheared off ring, in.

r avg = average of inner and outer radius, in.

Δ = ring deflection at a specific pressure, in.

The following conclusions were made:

1. Values from mechanical tests show a smaller scatter of results and generally higher values for both horizontal and axial shear than during the previous quarter. These higher values are indicative of improvements instigated in test cylinder fabrication.

2. Tests verify that resin percentage has been held extremely constant, furnishing an excellent base for comparison of cylinders with other resin percentages.

3. No correlation of data from the mechanical tests and the hydrotest results can be made due to the limited number of tests and because of the differences in failure mechanism (due to cylinder geometry) during biaxial hydrotest.

4. Tests will continue with emphasis placed on the determination of any correlation between results of ring tests and biaxial hydrotests.

V. PHOTOMICROGRAPHIC ANALYSIS

Photomicrographic analysis has been utilized to investigate the composite microscopic structure. This analysis has been used in a random manner to take a close look at some of the more obvious construction deviations. Photomicrographs included in this report, therefore, cannot be construed as typical of the entire cylinder but rather as extremely localized conditions which may indicate trends for improvement areas.

Photomicrographs are taken of the inner and outer layers of rings from test cylinders to determine any physical change. A well-fabricated cylinder will have straight uniform layers, even resin dispersion, very few voids in any area, and an overall uniform appearance.

Figures 16 through 20 show some good examples of the type of minor deviations which have appeared on several of the cylinders during this period. A brief description is included with each figure.

The following conclusions were made:

A. Density of the composites has improved since dams were added to mandrels to eliminate movement of circumferential filaments. This is apparent by examination of Figure 16 (showing a microscopic section of TW-3, which was built without dams) and of Figures 17, 18, 19, and 20 (microscopic sections of cylinders that had dams).

B. Ability of the winding machine to accurately place filaments is of extreme importance in the elimination of resin pocket areas.

C. A definite resin layer appears adjacent to the inner surface of the longitudinal layer. This has been concluded as being due to the method of fabricating the tape and is being investigated.

D. Very little layering between plies of prepreg is noted, confirming that application of heat during winding has helped to gain a more thorough dispersing of adjacent plies into a layer.

VI. FUTURE WORK

Additional design analysis will be conducted on methods of fabricating thick-walled cylinders. Most of the investigation will be directed toward fabrication and test methods for the 12-in. dia and 24-in. dia scale effect cylinders.

Several additional cylinders will be either completed or fabricated. TW-20, the 4-in. thick, 12.0-in. ID part will be completed and tested. TW-19 cylinder, 0.750-in. thick, required for creep and fatigue tests, will be fabricated. Two 0.500-in. thick x 6.0-in. ID x 11.40-in. long cylinders and two 0.750-in. thick x 6.0-in. ID x 11.40-in. long cylinders will be fabricated for shipment to David Taylor Model Basin.

Several cylinders, already fabricated (TW-16 to -18) will be hydrotested to furnish significant data related to step-cured method of fabrication. Creep and fatigue tests will begin on 5.0-in. long cylinders cut from TW-14 and TW-19. Permeability and diffusion tests will be completed on 4.0-in. long cylinders cut from TW-13.

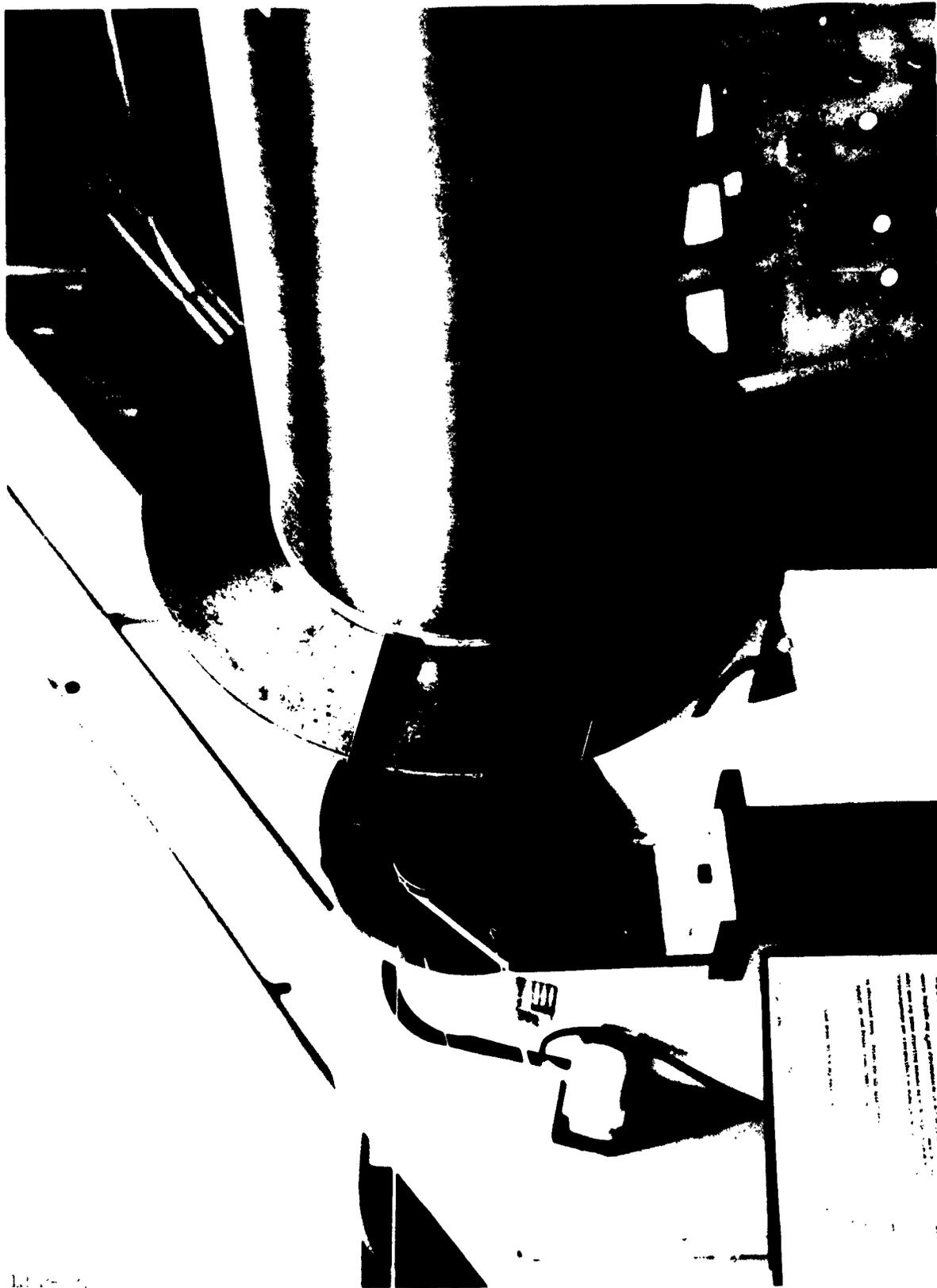
Photomicrographic analysis of typical cylinder cross sections will be made to closely examine cross section construction.

Tests of rings cut from cylinders will continue to determine if any significant correlatable values are possible.

Additional units of the Aerojet creep and fatigue facility will be completed.

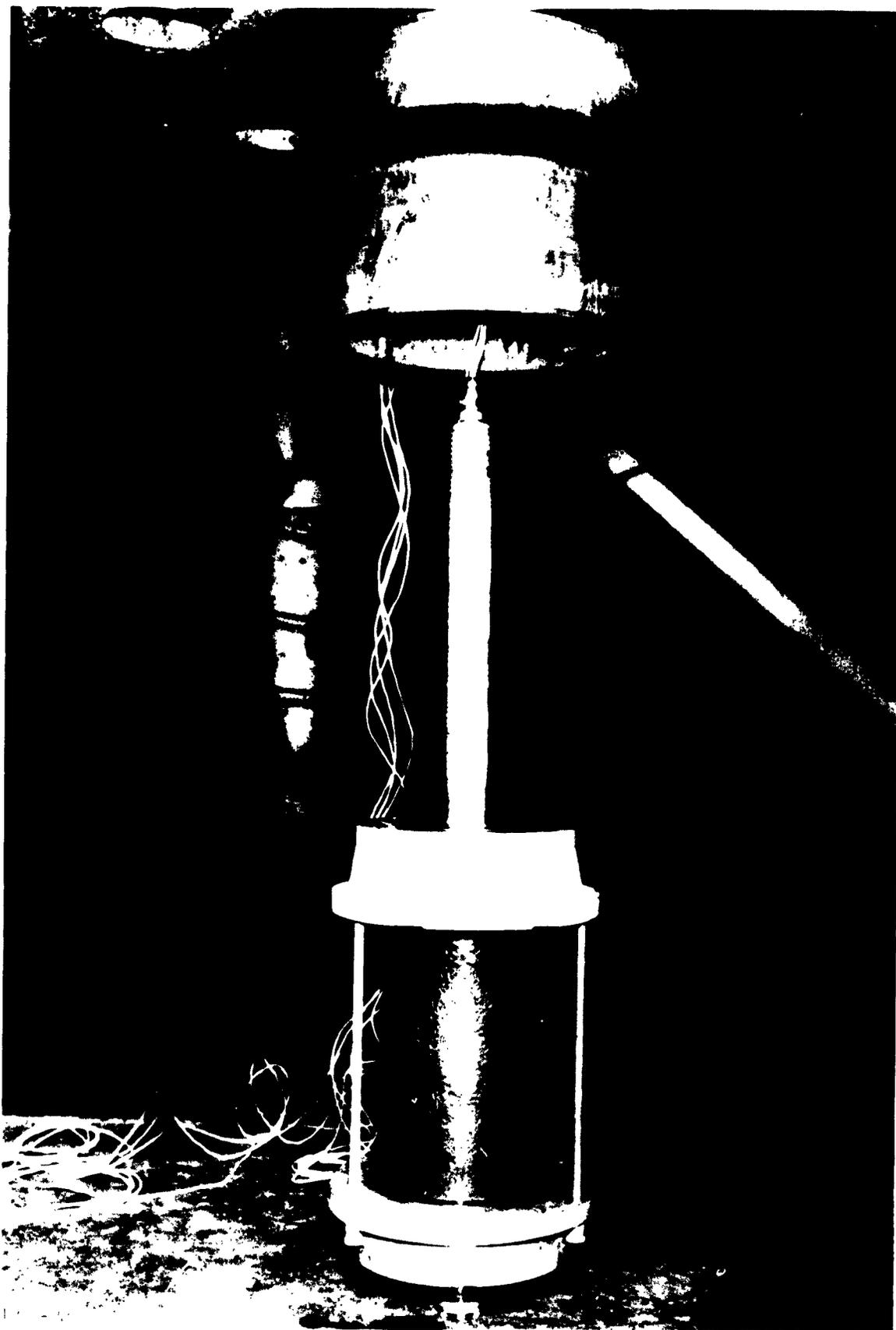
TABLE 1 (cont.)

Cylinder No.	Thickness in.	ID in.	Length in.	P _c psi	σ_{ϕ_1} psi	$E_{eff} \Delta$ X10 ⁶ psi	Weight/Displacement	Remarks
15-1	0.602	6.000	10.019	14,000	91,476	5.13	0.625 } 0.650 }	1.25-in. thick bulk cured cyl; 5 lb const. tension, 15-1 and 15-2
15-2	0.750	7.032	9.992	14,900	92,976	5.37		
16-1-2	0.750	6.00	11.4	Ready for test				Step-cured cylinder, 5 lb const. tension
17-1	0.526	6.000	11.40	DTMB Delivery Cylinder			0.567 } 0.567 }	2:1 ply dispersion, 5 lb const. tension. Reverse wound circs.
17-2	0.526	6.001	5.000	16,000	115,725	--		
18-1,-2,-3,-4	1.250	6.000	5.000	Ready for test				Step-cured cylinder, 5 lb const. tension
19-1,-2,-3	0.750	6.000	5.00	Creep and Fatigue tests				5 lb const. tension
20	4.00	12.00	--	In Process of Fabrication				(4) 1-in. steps - 5 lb tension
21-1,-2	0.500	6.000	11.40	(2) DTMB Delivery Chambers - in process				5 lb const. tension



Winding of Circumferentials on 12.0-in. Dia Mandrel

13-7-61



6.0-in. ID Cylinder Mounted on Test Fixture

Figure 2



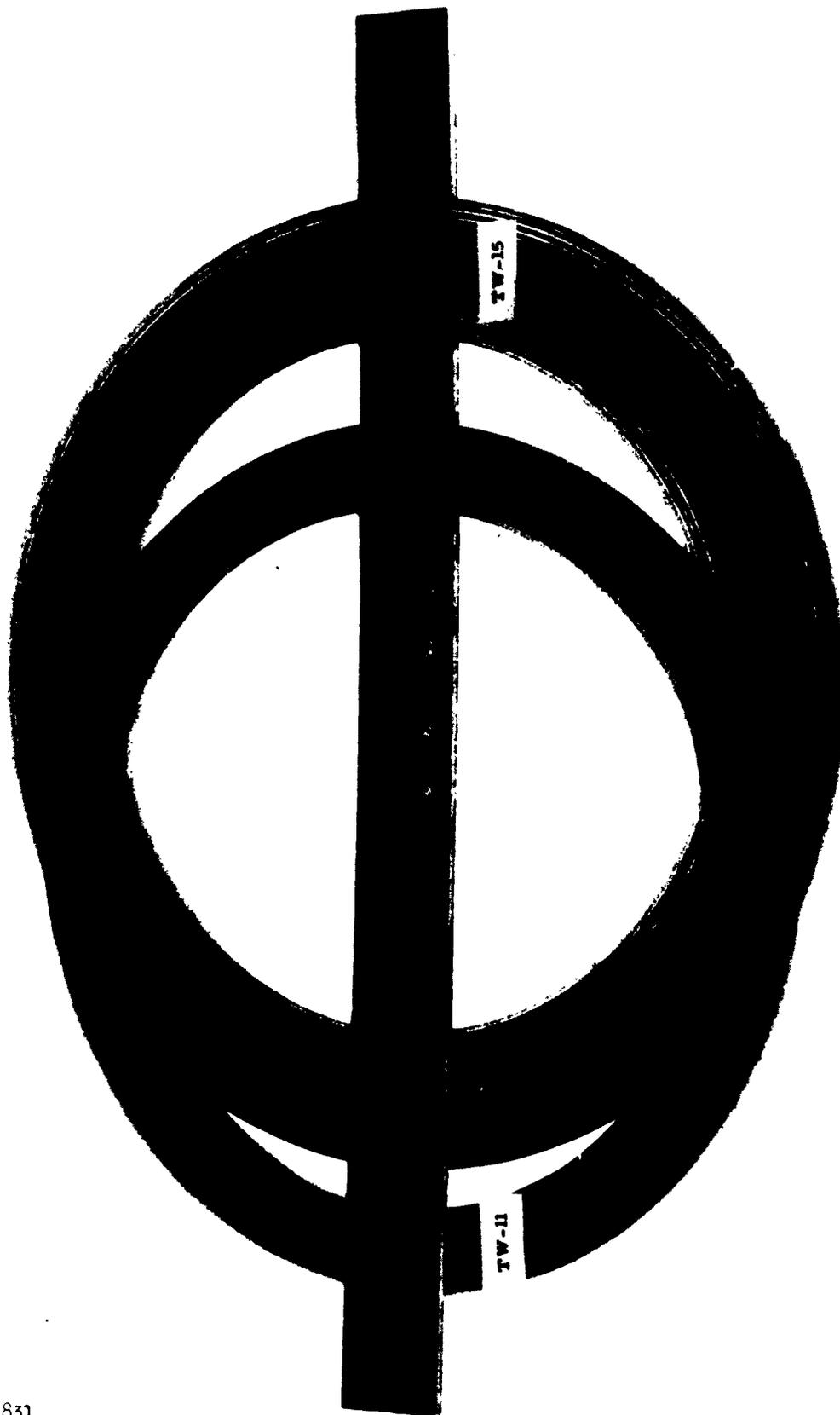
062-075

TW-10-1 Showing Typical Hydrotest Failure



TW-11 Cylinder and 6.0-in.-Dia Steel Mandrel

Figure 4



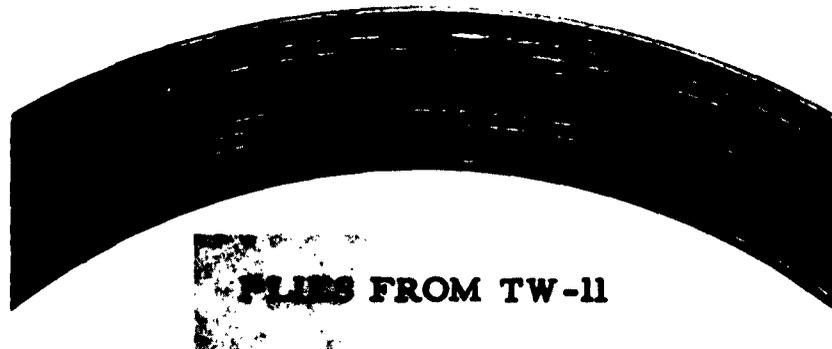
Polished Rings From Cylinders TW-11 and TW-15

1162-831



TW-15

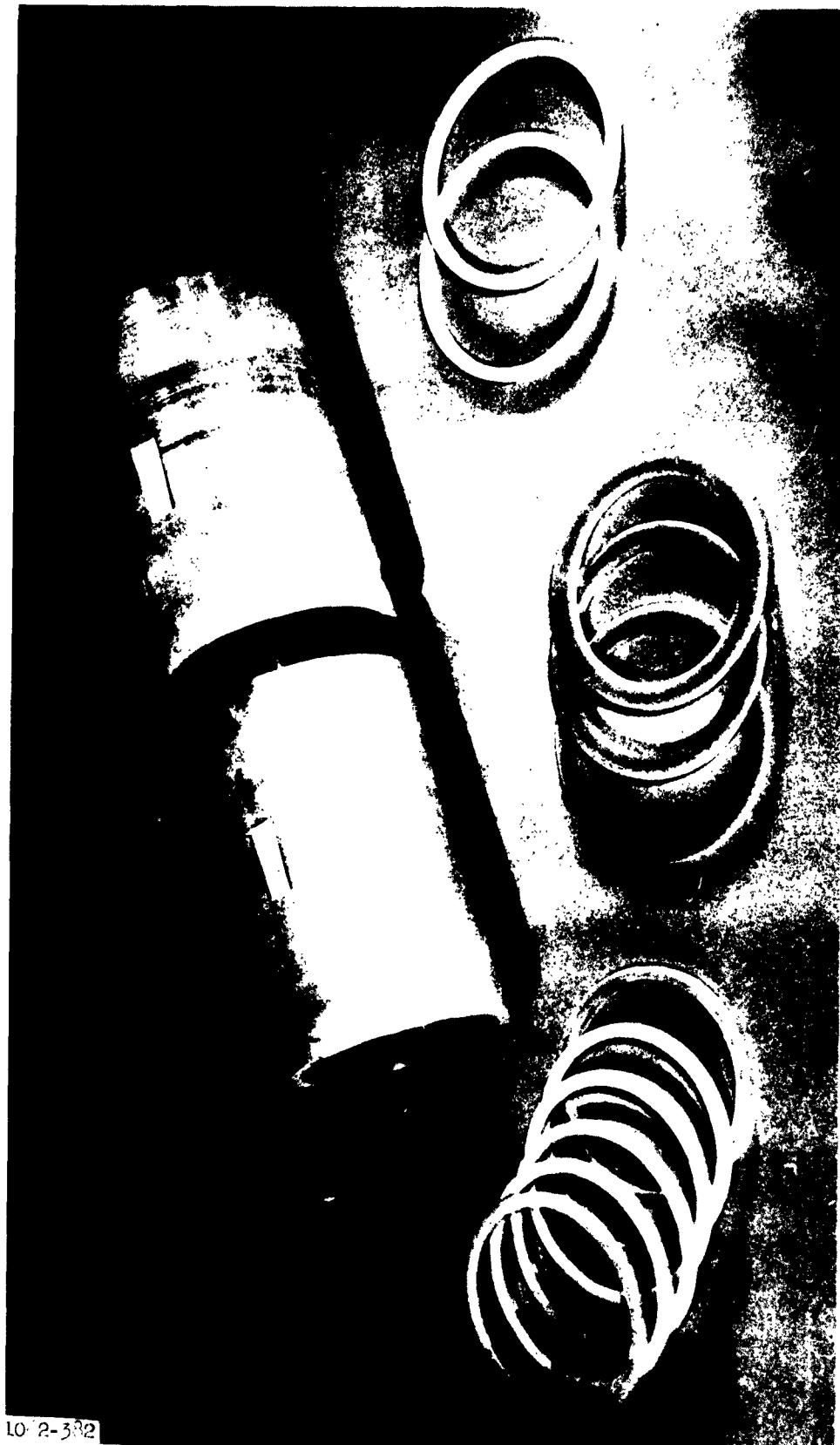
Shows Consistently Straight Circumferential Filaments & Uniform Longitudinal Filaments



TW-11

Notice the Wavy Condition in the Outer Plies Indicating a Loss of Tension & Fiber Movement.

Plies from Cylinders TW-11 and TW-15



Test Cylinders and Test Rings Cut From TW-11

Figure 7

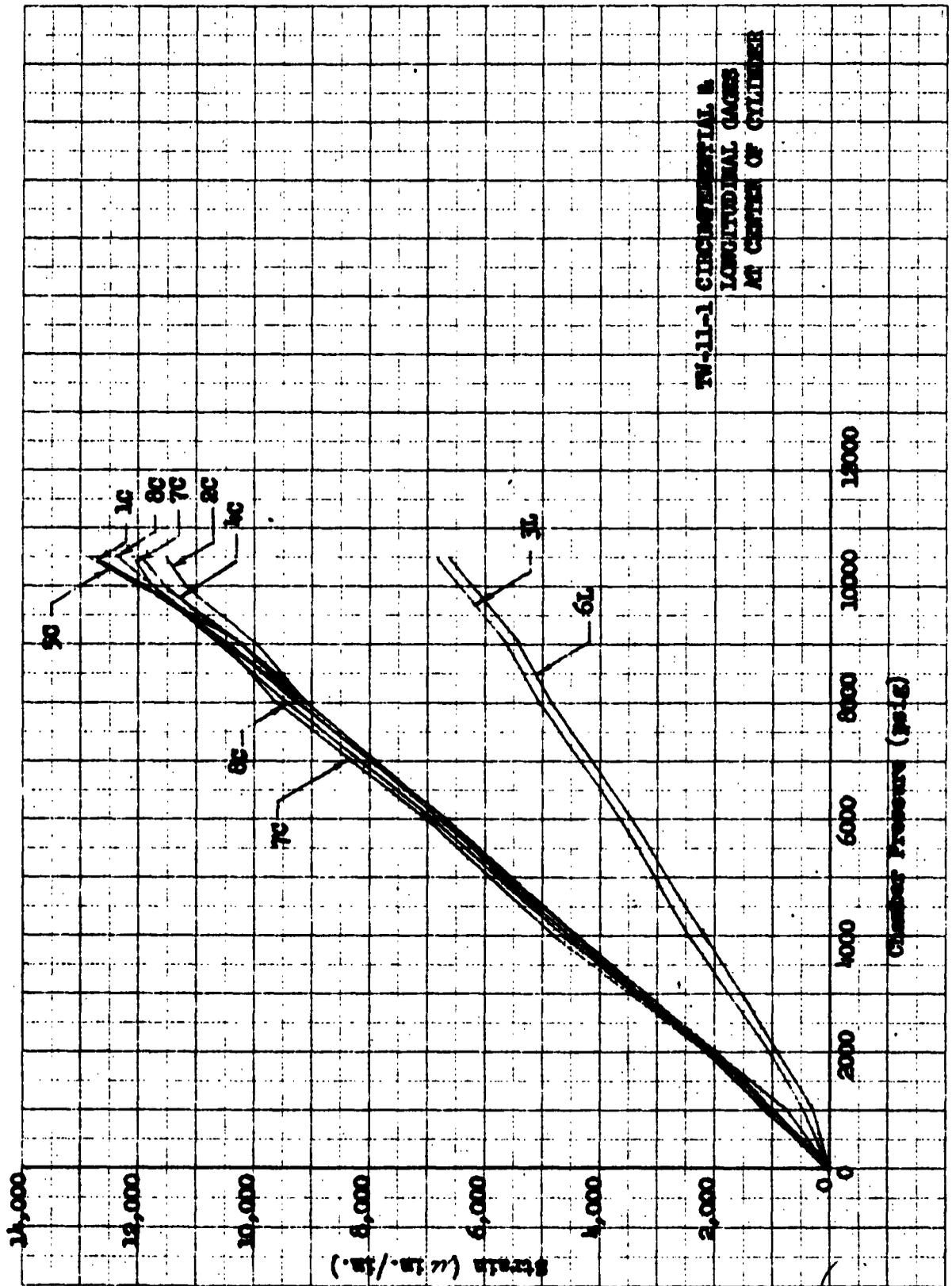


Figure 8

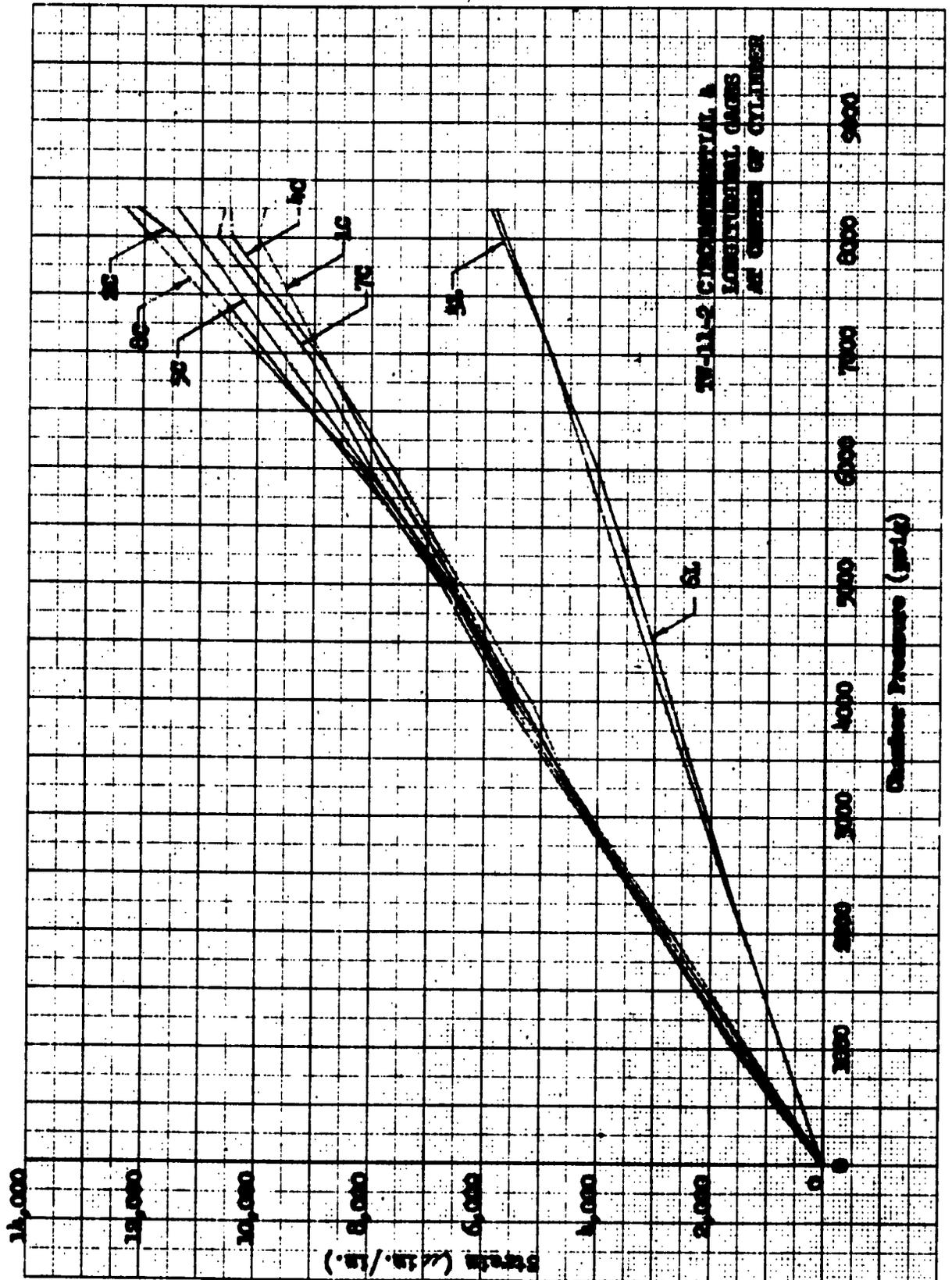
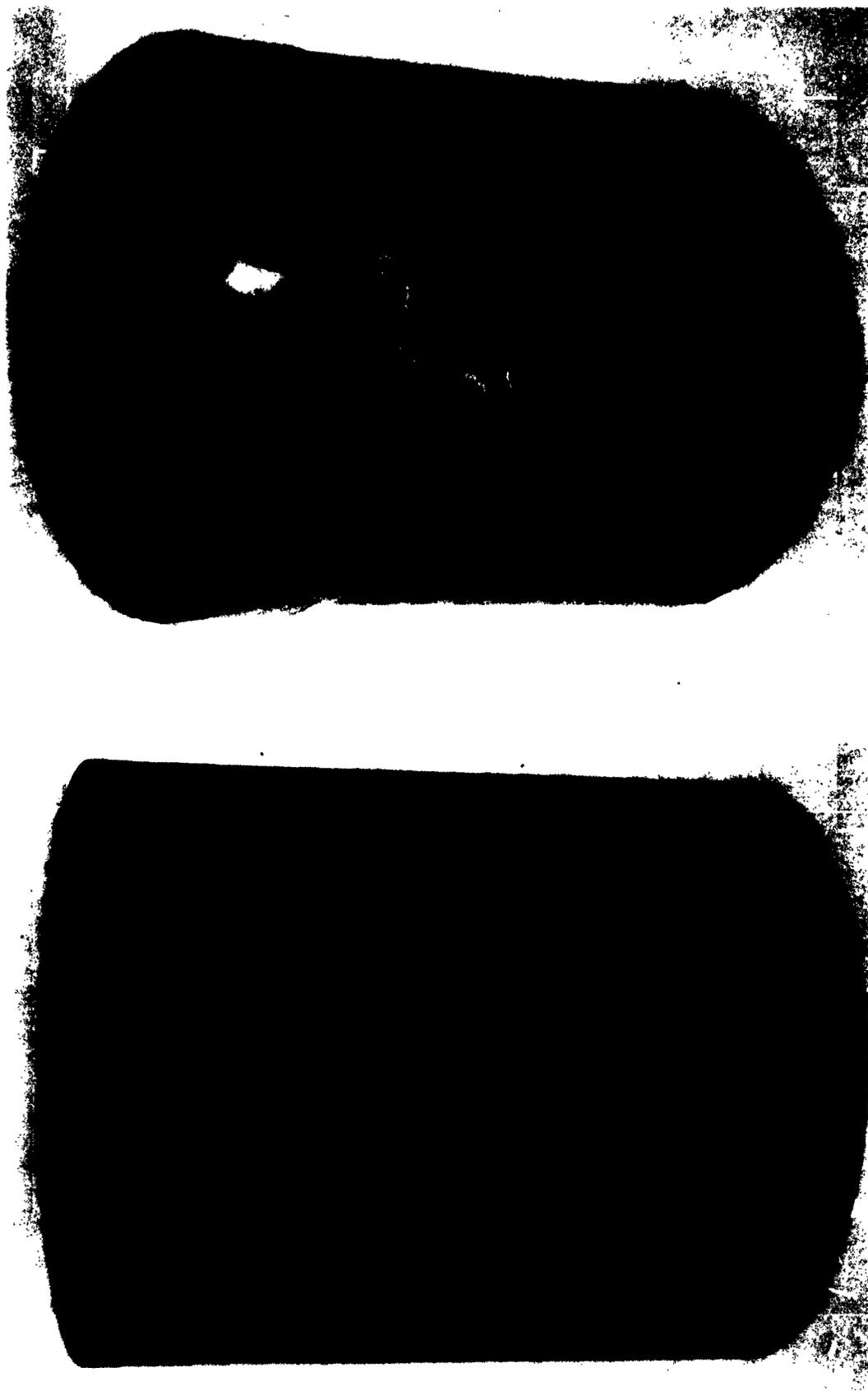


Figure 9



TW12-1 Cylinder, Outer & Inner Views After Hydrotest



TW15-2, Before and After Hydrotest

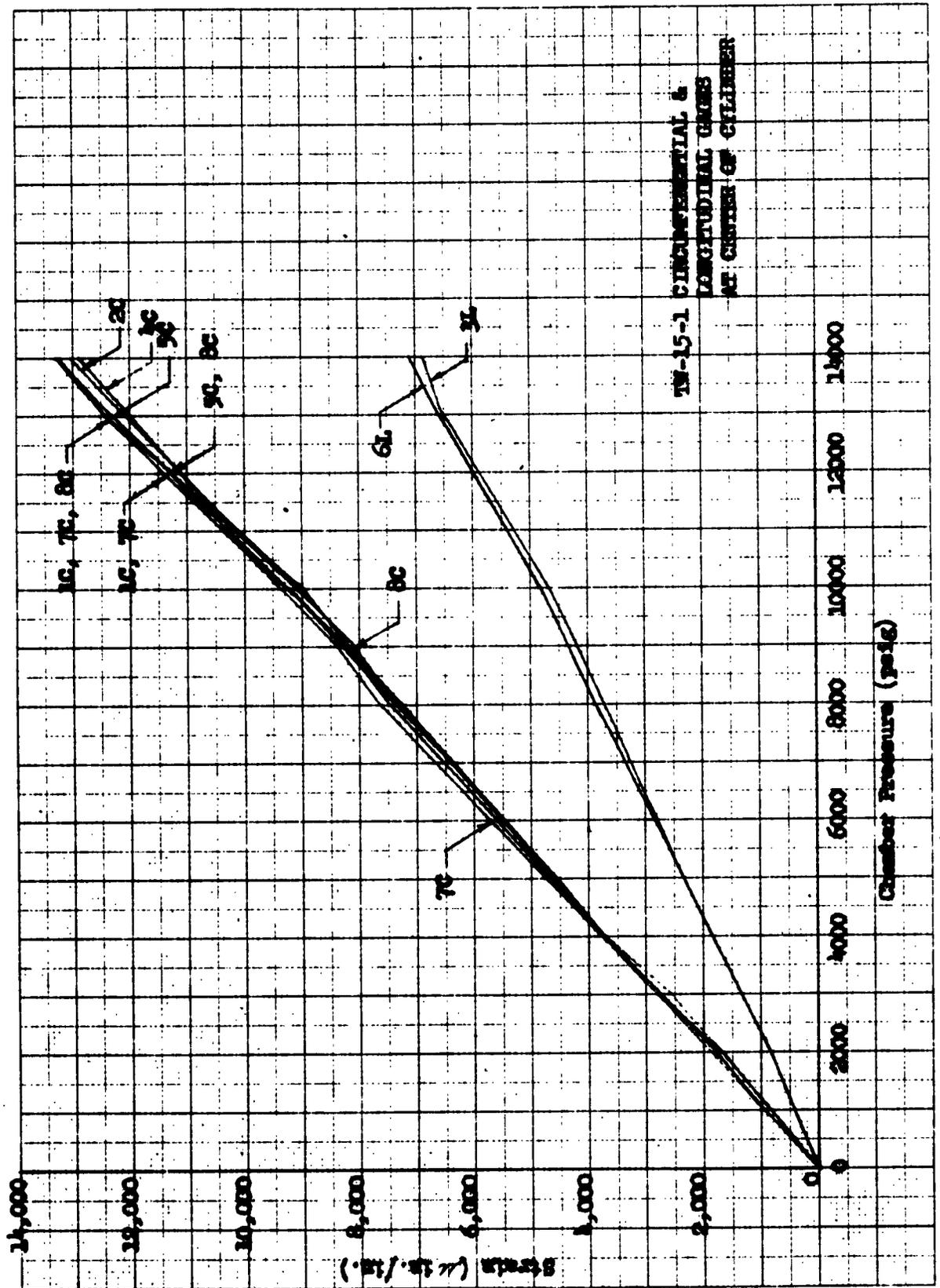


Figure 13

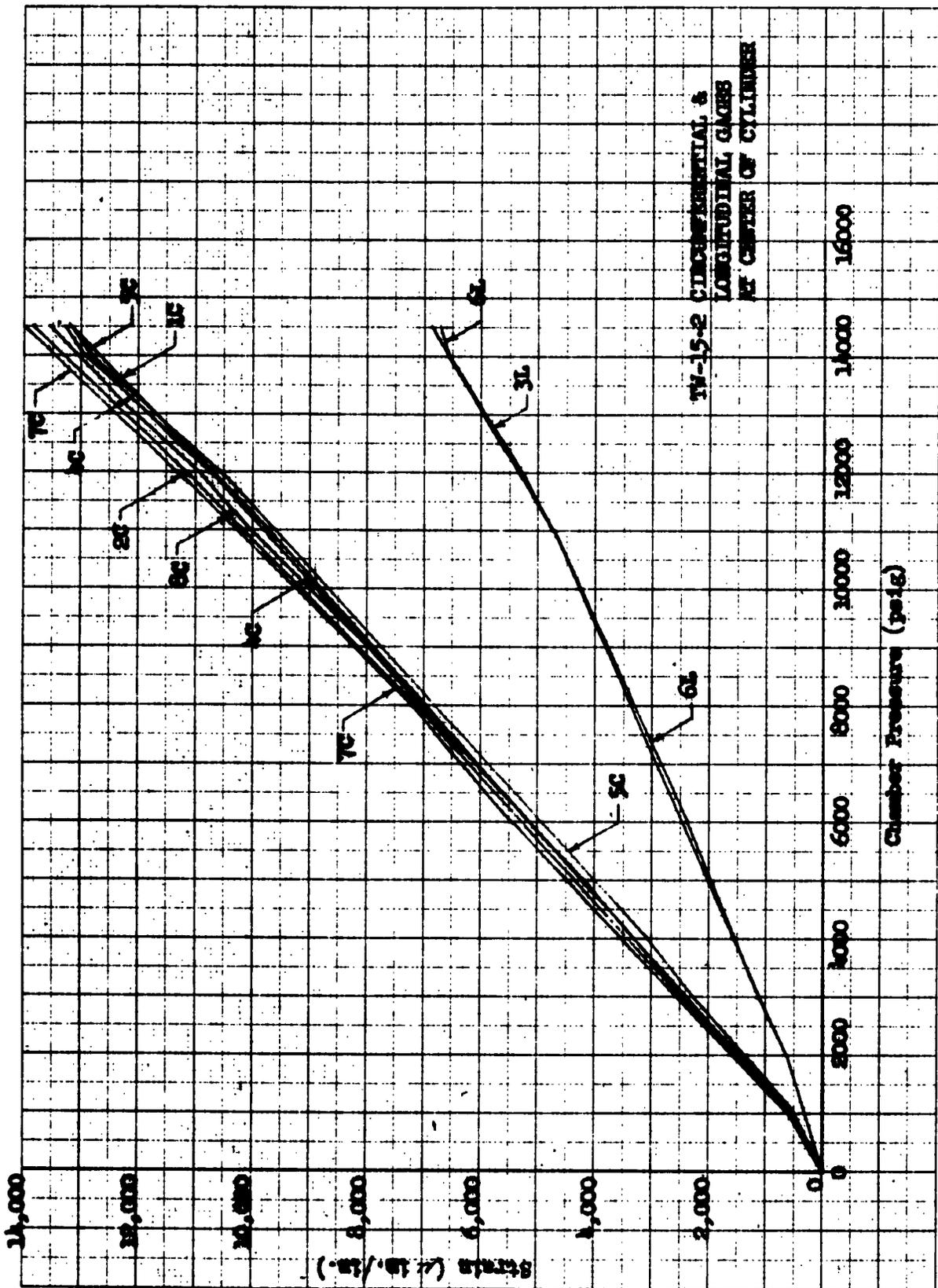


Figure 14



TW-18, 1.250-in. Thick X 6.0-in. ID Cylinder



Circ.

Long.

Circ.

(3) Outer Plies



Circ.

Long.

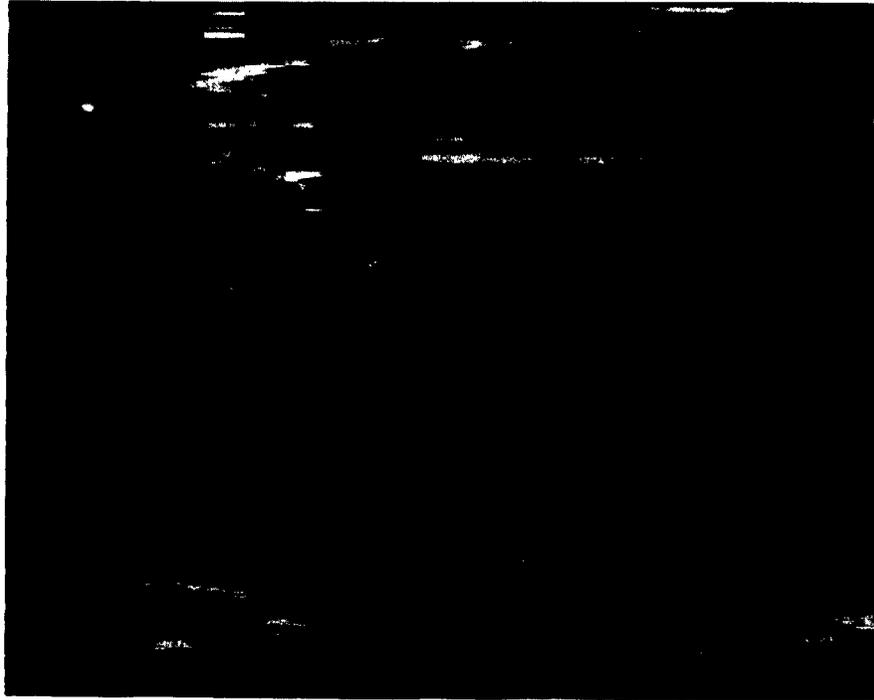
Circ.

(3) Inner Plies

TW-8 View Looking at Ends of Circumferential Filaments. Example of Insufficient Pressure During Cure and Voids in the Outer Plies Caused by Loss of Tension.

TW-8 Photomicrographs

Figure 16

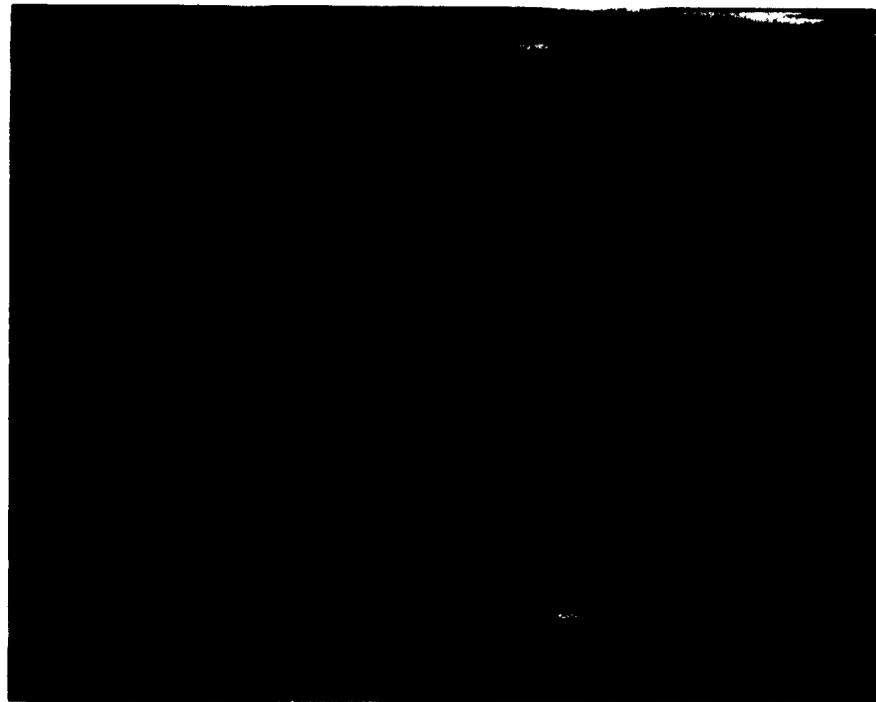


Circ.

Long.

Circ.

(3) Outer Layers



Circ.

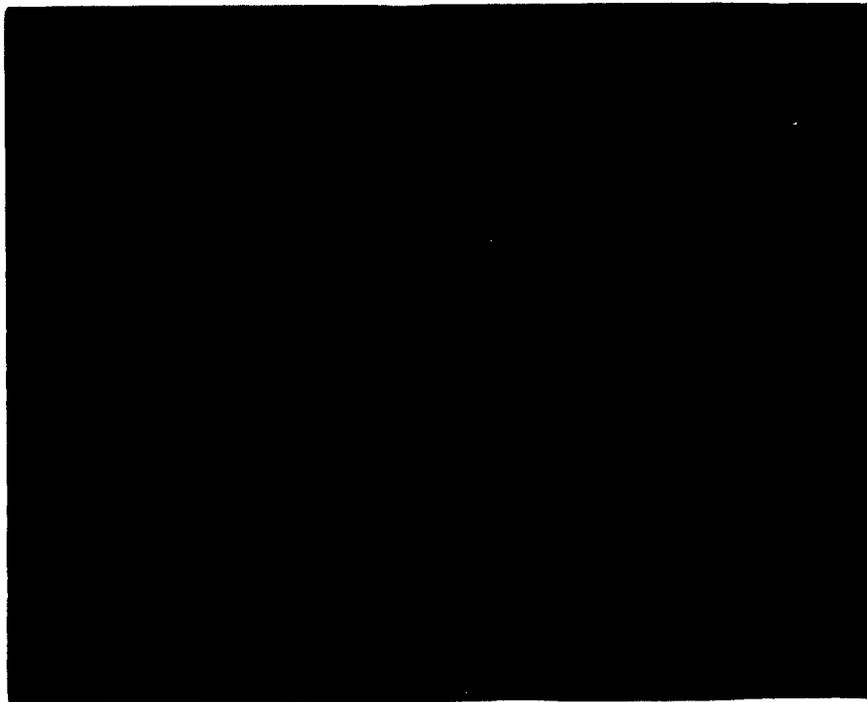
Long

Circ.

(3) Inner Layers

TW-9 Looking at ends of Longitudinal Filaments (100X).
A Good Example of Dense Windings with Some Indication of Resin
Planes Between Plies. The Wide Grey Area is Resin.

TW-9 Photomicrographs



.Circ.

.Long

Circ.

(3) Outer Plies



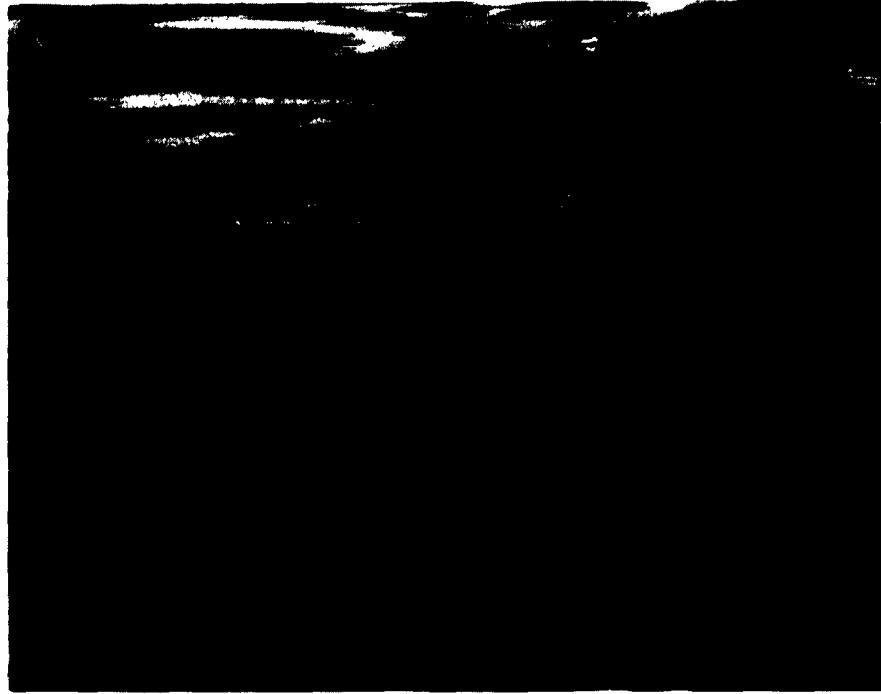
Circ.

Long.

Circ.

(3) Inner Plies

TW-12 Looking at Ends of Longitudinal Filaments (100X).
Resin Layer Between Inner Surface of Longitudinal and Circ.
This is Inherent in the Method of Fabricating Unidirectional Tape.

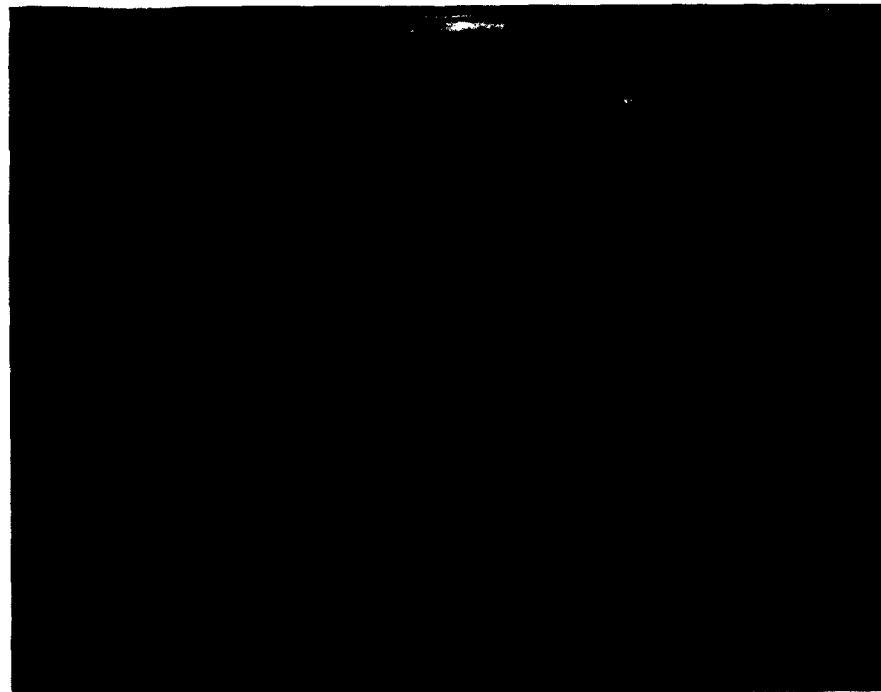


Circ.

Long.

Circ.

(3) Outer Plies



Circ.

Long.

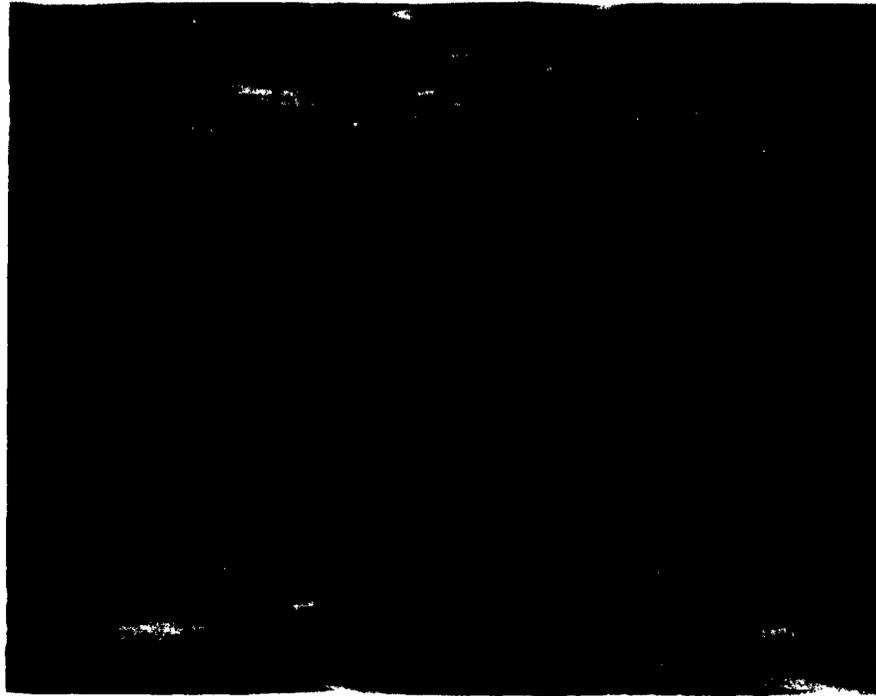
Circ.

(3) Inner Plies

TW-13 Looking at Ends of Longitudinal Filaments.
An Excellent Example of Uniform Construction with Good
Longitudinals and Few Resin-Rich Areas.

TW-13 Photomicrographs

Figure 19



Circ.

Long.

Circ.

Looking at ends of Longitudinal Filaments
Showing Good Longitudinal Layer



Circ.

Long.

Circ.

TW 15-1 Looking at Ends of Circumferential Filaments
Showing Generally Good Circumferential Filaments

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