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LINERS FOR NON-METALLIC TANKS

by

John T. Hoggatt

L. J. Workman

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FINAL REPORT

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ABSTRACT

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The uniaxial and biaxial elongation properties of Kapton polyimide film were determined at -423°F. Cylindrical liners were cyclic tested to failure at liquid hydrogen temperatures to establish the potential of Kapton as a filament-wound tank liner material for liquid hydrogen containment.

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LINERS FOR NON-METALLIC TANKS

by

John T. Hoggatt and L.J. Workman
The Boeing Company

SUMMARY

E. I. duPont's Kapton polyimide film, in 3- and 5-mil thickness, was evaluated to establish its stress-strain characteristics at -423°F. The program was divided into two tasks. In the first task, the strength properties were determined and a joint-bond study conducted with the film. A total of 82 uniaxial and 34 biaxial strain tests were performed. The joint-bond study incorporated four adhesive systems and three joint concepts. In Task II eight filament-wound cylinders were fabricated with 3-mil Kapton liners. These specimens were evaluated for ultimate strain and ultimate cyclic capabilities at -423°F.

Kapton film has a uniaxial elongation of 9% and a biaxial elongation of 15% at -423°F; sufficient elongation to serve as a filament-wound tank liner for the pressurized containment of liquid hydrogen. A liner demonstrated, in single-cycle burst tests, biaxial elongations in excess of 2.5%. The polyimide film, however, does not serve reliably in cyclic applications at -423°F. In cyclic tests, Kapton liners failed after six cycles at 1.2% strain.

G-207 adhesive system, a polyester, was the best of those evaluated for cryogenic usage. Elongation of the Kapton-to-Kapton adhesive bonded joint ranged from 1 to 3%. The strength of the joint was adequate. However, the ultimate tensile strength of the film was seriously lowered in the bonded region.

Based on the results of this program, Kapton film is deemed unsatisfactory for the pressurized containment of liquid hydrogen in non-metallic vessels due to its low cyclic reliability.

INTRODUCTION

The potential advantages of filament-wound fiberglass construction for cryogenic tankage and plumbing are widely known and have been demonstrated in the aerospace industry. These include high strength-to-weight ratio, insulative properties, and ease and low cost of fabrication. The development of this potential has been slow due to the lack of reliable, leak-free liners capable of meeting the strain requirements of filament-wound composites.

To realize the greatest weight saving in a filament-wound fiberglass tank, the tank should be designed for operational strains in excess of 1.5 percent, with a strain at burst of 3 to 4 percent. For room-temperature applications, and where the tank contents are not highly reactive, synthetic rubbers have been used as liner materials. They have a total strain capability far in excess of the fiberglass composite and the rubber is quite impermeable. Since the strains are essentially elastic, the rubber liner assumes its original size upon depressurization. As temperature is decreased, rubber and all polymeric materials exhibit severe decreases in yield and total strain capabilities, while the strain characteristics of the fiberglass composite appear to be only slightly affected.

Unsuccessful attempts have been made to utilize Teflon and Mylar film liners for cryogenic containment*. Each of these materials lacked sufficient elongations to withstand the required strains. Boeing, working at -320°F, had good test results with E.I. duPont's Kapton polyimide film in liner applications. Burst and cyclic test results indicated Kapton may serve as a liner at liquid hydrogen temperatures as well. This program, initiated by Boeing, was sponsored by NASA to investigate that potential.

The goal of this program was to achieve, at -423°F, a minimum of 25 cycles, at the highest possible strain rate, with a Kapton film liner.

* See References 2, 3, 4 and 5.

TEST PROGRAM

Task I

MATERIAL SELECTION

Kapton

Rolls of standard Kapton film were purchased from E.I. duPont and screened at Boeing using tests developed under an in-house program (Reference 1). It was discovered under this program that the biaxial strain characteristics of Kapton varied from roll to roll and sometimes within a given roll. These differences were not detectable in uniaxial strength tests at room temperature or -320°F, or in biaxial tests at room temperature. However, at -320°F a definite difference could be detected in the biaxial strain properties. Figure 1 shows the difference in strain properties between a considered "good" film and rejected material and the limits of acceptability. It was discovered that the limits of acceptability could be applied to both the 3- and 5-mil films.

Investigational efforts in-house and in conjunction with the E.I. duPont Company have failed to give an explanation for this phenomena.

All received film was screened by checking thickness, uniformity and quality. All material showing total thickness variation greater than 1/2 mil, "fish-eyes", or foreign matter was discarded.

Samples were taken periodically from the remaining material and tested at -320°F (LN_2) using the diaphragm burst test (biaxial strain). All material not producing acceptable strain curves was discarded.

Boeing studies (Reference 2) with Kapton have shown that there is no significant difference in the strength properties of Kapton between the roll and transverse directions. (tensile strength at -320°F: 45,000 psi roll direction; 43,500 psi transverse direction). However, for this program, to maintain uniformity, all test specimens were cut in the roll direction. On the test cylinders, the liners were constructed so that the roll direction was in the circumferential direction.

Plain Film - Uniaxial Strain

Three- and five-mil Kapton film specimens (Figure 2) were evaluated at -423°F for ultimate tensile strength and elongation. Each specimen was cut and evaluated in the roll direction. Summarized in Table I, are the results of these tests. The test equipment and procedures utilized are described in Uniaxial Tensile Tests.

Joint Configuration and Adhesive Studies - Uniaxial Strain

Three joint configurations and four adhesive systems were evaluated in this subtask. The joint configurations shown in Figure 3 and the adhesive systems shown below were evaluated with both 3- and 5-mil Kapton film. Seventy-two (72) tensile specimens were fabricated and tested at -423°F (see Table I for results). All samples were cut from the roll direction.

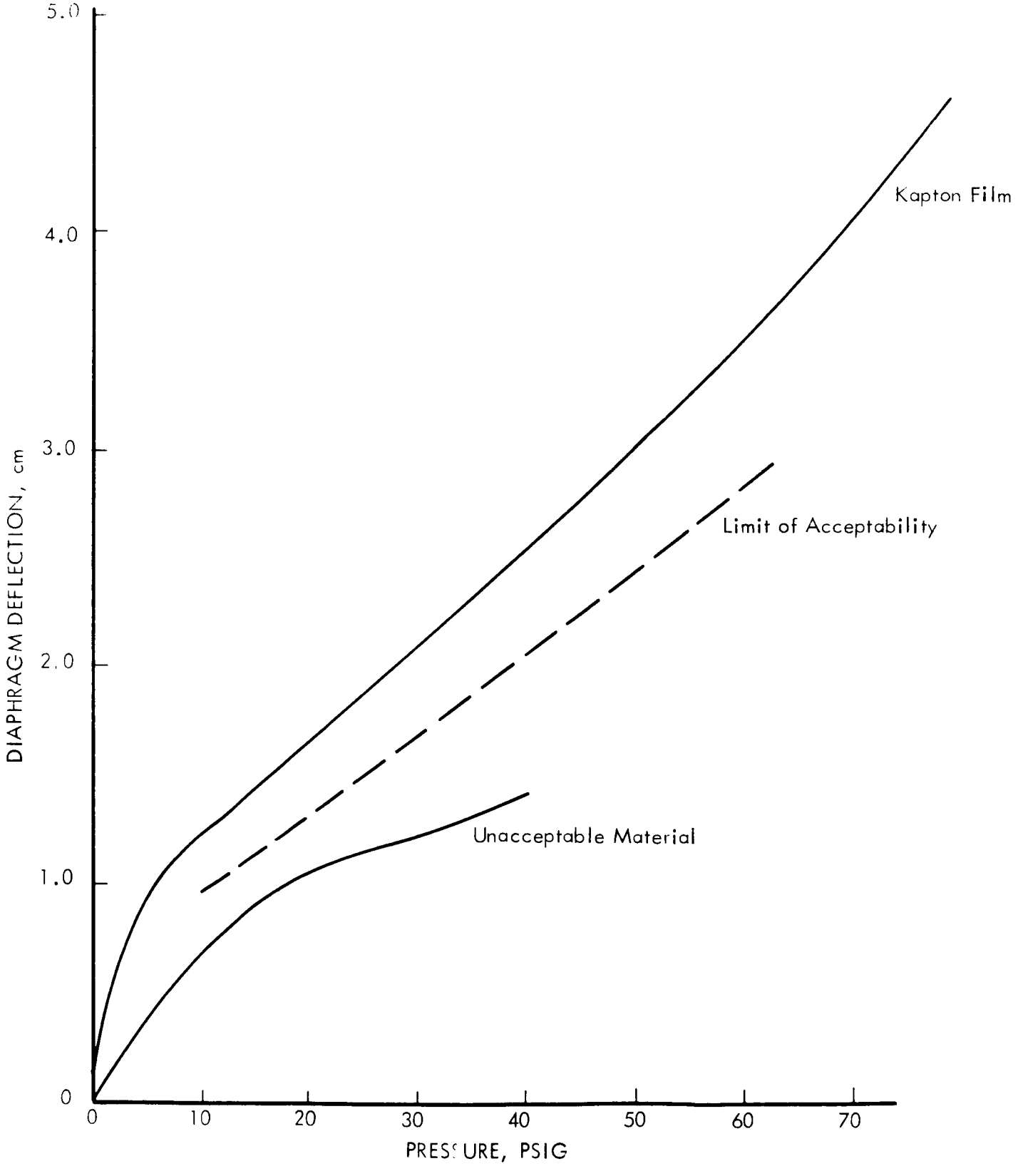


FIGURE 1 - DIAPHRAGM TEST - DEFLECTION OF KAPTON FILM AT -320°F

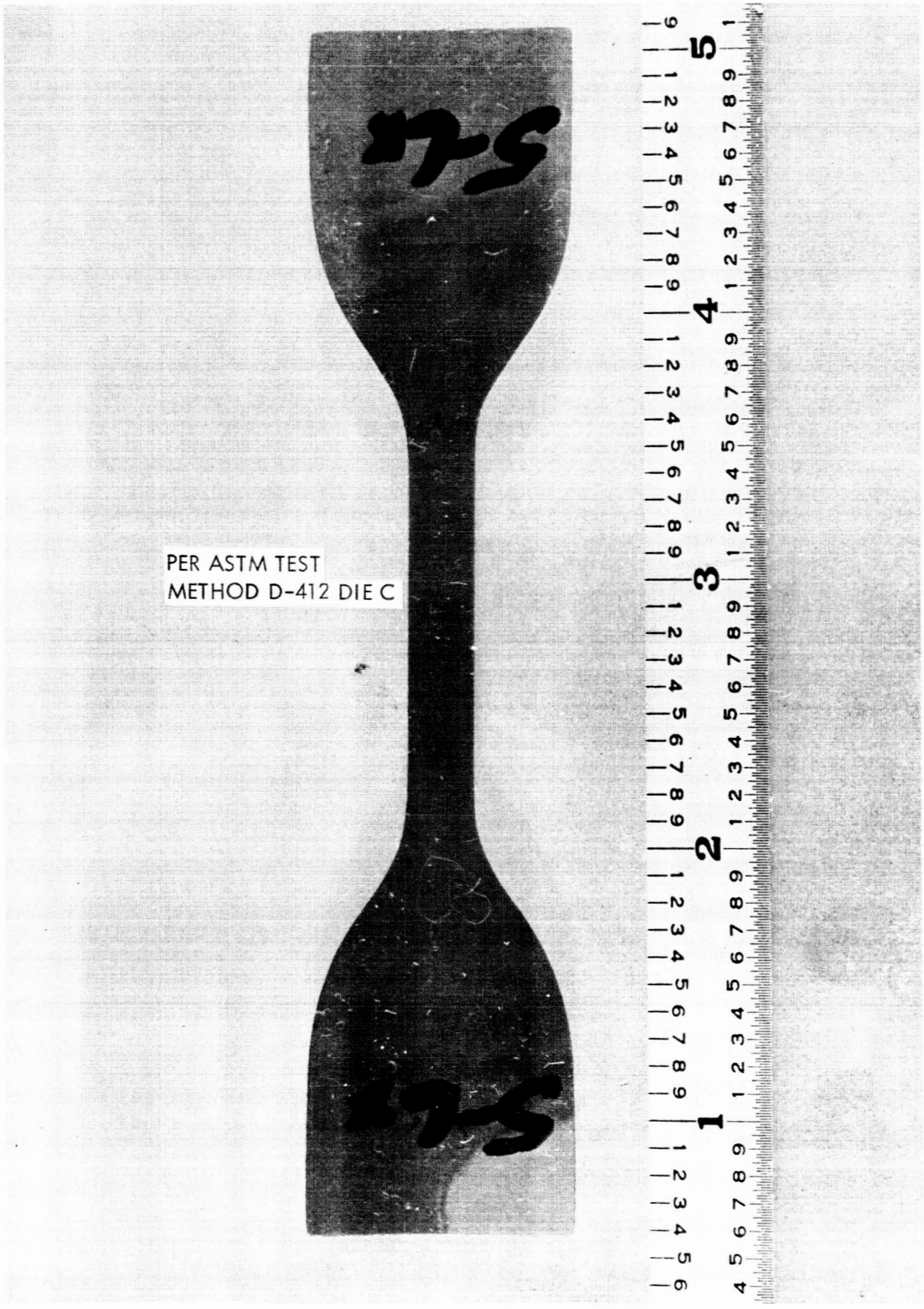
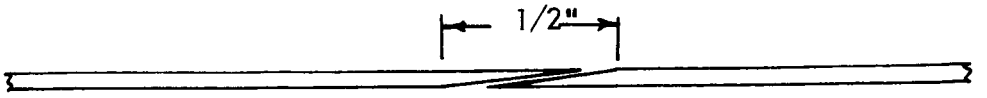
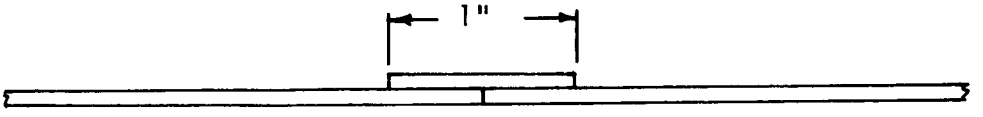


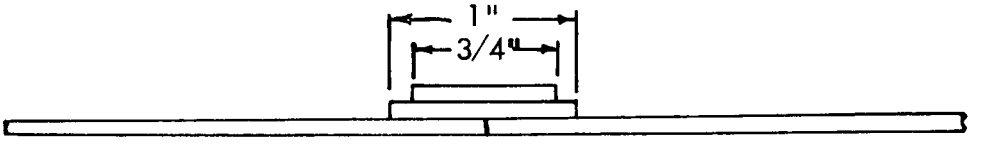
FIGURE 2 - TENSILE SPECIMEN - UNIAXIAL STRAIN



Configuration A - Lap Joint



Configuration B - Butt Joint with Doubler



Configuration C - Butt Joint with Reinforced Doubler

FIGURE 3 - JOINT CONFIGURATIONS - BOND STUDY

Adhesive Systems

Resin	Hardener	PHR	Resin Type
Epon 828[a]	Dion RP 7A[e]	15	Epoxy
Narmco 7343[b]	Narmco 7139	11	Polyurethane
46971[c]	RC-805	2.5	Polyester
G207B[d]	G207C	4.0	Polyester

[a] Shell Chemical Company

[b] Narmco Materials Division, Whittaker Corporation

[c] E.I. duPont de Nemours & Co., Inc.

[d] Goodyear Aerospace Corporation

[e] Chemical Process Company

The uniaxial bond specimens were fabricated as follows: 4-1/2" x 6" sheets of film material were cut from the desired rolls and mated to form a sheet 9" x 6". The lap joint specimens were an exception in that the final sheets were 8-1/2" x 6" due to the 1/2" overlap. After checking for alignment, all bond areas were masked and lightly sanded with 115 grit sandpaper. The lap specimens (Configuration A) were sanded to a feather edge. The bond areas were solvent cleaned with MEK three times prior to bonding with a 10 minute waiting period between cleanings and a 30 minute waiting period prior to bonding. The respective adhesive systems were applied to the films and the films positioned, secured and swept to remove all excess resins and entrapped air. A vacuum blanket was then placed over the specimens and a minimum of 20 in. Hg vacuum applied. After sweeping the specimens a second time, the adhesive systems were permitted to cure at 80°F for 12 hours and at 150°F for an additional 24 hours. Heat lamps were used to provide the temperature requirements. Six test specimens 1" wide were cut from each of the finished sheets and inspected (see Figure 4). From the six, three specimens were selected for test. The specimens were tested as described under Uniaxial Tensile Tests.

Plain Film - Biaxial Strain

Five, 5-mil diaphragms and five, 3-mil diaphragms were evaluated for their biaxial strain capability using the diaphragm burst test (see Diaphragm Burst Test). The specimens had an overall diameter of 9-1/2" with 3/8 diameter holes on a 4-inch radius for mounting bolts. The test area was 7 inches in diameter. All diaphragms were tested at -423°F. See Table II for the results.

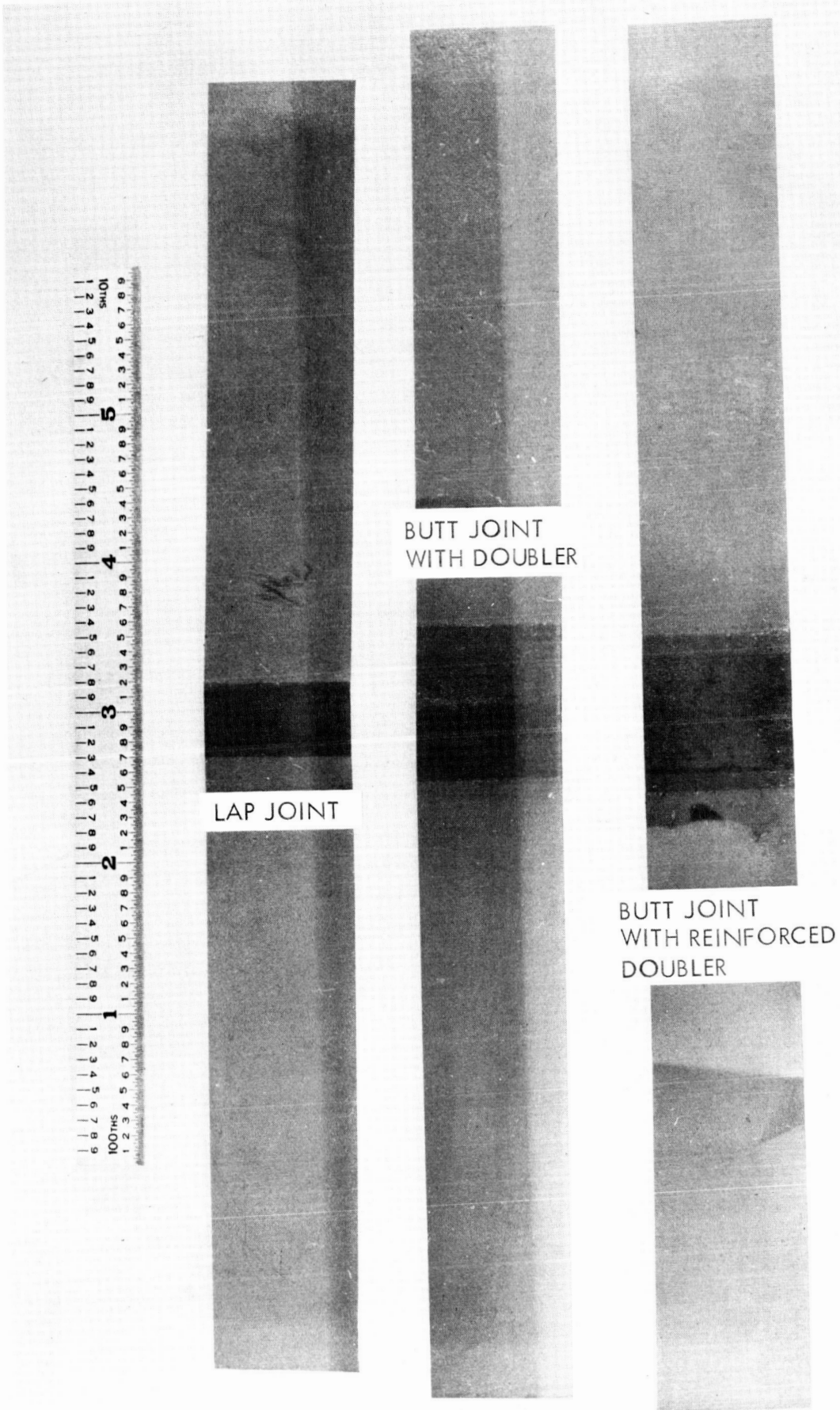


FIGURE 4 - TENSILE SPECIMENS - UNIAXIAL BOND STUDIES

Joint-Configuration and Adhesive Studies - Biaxial Strain

Two adhesive systems and two joint concepts were selected from the results of the uniaxial joint configuration studies for continuing evaluation in this portion of Task I. Goodyear's G-207 polyester adhesive and Narmco's 7343 polyurethane adhesive were the selected systems. The lap joint (Configuration A) and the butt-joint with a reinforced doubler (Configuration C) were the joint selections.

Three diaphragms were fabricated with each adhesive system in conjunction with each joint configuration for a total of 12 specimens using 3-mil Kapton film. Twelve (12) similar specimens were made from the 5-mil film. Each specimen was tested as described under Diaphragm Burst Test at -423°F (see Table III for results).

Task II

The purpose of Task II was to demonstrate the capabilities of Kapton polyimide film in a simulated filament-wound tank liner application. For this study eight cylinders 4-1/2" diameter x 16" long were fabricated using the film thickness, adhesive and joint configurations selected from the test results of Task I. These selections were 3-mil film with G-207 adhesive and a scarf joint.

Three cylinders were burst-tested and the remaining five cyclic tested to failure. Each cylinder was instrumented to measure the internal pressure, ultimate longitudinal strain and ultimate circumferential strain. Figures 5 and 6, respectively, illustrate how the strain measurements were made and the general specimen configuration.

Cylinder Fabrication

The same procedure was used to fabricate all 8 test cylinders.

A sheet of Kapton film was cut to size from the roll direction to permit a 1/2 inch overlap when wrapped over a 4-1/2 inch diameter mandrel. Each edge of the lap was then masked and scarffed, by hand, for a distance of 1/2 inch. The scarf was made using a fine grit abrasive paper. Each edge was then inspected for pinholes, tears, uniform thickness, etc.

The film and the bond areas were solvent cleaned, with MEK (Methyl Ethyl Ketone), three times prior to bonding.

Goodyear's G-207 adhesive system was applied to the bonding areas and the lap joint formed. The film was held in place by winding polyvinylalcohol tape, under tension, over the entire film. A sweeping of the bond line followed to remove any entrapped air and excess adhesive. The joint was permitted to cure 48 hours at room temperature. Final and complete curing of the adhesive is accomplished simultaneously with the curing of the filament wound case.

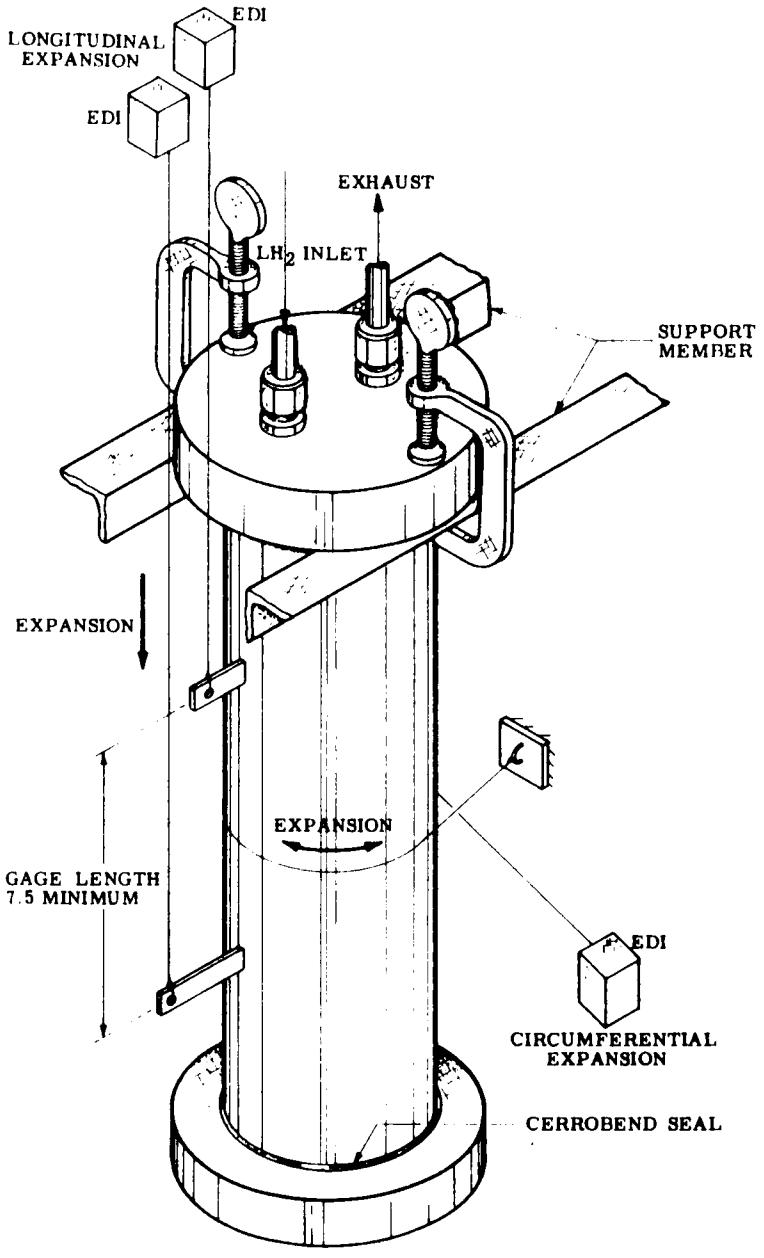


FIGURE 5 - INSTRUMENTATION OF TEST CYLINDER

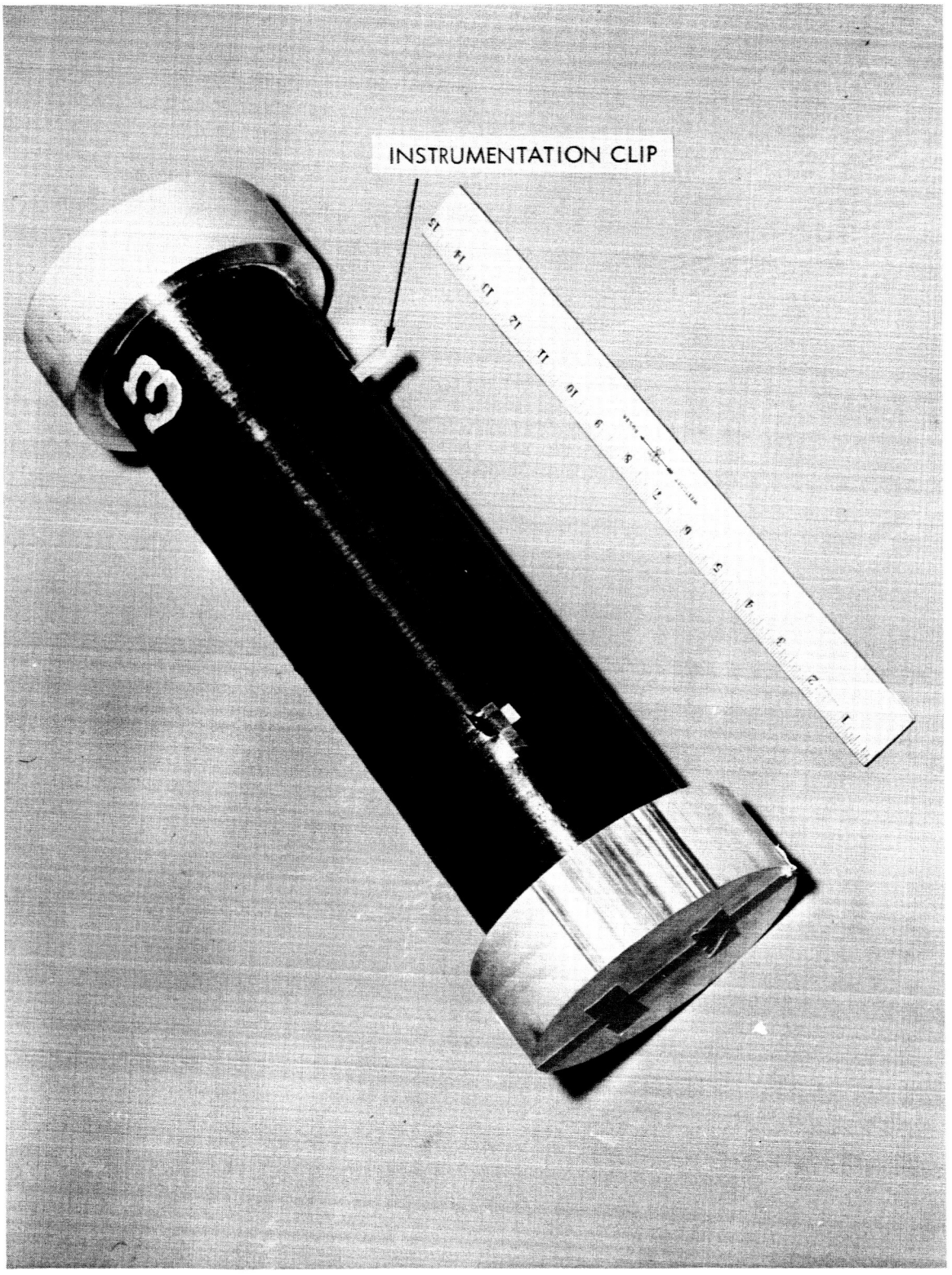


FIGURE 6 - TYPICAL TEST CYLINDER BEFORE TESTING

The polyvinylalcohol film was removed and the film again washed with MEK. The filament wound case was then wound directly upon the film surface. The case was fabricated using conventional filament winding techniques and the construction parameters shown in the following table:

Fabrication Parameters

Mandrel:	4-1/2" diameter hardwood - (2 piece)
Liner:	(a) Material - 3-mil Kapton film
	(b) Joint - 1/2 inch tapered scarf joint (Configuration A, Figure 2)
	(c) Adhesive - G-207 polyester adhesive system. 2
Case:	(a) Dimensions - 4-1/2 inch I.D. 16 inches long - nominal
	(b) Resin - Epon 828 epoxy resin with RP7A amine hardener (15 phr)
	(c) Reinforcements - 2 layers single end E-glass (HTS finish) with 128 ends per inch per layer. 1
	2 layers 116 style glass fabric-Volan A finish.
	1 layer 143 style glass fabric-Volan A finish.
	(d) Winding Tension - 4 oz. per end
	(e) Resin Content - 20-23%

1. Cylinder No. 1 contained 144 ends per inch per layer.

2. G-207 adhesive was coated on the liner of Cylinder No. 2 prior to case fabrication to study bonding characteristics. No improvement in strength or bonding properties was noted.

After completion of the case, each end of the cylinder was reinforced to permit potting and securing of the end caps. At this time the longitudinal strain clips were installed.

The cylinder was cured for 16 hours at 250°F, after which, it was removed from the mandrel, inspected and trimmed. The end caps were potted onto the cylinder using Cerrobend low melt (158°F) metal alloy. This completed the case preparation.

TEST METHODS

Uniaxial Tensile Tests

The following test equipment and parameters were used for all uniaxial tensile tests:

Machine: Riehle - 0 to 200 lb load cell

Loading Rate: 0.1 inch per minute

Cryostat: Boeing design (9" diameter x 18" deep)

Deflectometer: Baldwin Model PD-1M

Test Temperature: -423°F (specimens completely submerged in LH_2)

Measurements: Ultimate load versus head travel

A continuous plot of load versus head travel was recorded for each specimen. The test system (cryostat, loading rods, etc.) was calibrated prior to and following all testing for total system deflection and this correction was incorporated in all calculations. This correction factor was extremely small (.02 inch per 100 lbs load) as compared to the specimen deflection.

Diaphragm Burst Test

The test system shown in Figures 7 and 8 was used for all diaphragm testing. The procedure used was as follows:

The sample was inserted and secured in the test fixture. The upper chamber was then filled with liquid hydrogen and the entire chamber permitted to stabilize. Three thermocouples were used to monitor the temperature profile of the system. One thermocouple was located inside the upper chamber to measure specimen temperature. A second thermocouple was attached to the flange of the test fixture and the third attached to the EDI (Electronic Displacement Indicator). The third thermocouple was used to assure that the temperature of the EDI did not drop below the limits between which it was calibrated.

After equilibrium was maintained, the diaphragms were pressurized with gaseous helium at a rate not exceeding 60 psi/minute. A continuous plot of pressure versus deflection was made of each specimen from the initial pressurization to failure. Deflections were measured with the aid of an EDI as shown in Figure 7. Pressure readings were recorded with two transducers acting independently. These readings were compared after each test.

A liquid hydrogen level was continuously maintained over the specimens at all times. A resistance ladder hanging next to the test specimen measured the liquid depth and was monitored at the control panel.

Sample calculations are shown on Table II.

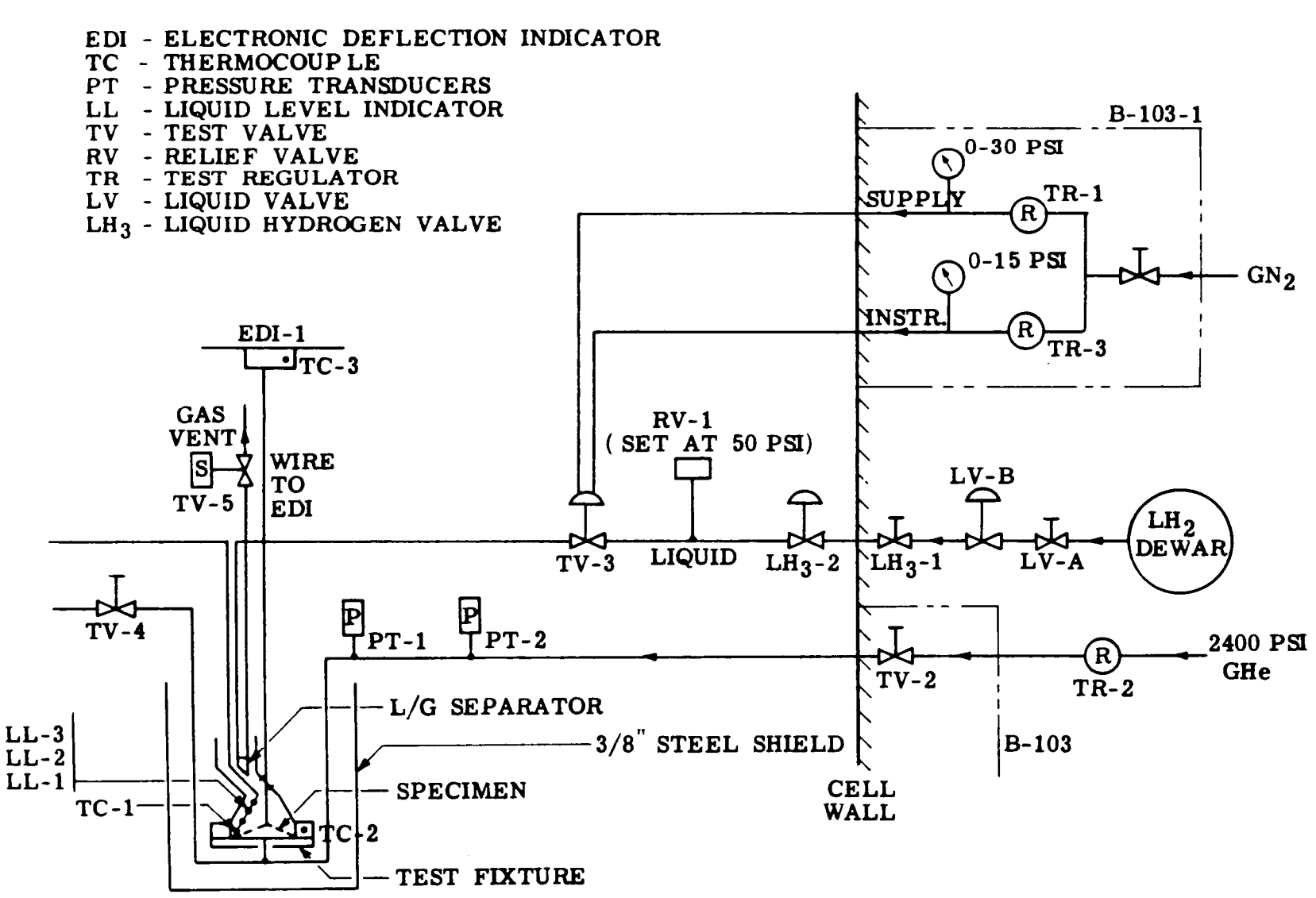


FIGURE 7 SCHEMATIC OF DIAPHRAGM BURST TEST FACILITY

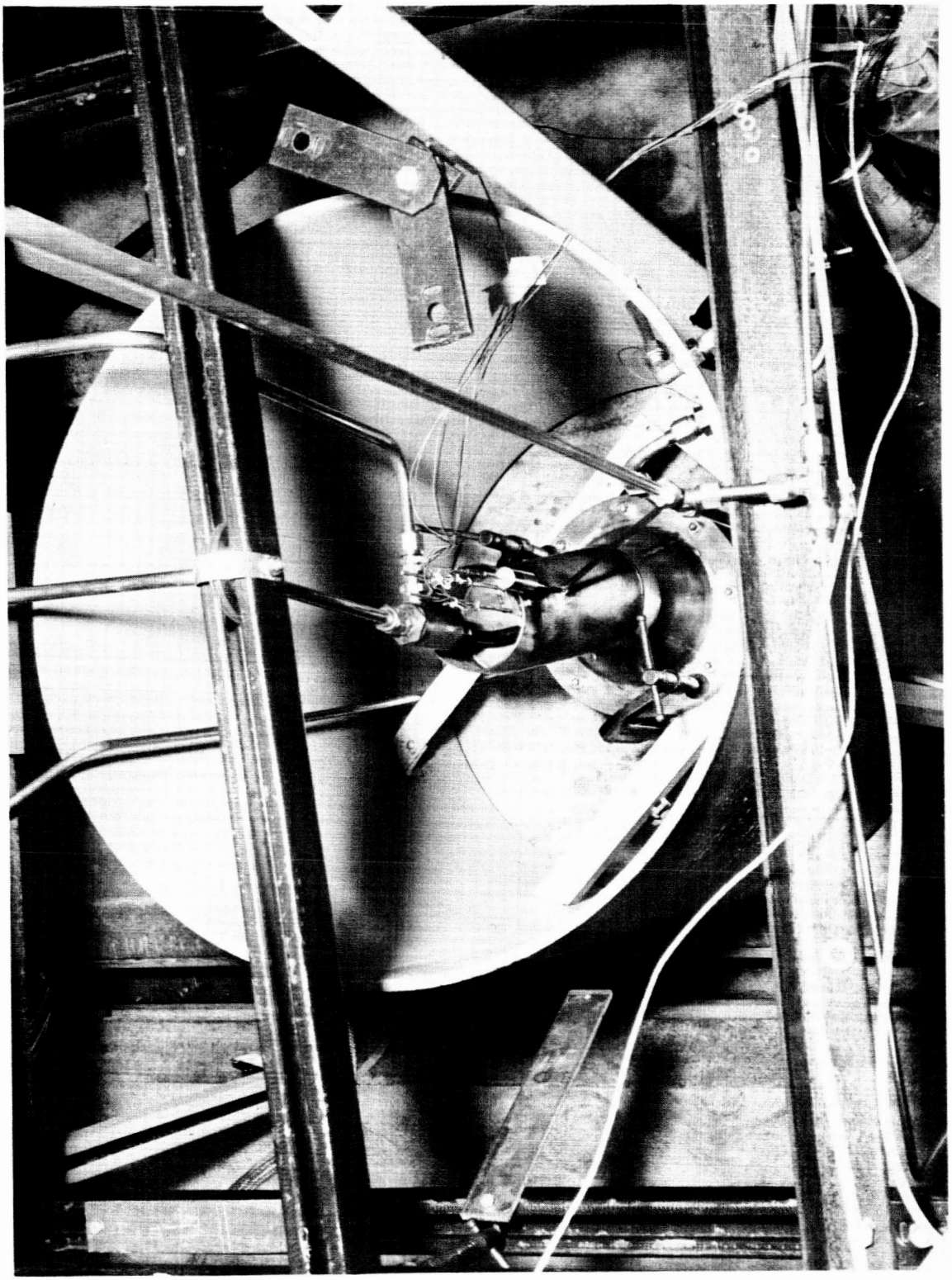


FIGURE 8 - DIAPHRAGM BURST TEST APPARATUS (-423°F)

Burst Test

The test equipment and flow diagram for the test apparatus is shown in Figure 9.

The test cylinder was mounted and secured by the top end cap as illustrated in Figure 10. The case and system were purged with gaseous helium after which the case was filled with liquid hydrogen. The liquid level sensors located approximately 12' above the case indicate when the case is filled. All three level sensors must be on before the test starts. Once the specimen is filled the case is pressurized to failure with gaseous helium. The rate of pressurization was approximately 800 psi/minute. The specimen was instrumented to record ultimate pressure, longitudinal strain and circumferential strain.

The ultimate strain was recorded by two transducers. One was attached to a recorder and records pressure vs. time. The second was connected to an x-y plotter that records pressure vs. circumferential case growth. Both pressure readings are compared after each test.

The circumferential growth was measured with the aid of an EDI (Electronic Displacement Indicator) as shown in Figure 5. The response of the EDI is furnished to the x-y plotter.

Longitudinal expansion or growth measurement utilizes two EDI's. One is attached by a fine wire to the upper clip (see Figure 5) of the case and the second to the lower clip. During pressurization the case expands and both clips tend to move downward. The downward movement is measured by the EDI's and recorded. The total longitudinal elongation is determined by subtracting the two EDI readings. The total strain can then be calculated from the known gage length between clips.

Cyclic Test

Cyclic tests were conducted in much the same manner as the burst test except the specimen was completely submerged in liquid hydrogen during the test. The flow diagram is shown in Figure 11.

The specimen was installed by the upper end cap as shown in Figure 10. The longitudinal and circumferential strain measuring equipment was attached in the same manner as shown. All EDI's were connected to recorders which produced graphs of longitudinal growth vs. time and circumferential growth vs. time.

Pressure transducer #1 was connected to a recorder which recorded pressure vs. time. Pressure transducer #2 was connected to a cam regulator which controlled the rate of pressurization.

The outer chamber was filled with liquid hydrogen until the test specimen was completely submerged. Simultaneously the interior of the test specimen was also filled with LH_2. Liquid level sensors (see Figure 11) indicated when both the chamber and the specimen were filled. When the system reached equilibrium the specimen was pressure cycled to failure.

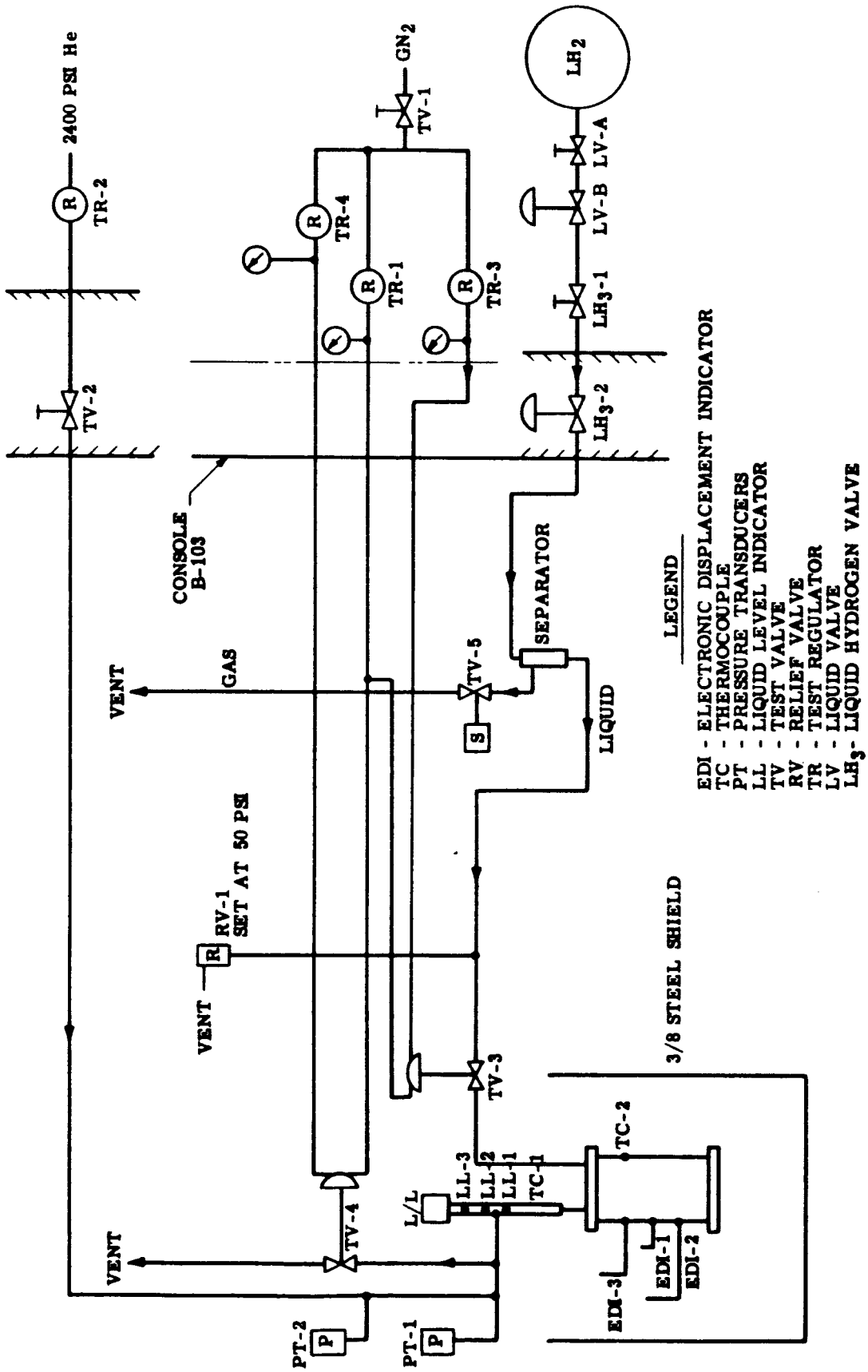


FIGURE 9 - BURST TEST FLOW DIAGRAM

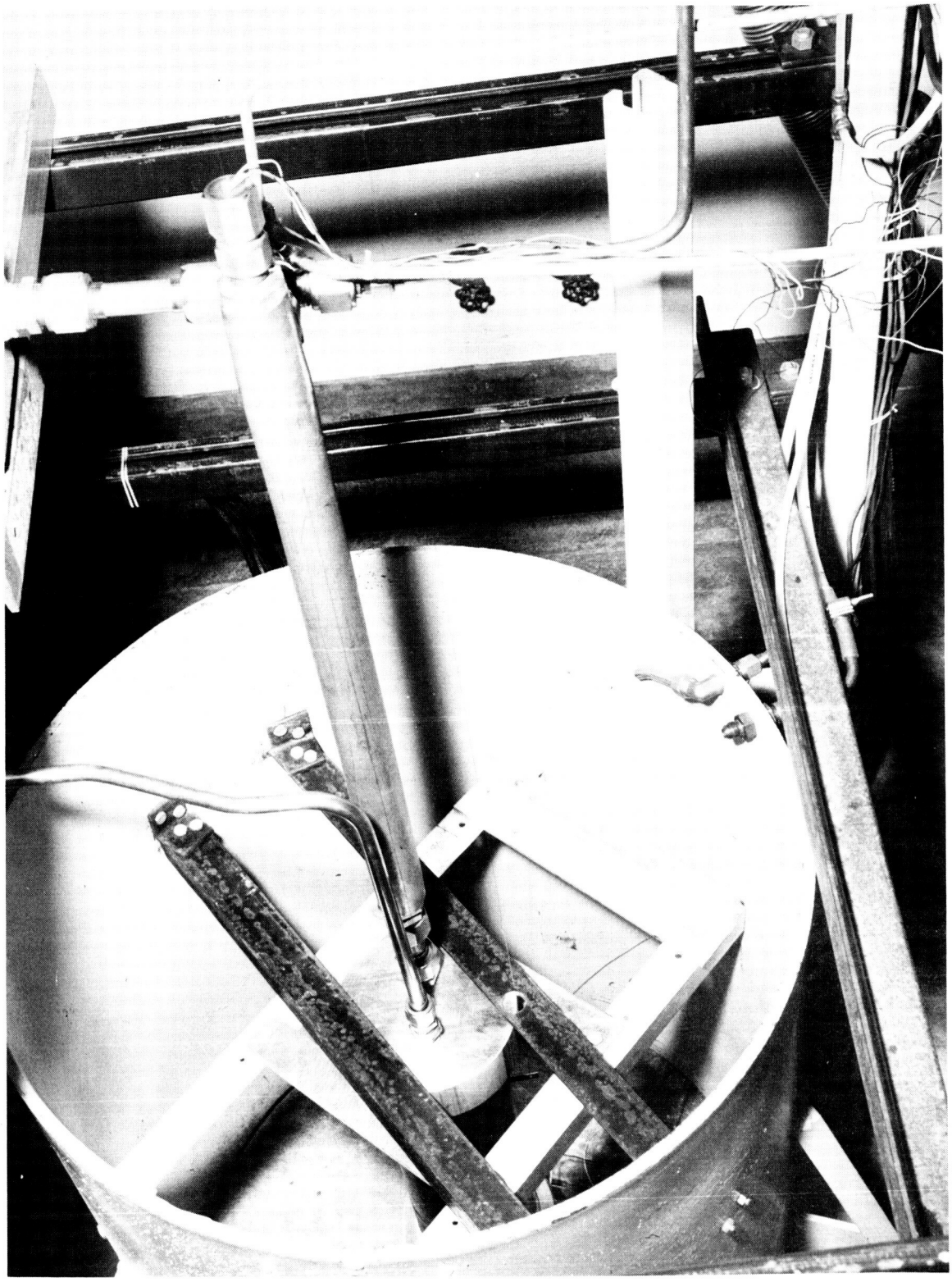


FIGURE 10 - CYLINDER TEST APPARATUS - (-423°F)

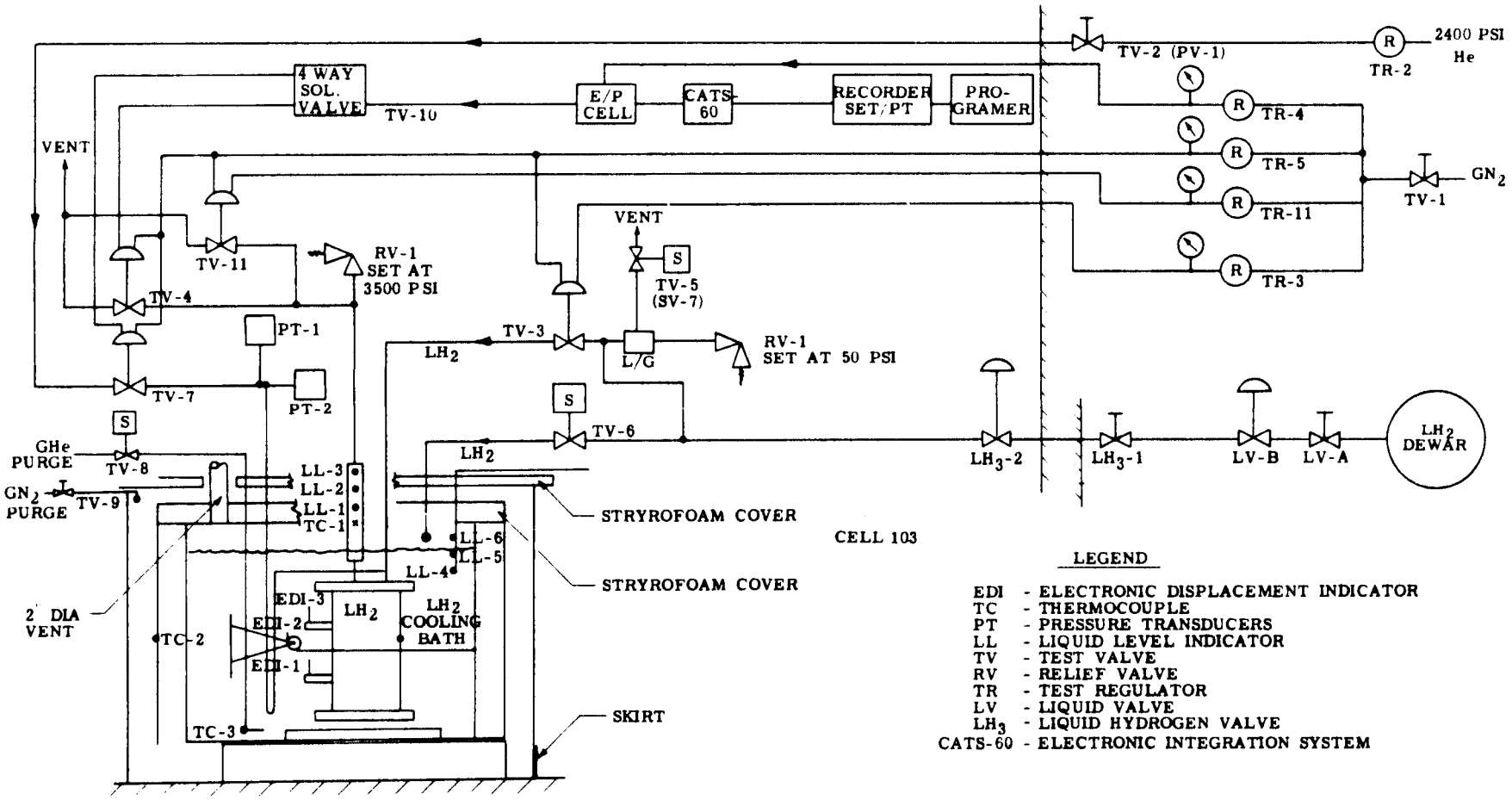


FIGURE 11 - CYCLIC TEST FLOW DIAGRAM

Gaseous helium was utilized for pressurization. The gas was cooled in the liquid hydrogen container prior to entering the test specimen to minimize hydrogen loss. The pressure was programmed and regulated with the aid of a cam and valve system.

The interior pressure, ultimate longitudinal growth and ultimate circumferential growth were recorded on each cycle.

Specimen leakage was determined by measuring pressure decay at the beginning and peak of each cycle and also by monitoring the temperature in the exterior tub. When leakage occurred, the escaping gas and vaporizing liquid caused a slight but noticeable rise in temperature in the tub. All tests were terminated at the first noticeable sign of leakage. This same procedure was utilized to check for liner integrity prior to the first cycle.

DISCUSSION OF RESULTS

Uniaxial Tests

Three-mil Kapton film exhibited an ultimate tensile strength of 49,000 psi and an ultimate elongation of 9.6% at -423°F. This was slightly higher than the five-mil film which had a strength of 44,200 psi and an elongation of 7.8%. (See Table I). Both film gages exhibited identical stress-strain curves as illustrated in Figure 12. The joint configuration and adhesive studies results also showed slightly higher strengths with the 3-mil film.

Goodyear's G-207 polyester adhesive system consistently produced higher strength joints than either of the other three adhesive systems, regardless of material thickness, and consequently was selected for further evaluation in the biaxial tests of Task I. Narmco 7343 polyurethane system was selected as the alternate adhesive.

Based on the results shown in Table I and Figure 13, joint configurations A and C were chosen for evaluation with the selected adhesive systems.

All the bonded tensile specimens failed in, across or adjacent to the bond area with no adhesive failure occurring. Figure 14 shows typical specimen failures. Failure A was the prevailing type of fracture. As shown by the results, the strength of the bond area was approximately 45% that of the plain film with an even greater reduction occurring in the ultimate elongation. The elongation value, however, is comparable to that of the plain film at corresponding stress values indicating that both specimens follow the same stress-strain curve. It should be stressed, that all failures resulted from a lack of film strength in the bond area and not in the bond itself.

Biaxial Tests

Plain Film

The results of the plain film tests are tabulated in Table II. The data shows that the 3- and 5-mil films produced comparable average stress values of 37,600 psi and 39,600 psi, respectively. The ultimate strains of the two material thicknesses were however considerably different with the strain values of the thin film being significantly higher and having less variation. A typical diaphragm failure is shown in Figure 15. Stress-strain curves are shown in Figure 16.

The data show that the 3-mil film has an average ultimate strain of 15% at -423°F. This strain when compared to the average uniaxial strain of 9.6% seems high. It should be noted that several assumptions are made in the biaxially strain value calculations which depending on their magnitude, may or may not influence the strain value to a significant degree. It is assumed that the diaphragm forms a perfect arc of a circle when pressurized, straining the film equally over the surface. This is a large and erroneous assumption if precise comparison between uniaxial and biaxial strains are to be made, since there is a definite strain gradient across the pressurized diaphragm. This assumption is valid however, for qualitative comparisons of biaxial strains. Another assumption is that no elongation occurs from the flange area. Due to the equipment design and the diminishing strain level at the flange area, this elongation is negligible.

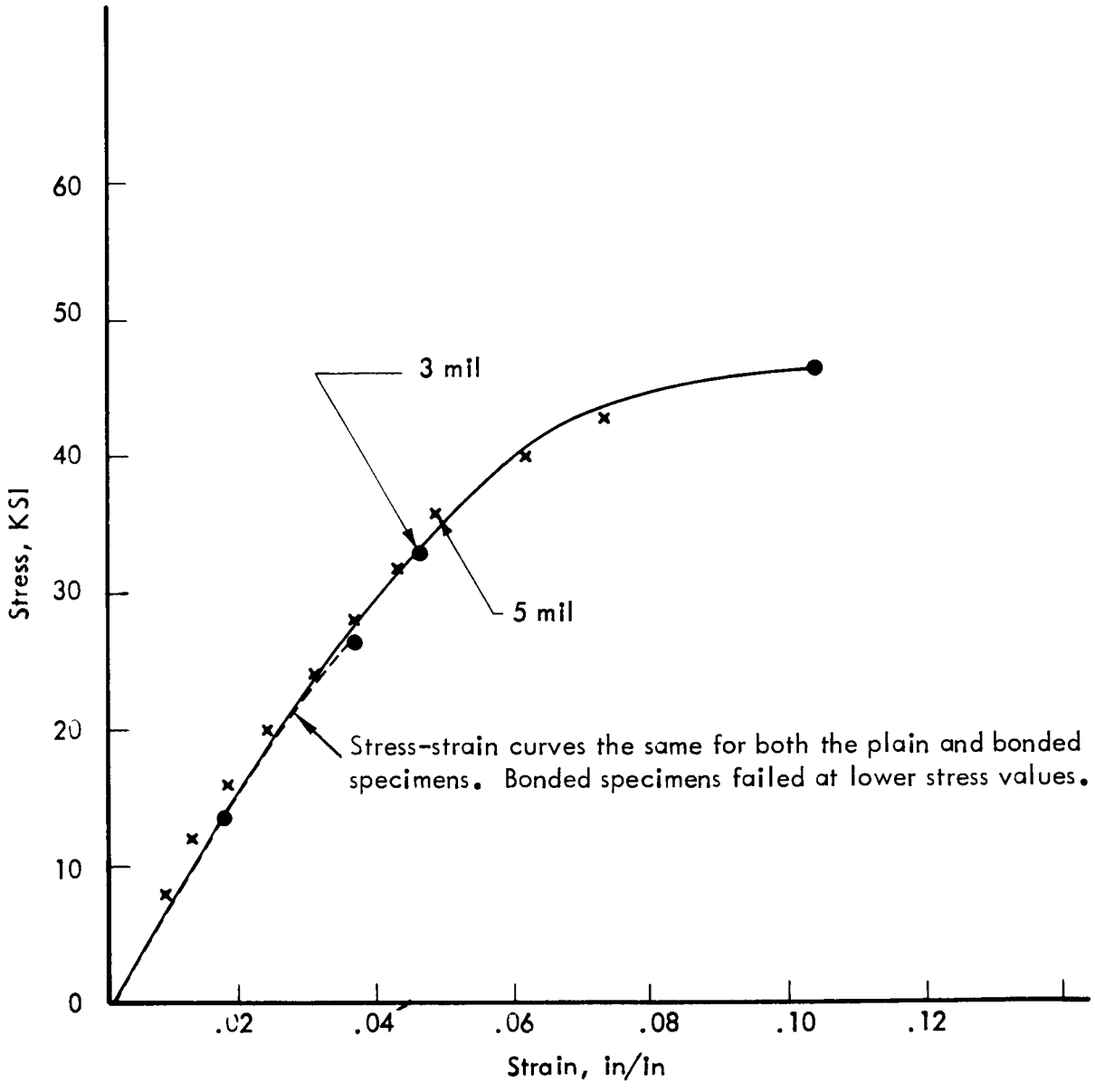
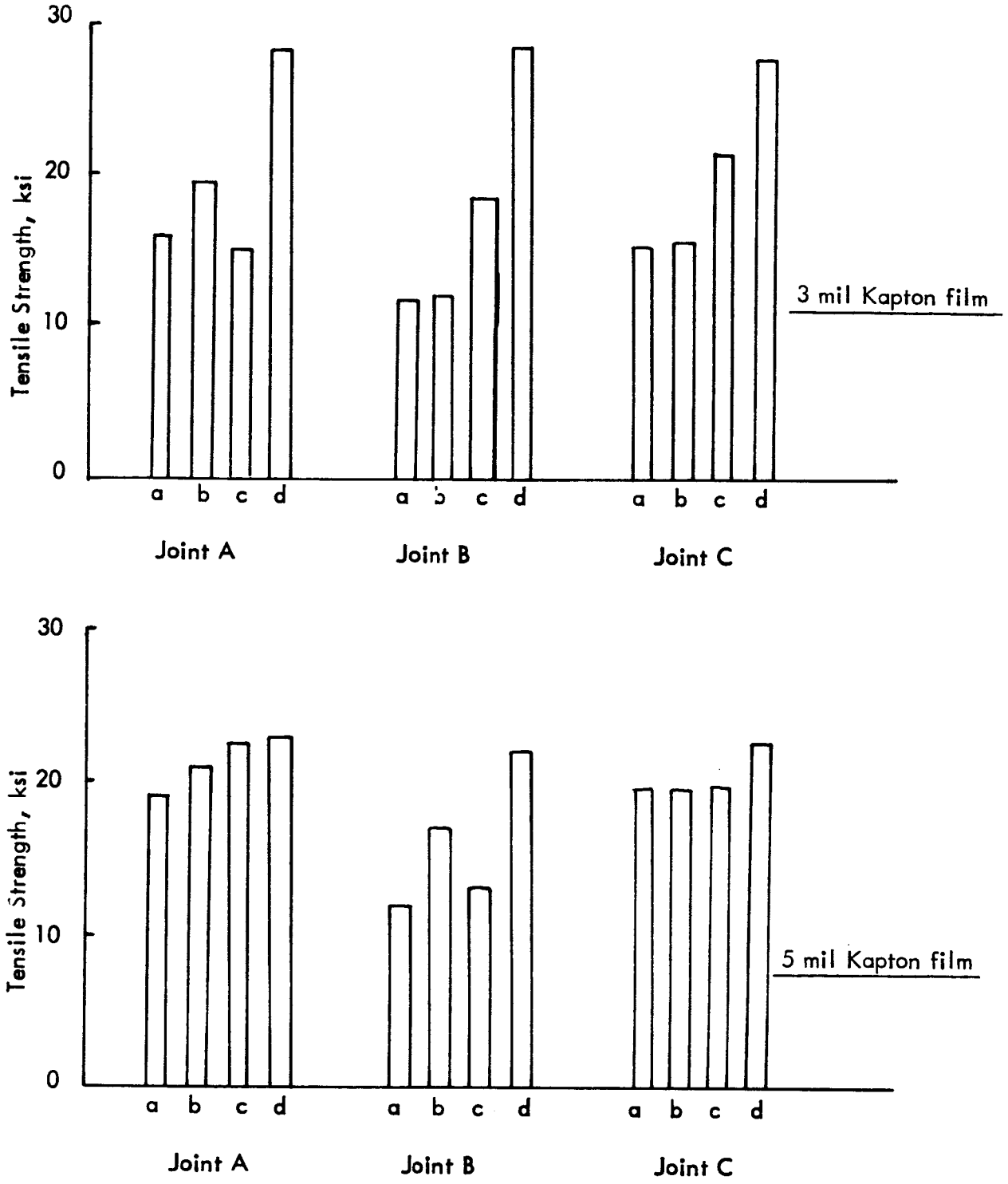


FIGURE 12 - UNIAXIAL STRESS-STRAIN CURVE FOR 3 AND 5 MIL KAPTON FILM - PLAIN AND BONDED (-423°F)



a - DuPont 6971 (Polyester)
b - Epon 828/RP7A (Epoxy)
c - Narmco 7343/7139 (Polyurethane)
c - Goodyear G-207 (Polyester)

FIGURE 13 - STRENGTH RESULTS - UNIAXIAL BOND STUDY (-423°F)

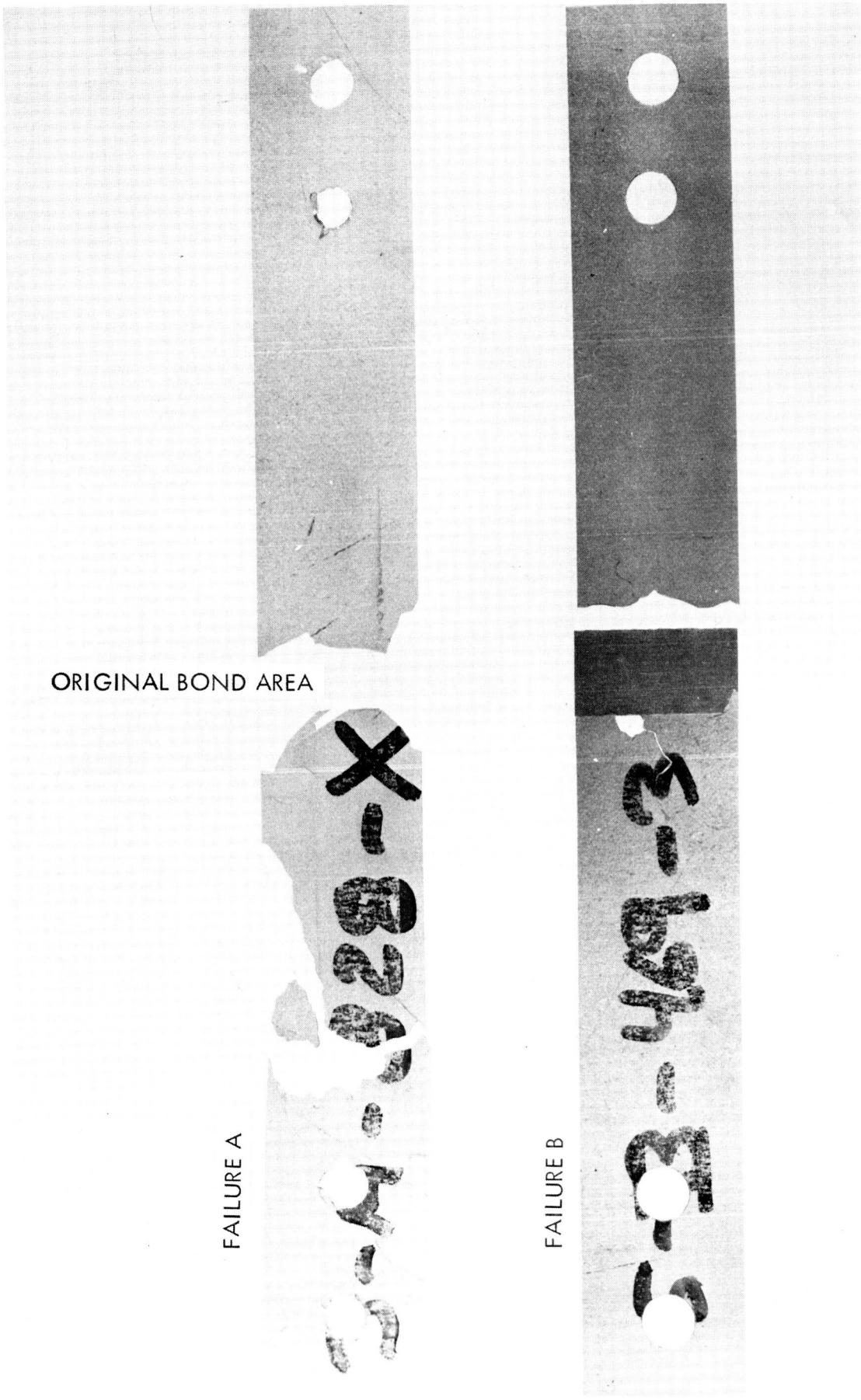


FIGURE 14 - KAPTON FILM UNIAXIAL TENSILE SPECIMENS AFTER TEST (-423°F)

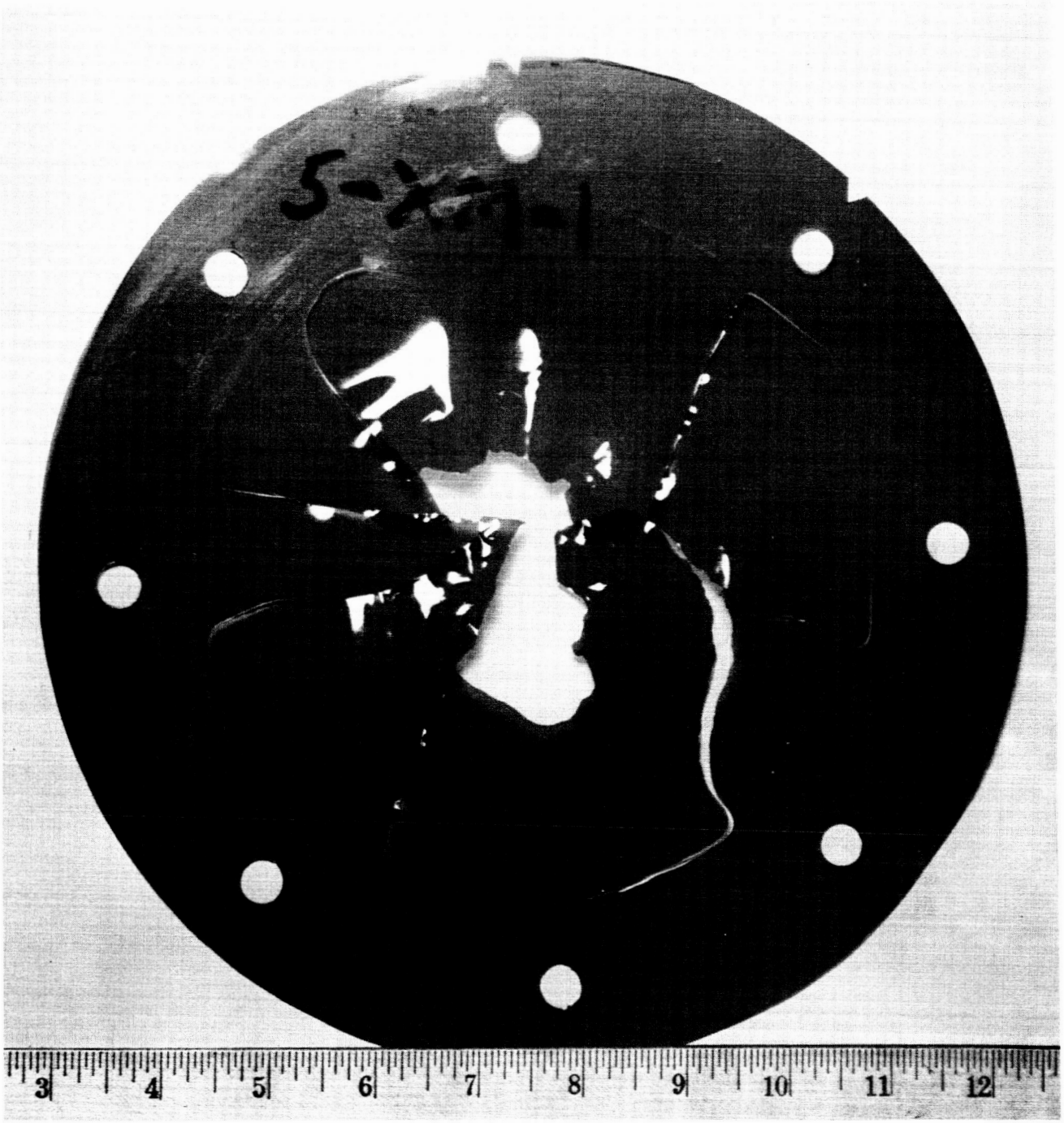


FIGURE 15 - KAPTON FILM BIAXIAL DIAPHRAGM TEST SPECIMEN AFTER TEST (-423°F)

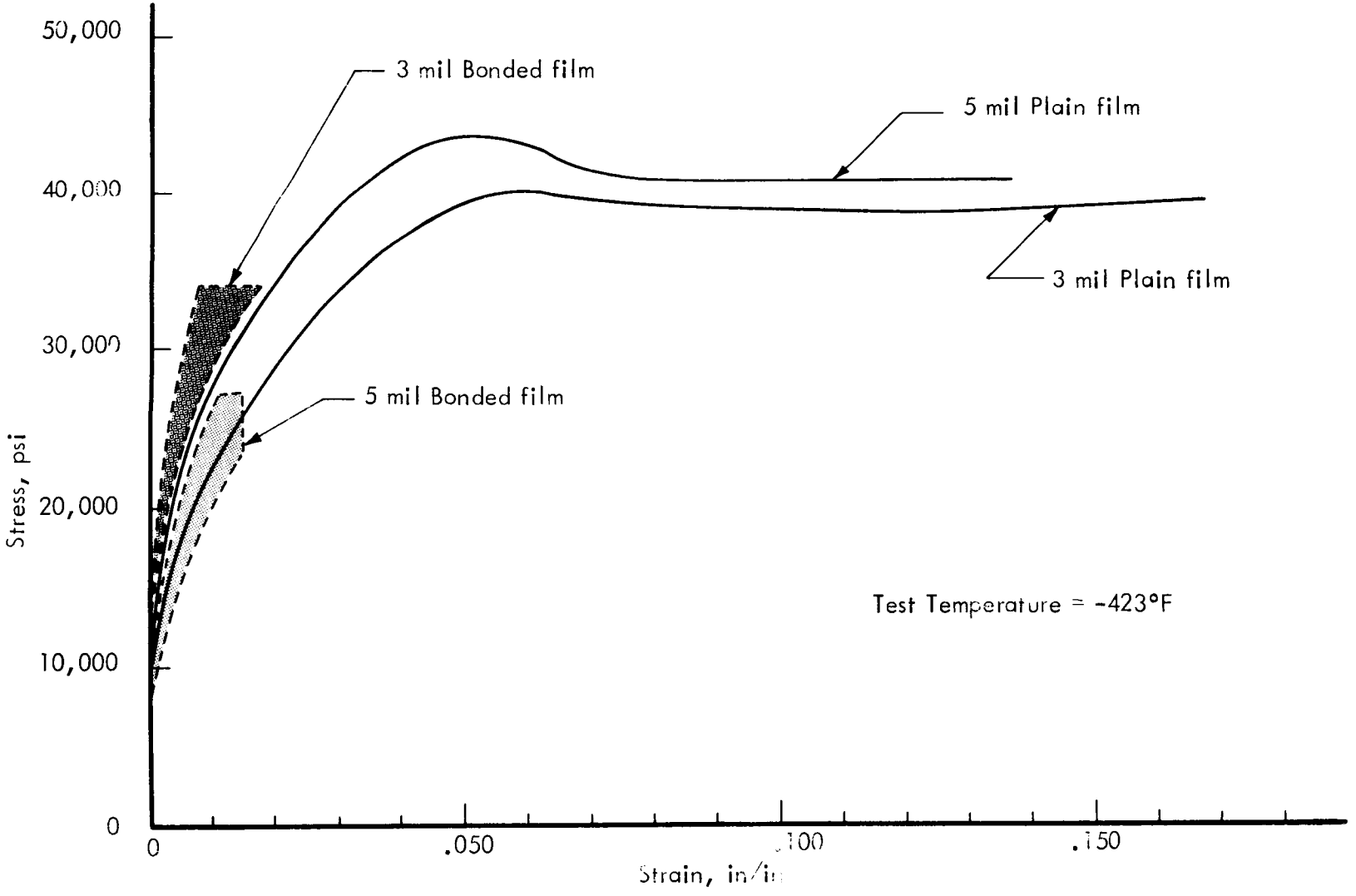


FIGURE 16 - TYPICAL BIAXIAL STRESS-STRAIN DIAGRAM FOR KAPTON FILM - PLAIN AND BONDED SPECIMENS

Bonded Film

Tabulated in Table III is the data obtained on the joint concept studies. The two adhesives and two joint configurations were selected from the uniaxial test results.

The biaxial strain capabilities of the evaluated joint concepts were considerably below that of the pure film. The ultimate strains were equivalent for both film thicknesses and seemed independent of the adhesive system or joint configuration used. The stress-strain curves are shown in Figure 16.

This subtask completed the work in Task I. Three-mil Kapton, G-207 adhesive system and a scarf joint were the parameters selected to be used in Task II for fabrication of test cylinders.

Cylinder Tests

Burst Tests

Three cylinders were burst tested and failed at an average internal burst pressure of 1150 psi (see Table IV). In each instance, the fiberglass case failed with no liner leakage prior to burst. Figures 18, 19 and 20 show the condition of each cylinder after test. Longitudinal and circumferential strains over 2.5% were obtained. Figure 17 shows the stress-strain curves obtained for the three cylinders.

Cyclic Tests

The results of the five cyclic tests are summarized in Table IV. Figures 21 through 26 show the type of liner failure that occurred in each instance. Cylinder No. 4 failed on the 5th cycle, with extensive damage to the fiberglass case (see Figure 21). In this specimen it was difficult to determine if failure was in the case itself or whether liner leakage, at the high strain level, initiated the case failure. Since subsequent tests, at lower strain levels, failed to perform satisfactorily, an additional test at the 2% strain level was not warranted.

Tests specimens 5, 6 and 8 failed similar to one another. The liner was excessively crazed as shown in Figures 22, 23 and 24. No delamination was noted in the bond between the liner and the fiberglass case except in the immediate vicinity of a leak area. This delamination is due to the high pressure release of the liquid hydrogen. Figure 25 shows the extent of the leakage in one of the cylinders. A soap solution was used for photographic and visual observation.

A failure in the bonding area was the cause of leakage in Cylinder No. 7. (see Figure 26). The adhesive bond remained intact, with the failure occurring across the bond area in a random manner.

NASA studies (Reference 3) indicate it may be possible to improve liner cyclic capabilities by obtaining a high strength bond between the film liner and the fiberglass case. The strength of the liner-to-case bond in this program appeared good and specific strength values were not obtained. However based on NASA results, this area may warrant investigation.

CONCLUSIONS

Three-mil Kapton film demonstrated adequate elongation (over 2.5% biaxially) in both Task I and Task II for the pressurized containment of liquid hydrogen. However, the material failed to demonstrate good cyclic capabilities which is a basic requirement for reliable service. Based on these results, Kapton film is deemed inadequate for the pressurized containment of liquid hydrogen in non-metallic vessels in which cyclic loading will be imposed upon the liner. It is considered a serviceable material for unstrained applications at -423°F or in pressurized applications in which cyclic capabilities are not a requirement.

Goodyear's adhesive system, G-207, performed satisfactorily at -423°F. No liner failures in the filament wound cylinders can be attributed to a failure in the adhesive joint.

The 1/2" tapered lap joint was the best configuration of the three evaluated and had adequate strength for liner applications. However, failures occurring across the bonded area in each test indicate that an improved joining process resulting in greater ultimate elongation and strength in the bonded area is required.

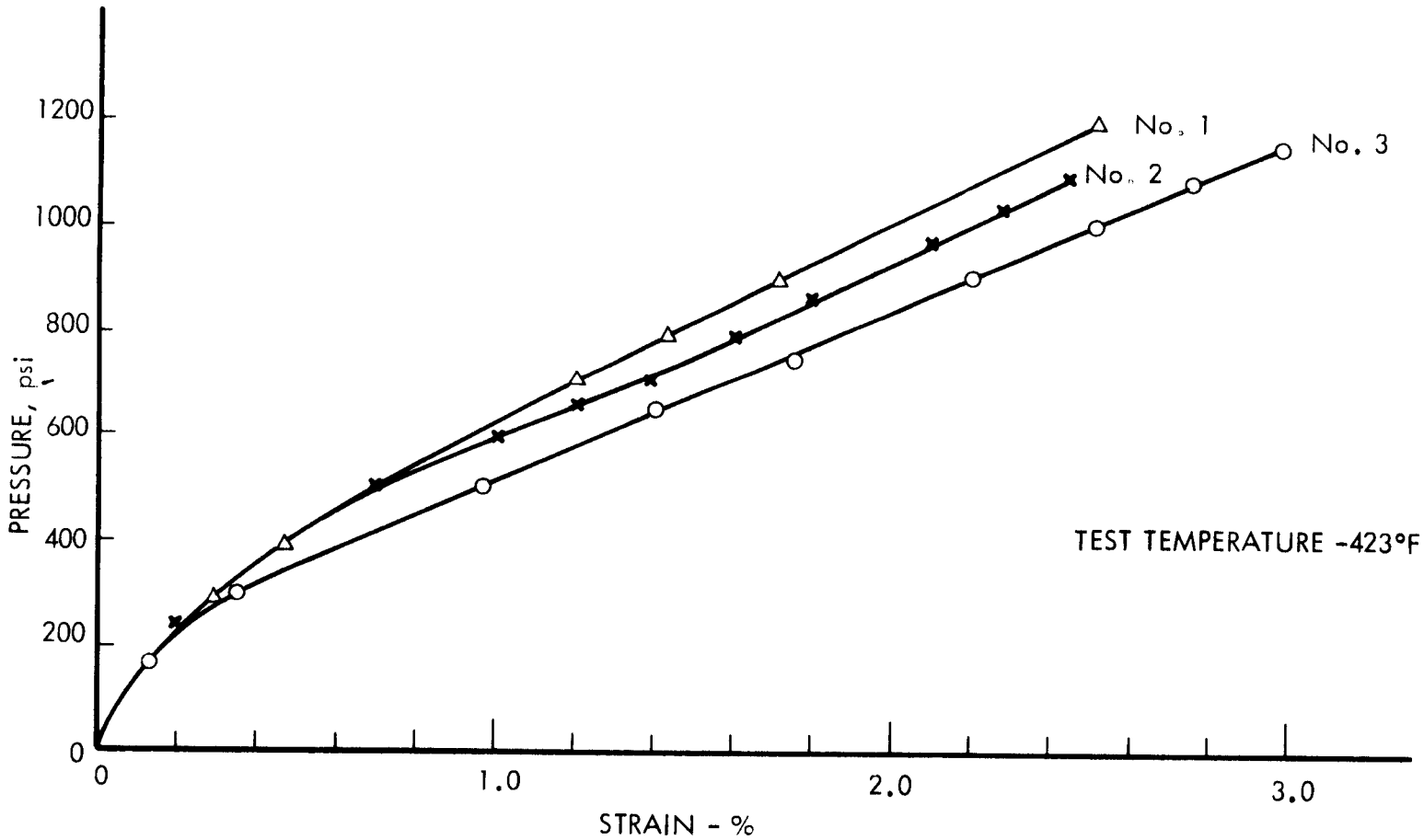


FIGURE 17 - STRESS-STRAIN DIAGRAM - KAPTON FILM LINED CYLINDER BURST TESTS

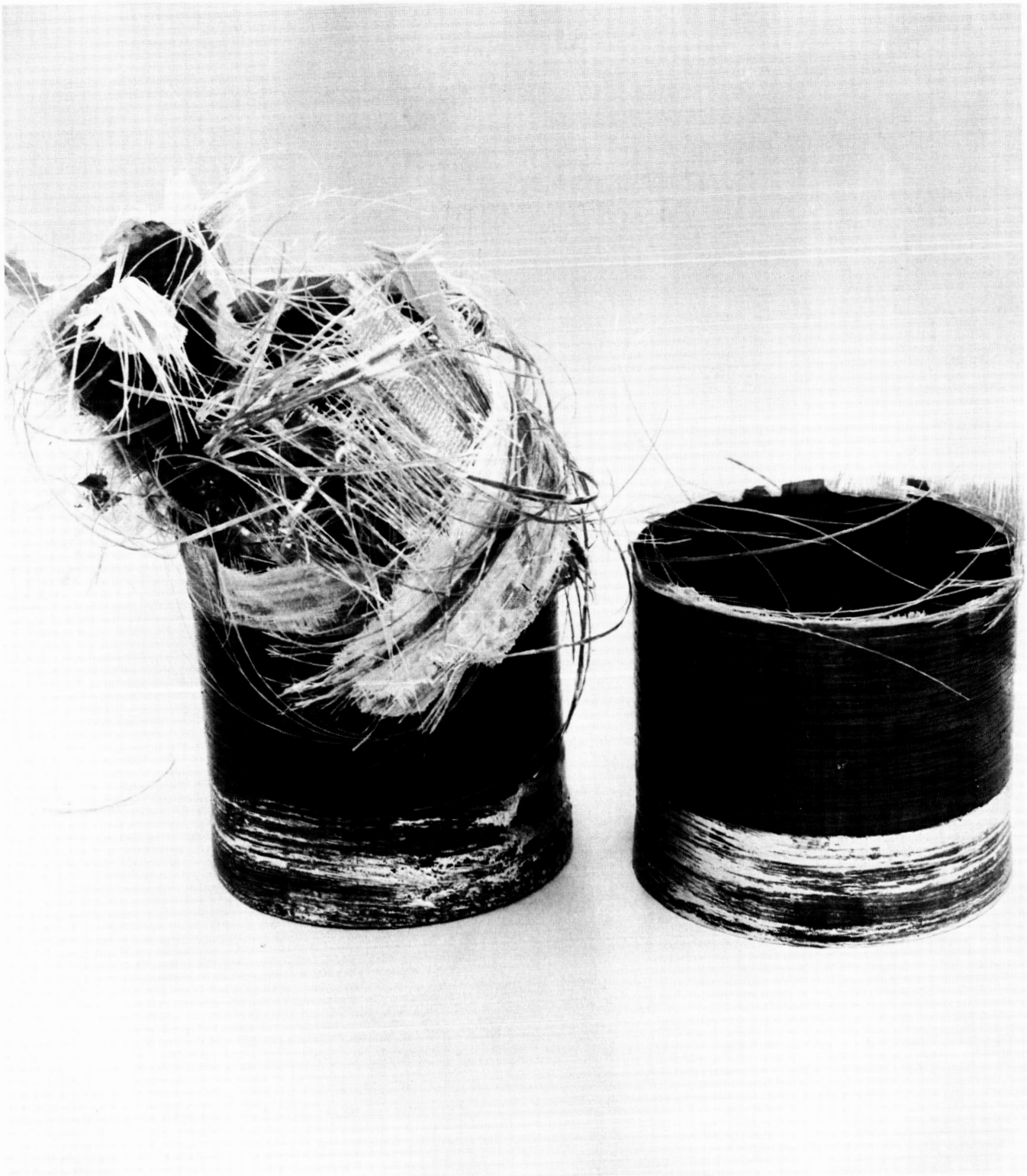


FIGURE 18 - CYLINDER NO. 1 AFTER BURST TEST

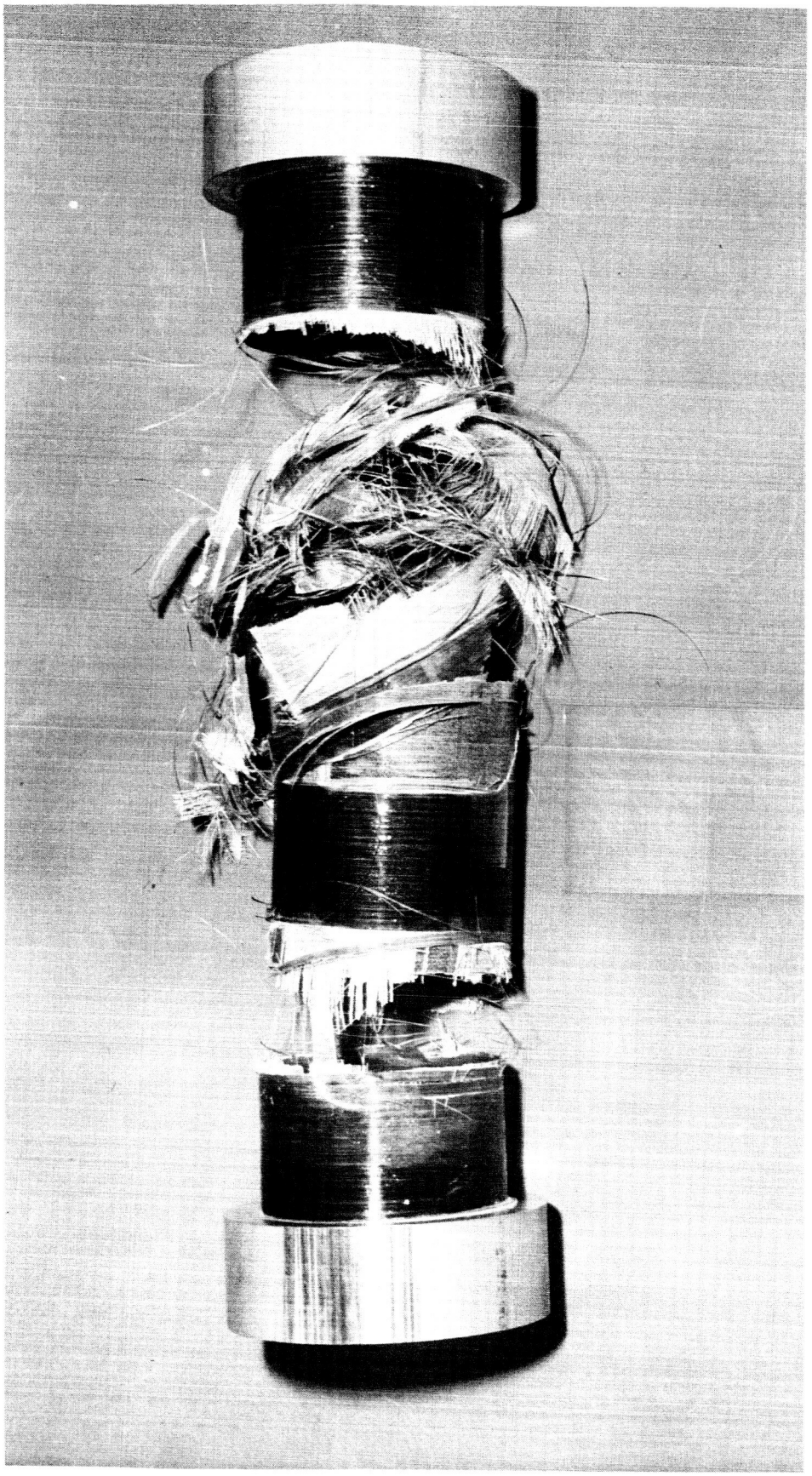


FIGURE 19 - CYLINDER NO. 2 AFTER BURST TEST

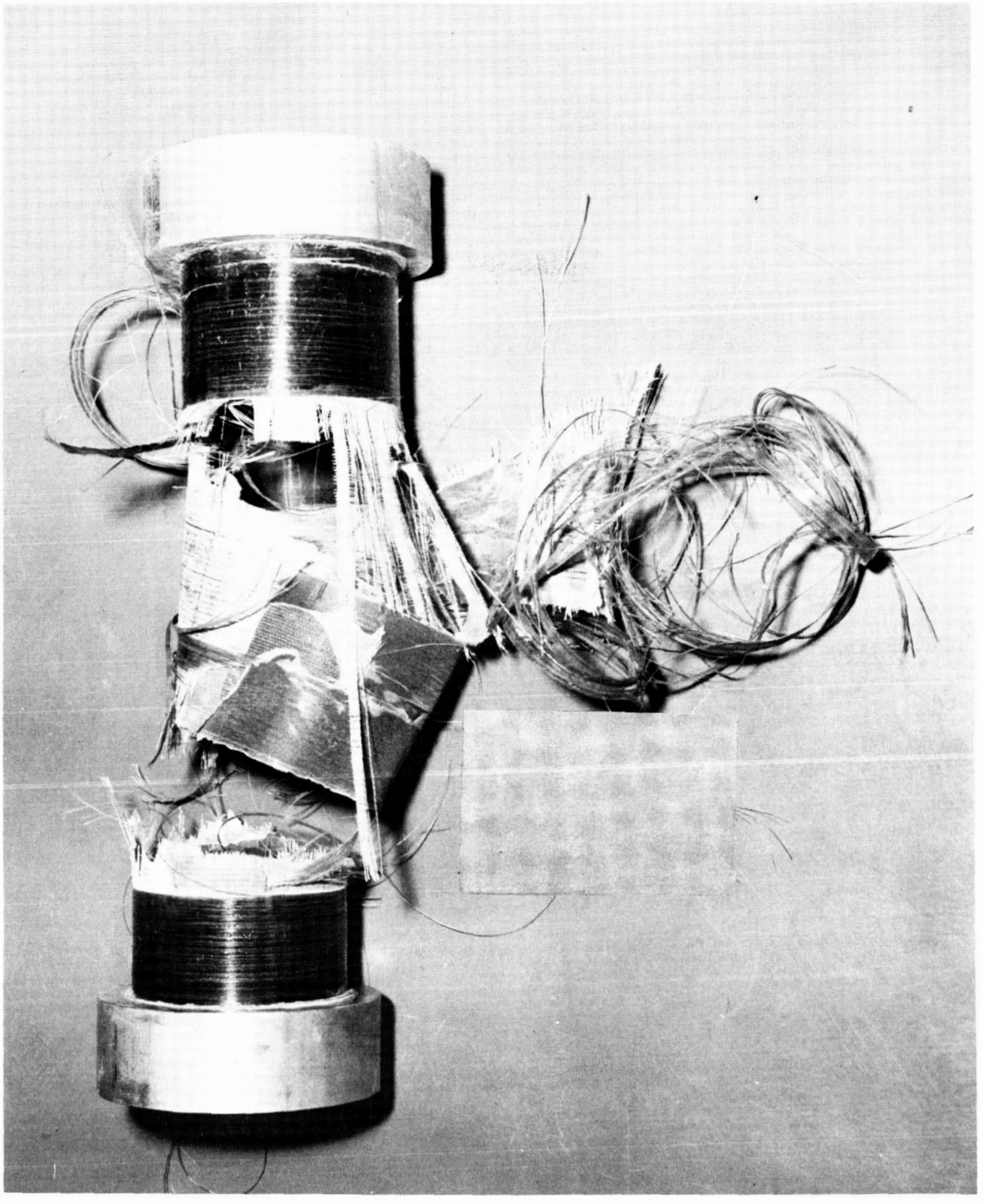


FIGURE 20 - CYLINDER NO. 3 AFTER BURST TEST

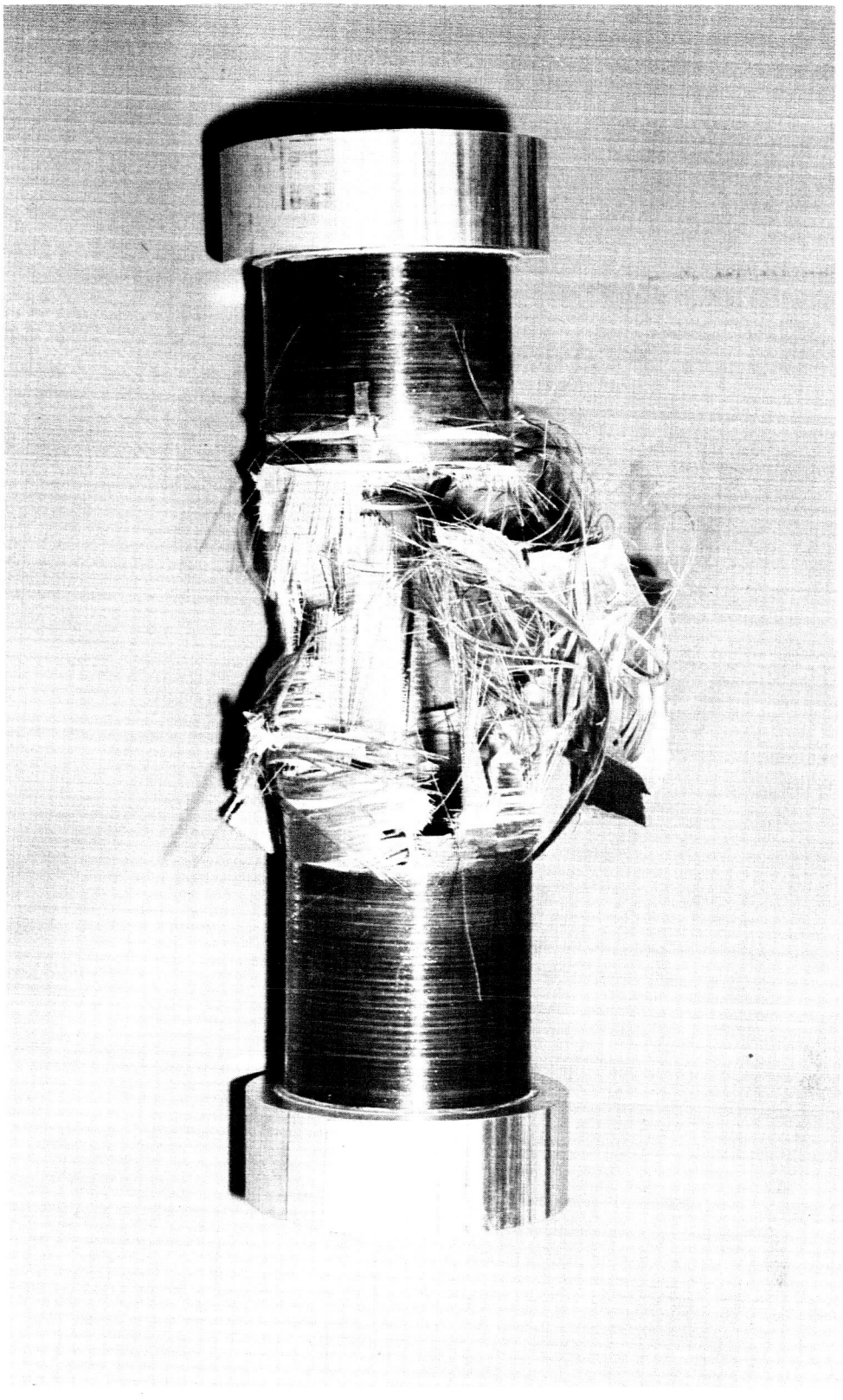


FIGURE 21 - CYLINDER NO. 4 AFTER CYCLIC TEST



FIGURE 22 - CYLINDER NO. 5 AFTER CYCLIC TEST



FIGURE 23 - CYLINDER NO. 6 AFTER CYCLIC TEST



FIGURE 24 - CYLINDER NO. 8 AFTER CYCLIC TEST

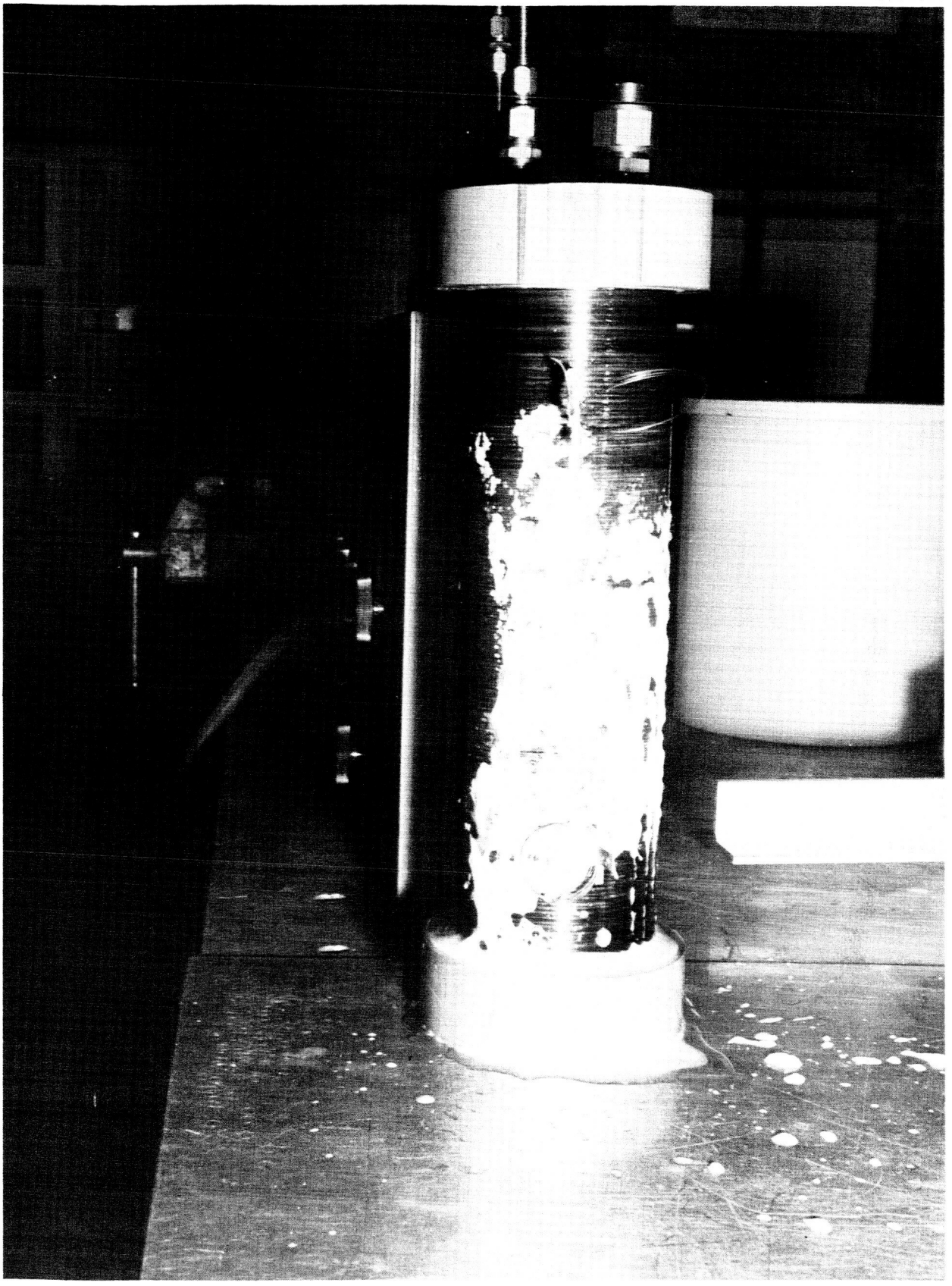


FIGURE 25 - LEAKAGE OF CYLINDER NO. 5 AFTER CYCLIC TEST (BENCH TEST)

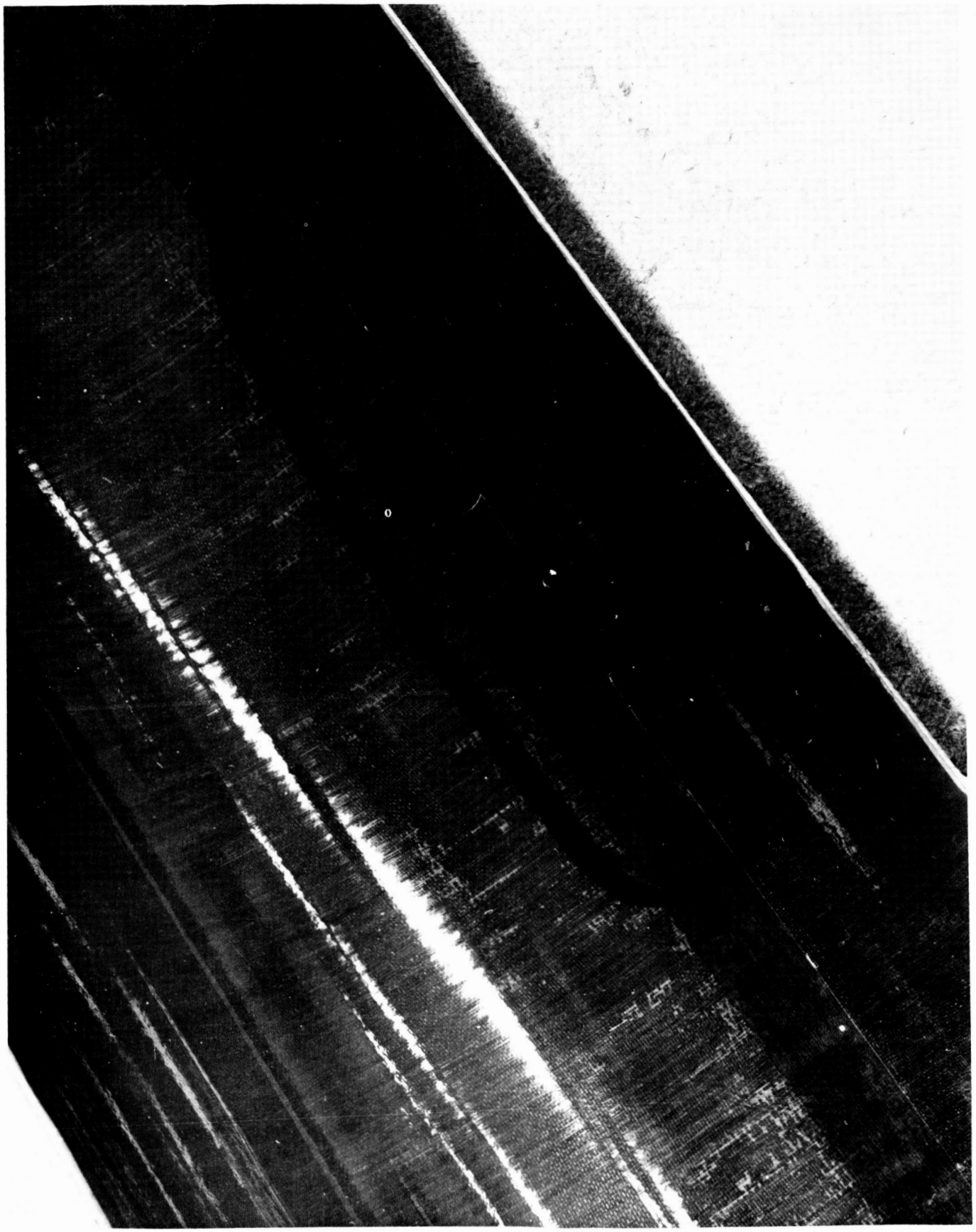


FIGURE 26 - CYLINDER NO. 7 AFTER CYCLIC TEST

TABLE 1
PLAIN KAPTON FILM AND BONDED JOINT UNIAXIAL STRAIN TESTS (-423°F)

Test Specimen	Film Thickness (Mils)	Adhesive System (1)	Joint Config. (2)	No. Specimen	Tensile Strength (psi)	Ultimate Elongation (%)
Uniaxial	3	Plain	Plain	5	49,000	9.6
"	5	Plain	Plain	5	44,200	7.8
"	3	1	A	3	15,200	1.54
"	3	1	B	3	18,600	2.28
"	3	1	C	3	21,200	1.91
"	3	2	A	3	19,500	1.98
"	3	2	B	3	11,800	1.48
"	3	2	C	3	15,500	1.42
"	3	3	A	3	28,300	3.06
"	3	3	B	3	28,500	3.08
"	3	3	C	3	27,700	2.79
"	3	4	A	3	16,000	1.48
"	3	4	B	3	11,700	1.36
"	3	4	C	3	15,200	1.48
"	5	1	A	3	22,600	2.71
"	5	1	B	3	13,000	1.67
"	5	1	C	3	19,900	2.34
"	5	2	A	3	21,000	2.59
"	5	2	B	3	16,900	2.22
"	5	2	C	3	19,700	2.47
"	5	3	A	3	23,000	3.06
"	5	3	B	3	22,100	2.74
"	5	3	C	3	22,700	2.94
"	5	4	A	3	18,900	2.28
"	5	4	B	3	12,000	1.6
"	5	4	C	3	19,700	2.47

(1) Adhesive Systems

1 - Narmco 7343 (polyurethane)
2 - Epon 828/RP7 (epoxy)
3 - Goodyear G-207 (polyester)
4 - DuPont 46971 (polyester)

(2) Joint Configurations

A - .500" Lap
B - Butt with 1" Doubler
C - Butt with 1" Doubler reinforced with .75" Doubler.

TABLE II

BIAXIAL DIAPHRAGM DEFLECTION TEST RESULTS - PLAIN KAPTON FILM (-423°F)

Specimen No.	Film Thickness (mils)	Burst Pressure (psi)	Ult Deflection (in.)	Ult Stress (psi)	Ult. Strain %
3-1	3	43.5	1.69	32,500	14.7
3-2	3	67.5	Unknown	--	--
3-3	3	50.7	1.87	35,600	17.8
3-4	3	57.0	1.87	40,000	17.8
3-5	3	48.0	1.32	42,400	9.6
			AVG.	37,600	
5-1	5	96.7	1.96	39,700	19.0
5-2	5	35.0	.68	32,800	2.7
5-3	5	69.0	1.16	40,500	6.6
5-4	5	79.0	1.33	41,700	9.6
5-5	5	63.0	.95	43,600	5.0
			AVG.	39,600	

(1) Stress $= \frac{PR}{2t}$ where P = Pressure (psi) and t = film thickness (inches)
R = radius of curvature

(2) Strain $= \frac{S - D}{D}$ where $S = \frac{r^2 + h^2}{2h} \times \Phi_{rad}$; S = length of arc subtended by Φ (inches)
r = radius of diaphragm (inches)
h = deflection height (inches)
Φ = central angle in radians
D = diameter of diaphragm (inches)

TABLE III

BIAXIAL DIAPHRAGM BURST TEST RESULTS - BOND STUDY (-423°F) KAPTON FILM

Spec. No. [1]	Film Thk. (Mils)	Burst Pressure (psi)	Ult. Deflection (in.)	Ult Stress (psi)	Ult. Strain (%)
D3-A-734-1	3	7	.28	25,300	0.48
-2	3	13.5	.45	31,200	1.14
-3	3	11	.44	26,000	1.09
D3-C-734-1	3	15	.4	38,800	0.86
-2	3	13	.48	28,200	1.32
-3	3	13	.39	34,400	0.82
D3-A-207-1	3	12	.38	32,600	0.79
-2	3	11	.44	26,000	1.09
-3	3	18.5	.58	33,500	1.78
D3-C-207-1	3	17	.52	34,000	1.49
-2	3	3	.15	20,500	0.14
-3	3	10	.62	16,700	2.04
D5-A-734-1	5	16	.45	22,200	1.14
-2	5	20.5	.52	24,600	1.49
-3	5	11	.38	18,000	0.79
D5-C-734-1	5	17	.43	24,700	1.03
-2	5	13.8	.45	19,100	1.14
-3	5	19	.41	28,800	0.91
D5-A-207-1	5	16	.42	23,700	0.97
-2	5	13.5	.37	22,600	0.75
-3	5	19.6	.46	26,600	1.20
D5-C-207-1	5	16.2	.43	23,500	1.03
-2	5	21.5	.49	27,400	1.37
-3	5	14	.41	21,200	0.91

[1] D3-A-734 Series, D5-A-734 Series — Lap joint with NARMCO 7343 Adhesive

D3-C-734 Series, D5-C-734 Series — Butt joint with Reinforced Doubler - NARMCO 7343 Adhesive

D3-A-207 Series, D5-A-207 Series — Lap Joint with G-207 Adhesive

D3-C-207 Series, D5-C-207 Series — Butt joint with Reinforced Doubler - G207 Adhesive

TABLE IV
KAPTON FILM LINED - CYLINDER TEST RESULTS (-423°F)

Cylinder No.	Type Test	Cycle	Pressure (psi)	Composite Stress (psi)	Longitudinal Strain (%)	Circumferential Strain (%)
1	Burst		1200	106,000	2.88	2.5
2	Burst		1100	100,000	2.42	2.4
3	Burst		1150	104,000	2.89	3.0
4	Cyclic	First	920	83,000	2.01	2.1
		Second	940	84,500	2.04	2.1
		Third	920	83,000	1.98	2.04
		Fourth	900	81,000	1.93	2.02
		Fifth	Failure			
5	Cyclic	First	820	74,000	1.65	1.95
		Second	770	69,000	1.77	1.89
		Third	750	67,500	1.53	1.61
		Fourth	Failure			
6	Cyclic	First	700	63,000	1.50	1.58
		Second	650	58,500	1.43	1.55
		Third	Failure			
7	Cyclic	First	600	54,000	1.18	1.2
		Second	590	53,000	1.25	1.2
		Third	600	54,000	1.35	1.12
		Fourth	550	49,500	1.35	1.12
		Fifth	600	54,000	1.35	1.05
		Sixth	Failure			
8	Cyclic	First	720	65,000	1.48	1.47
		Second	680	61,000	1.45	1.51
		Third	670	60,000	1.41	1.47
		Fourth	Failure			

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4. Toth, J.M., Sherman, W.C., Soltysiak, D.J., "Investigation of Structural Properties of Fiberglass Filament-Wound Pressure Vessels at Cryogenic Temperatures", Douglas Aircraft Company, NASA CR-54393, September 1965.

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Plastics Technical Evaulation Center Picatinny Arsenal Dover, New Jersey 07801	1