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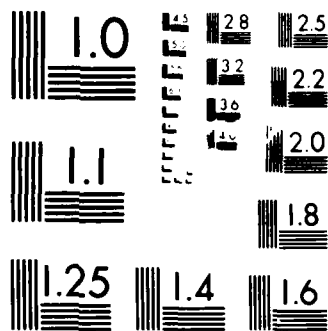
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EXPERIMENTAL AND ANALYTICAL INVESTIGATION
OF A STEEL PRESSURE VESSEL OVERWRAPPED
WITH GRAPHITE BISMALEIMIDE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In this report we present the results of an analytical (finite element) and experimental investigation of the stress-strain response of a composite cylinder subjected to an internal pressurization cycle. The composite cylinder is constructed of a steel liner and a graphite-bismaleimide outer shell. Results are also presented for cases where the structure was subjected to a temperature cycle above the manufacturer's specified operating temperature. (CONT'D ON REVERSE)		

20. ABSTRACT (CONT'D)

The results indicate a delayed strain response in the composite outer shell and only small changes in burst pressure and strain-to-failure for temperature cycles up to 200°F higher than the manufacturer's specified temperatures.

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INTRODUCTION

Recently there has been considerable interest in lengthening gun tubes without changing the center of gravity. One way to accomplish this is to use a lighter material to replace a portion of the additional steel tube length. Two such lighter materials are organic composites such as graphite-epoxy or graphite-bismaleimide. The fibers may be oriented in a composite to have higher strength and stiffness in a desired direction than the gun steel. Work is in progress to determine the structural effectiveness of gun tubes manufactured using a steel liner and a graphite-epoxy or graphite-bismaleimide outer shell. The composite outer wraps have manufacturer prescribed continuous operating temperatures. These operating temperatures are usually set at the cure temperature of the composite: 350°F for epoxy matrix composites and 450°F for bismaleimide matrix composites. However, in certain firing scenarios for tank cannon, the operating temperature may reach 650°F. Thus, a problem to be addressed in the development of organic-composite wrapped gun tubes is temperature effects on the combined structure. A subscale test was initiated to answer this concern. This report covers the results of the subscale testing and the finite element analysis of the subscale model. The subscale model is based on an experimental gun tube and some comparisons are made with the actual gun tube results.

TEST SPECIMENS

The steel liner for the subscale test specimens had an inner diameter of 2.0 inches and an outer diameter of 2.34 inches. Figure 1 is a schematic giving the liner details. The steel was 4130 seamless mechanical tubing heat treated to a hardness of 34-36 Rockwell "C". A standard ASTM tensile test was

conducted to determine the 0.1 percent offset yield strength (120 Ksi) and the ultimate strength (140 Ksi). The composite jacket is a graphite-bismaleimide produced by Fiberite Corporation. Its cure temperature is 450°F and it is wound and wrapped on the steel liner in the same manner as the full-scale gun tube specimen denoted as CTL III. The layup is again approximately half-scale and is made up of two longitudinal layers alternating with two circumferential layers. Sixteen layers are applied in this way. Lamina properties for this material are given in Table I.

SIMULATED FIRING TEMPERATURE CYCLE

The main purpose of this project was to determine the effects of a temperature cycle on the operation of the total structure. A method was devised to heat the cylinders using a resistance heating unit inserted in the bore. This was used to simulate heating experienced in a gun, i.e., heating from the bore outward. Figure 2 is a schematic depicting the heating arrangement; it also shows a specimen instrumented with thermocouples to permit temperature measurements at the liner-composite interface as well as at the outside diameter (OD) of the composite. This specimen was not pressure tested, but was used solely to establish correlation voltage settings on the ceramic heater power supply and OD thermocouple readings for the desired interface temperature. This allowed the actual test specimens to be constructed without obstruction of gages and wires at the composite-steel interface and to be subjected to a known temperature cycle. The cycles chosen were based on the firing scenario which brings the liner-composite interface to a temperature of 650°F. The pressurization tests were conducted on specimens which were held at the 650°F temperature for one, two, or three hours. Two uncycled specimens as well as two specimens for each

TABLE I. MATERIAL PROPERTIES OF STEEL AND COMPOSITES USED IN THE ABAQUS ANALYSIS

Material	E_{θ} x10 ⁶ psi	E_r x10 ⁶ psi	E_z x10 ⁶ psi	ν_{rz}	$\nu_{r\theta}$	$\nu_{2\theta}$	G_{rz} x10 ⁶ psi	$G_{r\theta}$ x10 ⁶ psi	$G_{z\theta}$ x10 ⁶ psi
Hoop lamina Im6	21.0	1.0	1.0	0.40	0.02	0.02	0.37	0.61	0.61
Axial lamina G50	1.3	1.3	31.0	0.01	0.39	0.39	0.79	0.47	0.79
Steel 4130	30.8	30.8	30.8	0.30	0.30	0.30	11.5*	11.5*	11.5*

$$*G = \frac{E}{2(1+\nu)}$$

of the hold times were pressure tested. An additional temperature cycle of 750°F for one hour was also included in the testing, although no firing scenario is given in which the temperature reaches this level. Two specimens subjected to this temperature cycle were also tested. Ten specimens were then pressure tested to determine the effects of temperature on the structure performance.

PRESSURIZATION TEST

Figure 3 shows a test specimen installed in the press and ready to be pressurized. There is a space between the end caps and the test cylinder so that no compressive end loads are applied to the cylinder; however, the interface between the high pressure seal and the cylinder may introduce some axial loads. The pressure source is an intensifier system. The pressure is measured at the specimen by a bulk modulus cell (strain gage cell). Strain gages are also mounted on the OD of the composite cylinder. This combination allows a plot of strain versus pressure to be produced on an X-Y recorder. Strain was also measured using an SR-4 strain indicator.

PRESENTATION AND DISCUSSION OF RESULTS

General

This was to be a rather straightforward investigation of the effects of various temperature cycles on the stress-(pressure) strain response and the burst pressure of the composite cylinders. However, in the initial pressurization tests of cylinders that had not been exposed to a temperature cycle, it was noted that the pressure in the cylinder could be raised to considerable levels without obtaining any circumferential strain response on the OD of the composite. The cause of this "strain lag" became the subject of much discussion. This phenomenon was noted in laboratory cycling of sections of 105-mm tubes that

were previously field fired in such a way as to achieve high composite temperatures. The original explanation for this phenomenon in the field fired tubes was that thermal degradation was occurring in the composite. However, the discovery of the effect in the small cylinders unexposed to any temperature cycle other than the curing process, leads one to believe that this phenomenon is a result of the manufacturing process. The results suggest that a gap exists between the steel liner and the composite outer shell and that it may be at least partially attributed to the difference in thermal expansion coefficient of the two materials.

FINITE ELEMENT ANALYSIS

The finite element code ABAQUS was used to obtain stresses, displacements, and strains in a steel cylinder wound with a graphite-bismaleimide composite. The motivation behind this analysis was to gain a better understanding of the delayed strain response observed during internal pressurization of these cylinders. Initially, half of the cylinder was modeled with the symmetry plane being perpendicular to the axial direction. However, it was found that using a simple ring model produced results that were almost identical to those of the half-sized model.

Four different cases were considered:

1. A steel cylinder with no jacket.
2. A steel cylinder with a composite jacket (no gap).
3. A steel cylinder with an adhesive layer and composite jacket.
4. A steel cylinder with a gap and a composite jacket.

In each case mentioned above, eight-node axisymmetric hybrid elements were used. The hybrid elements were preferred over the conventional elements because they calculate the mean stress more accurately. The calculation of mean stress becomes increasingly more important as the zone of plastic deformation grows in magnitude. Since it is known from past experience that the hybrid element calculates stress more accurately, it is considered to be the correct solution when percent error is mentioned. The benefits of using the hybrid element as opposed to the conventional element are apparent only in the accuracy of the stresses calculated, while the accuracy of the displacements is virtually unchanged. Figure 4 shows the advantage of using the hybrid element for case 1 involving the steel cylinder. The internal pressure is 22.5 Ksi which is approximately equal to the failure pressure. The radial, axial, hoop, and mean stresses are plotted as a function of radial position. For each stress the smooth curve is the result of using the hybrid element, while the oscillating curve is the result of using the conventional element. Table II shows the comparison between the hybrid and conventional elements at the inner radius of the steel. For each stress, other than the von Mises' stress, the magnitude of the error is the same, 5.7 Ksi. This translates into large errors for the stresses with small magnitudes such as the radial and axial stress.

TABLE II. STRESSES AT THE INNER DIAMETER FOR THE STEEL CASE

	Radial	Axial	Hoop	Mean	von Mises
Hybrid	-22.2	-0.7	127.2	34.8	139.9
Conventional	-16.4	5.0	132.9	40.5	139.9
% Error	26%	+600%	4.5%	16.4%	0%

The benefits of using the hybrid element in cases involving extensive plastic deformation need to be weighed against the increased computation time necessary to calculate the mean stress values.

In addition to using the hybrid element, a nonlinear geometry option was also used to account for the change in bore area due to plastic deformation. Without implementing this option, the program models the structure to be less compliant than it is in actuality. For case 1 (the all-steel cylinder), the nonlinear geometry option produces displacements that are 25 percent larger at the outside diameter of the cylinder than the linear geometry default option. These larger displacements are more representative of the actual state of the cylinder. The stresses for either option are within one percent of each other.

An elastic-plastic material model with strain-hardening was used to define the steel's material response. Young's Modulus for the steel was 30.8 MPsi, Poisson's ratio was 0.3, and the proportional limit was 103.7 Ksi. A piecewise linear curve was used to model the strain-hardening region of the steel's stress-strain curve. The composite was assumed to be linearly elastic with the properties given in Table I.

Friction between the composite and steel with a gap present was assumed to be negligible. Interface elements were used in case 4 to model the gap between the steel and the composite. These elements have the ability to determine if two surfaces have touched after loading of the structure has begun. If contact does occur, it then begins to transmit the load between the two surfaces.

DISCUSSION OF RESULTS

Finite Element Analysis

Case 1: All-steel cylinder with no jacket.

The all-steel cylinder was studied to insure that our model was accurately representing the large plastic deformations that occur as the cylinder approaches failure. The comparison between our finite element model and experiment is shown in Figure 5. The radial displacement at the outside radius of the steel was plotted at various internal pressures up to failure. The two curves show excellent agreement with the experimental failure pressure being 22.3 Ksi and the finite element being 21.6 Ksi. The failure in the finite element model was assumed to occur when the solution encountered numeric instability for a reasonably small pressure increment.

Case 2: A steel cylinder with a composite jacket with no gap.

Case 3: A steel cylinder with an adhesive layer and composite jacket.

Cases 2 and 3 were investigated to determine if the delayed strain response at the outside diameter of the composite could be caused by the addition of an adhesive layer at the steel-composite interface. Case 2, with the composite in intimate contact with the steel, is a baseline case to be compared with case 3. Figure 6 shows the radial displacement versus pressure response for cases 2 and 3 along with data points from the experiment. As expected, case 2 shows no strain delay at the outside of the composite. In case 3, an adhesive layer having a thickness of 0.007 inch is added between the steel and the composite. This case is investigated to determine if a very compliant layer could be the cause of the delayed strain response. The adhesive was modeled using 50 and 500 Ksi for Young's Moduli and running subcases for each of those moduli with a Poisson's ratio of 0.2 and 0.4. The adhesive was assumed to be isotropic and linearly elastic for each of the four adhesive models. The most compliant

adhesive model was plotted in Figure 6. As can be seen, the addition of an adhesive layer cannot explain the delayed strain response observed in the experiment. This result led to the next model where the adhesive layer is replaced by a space (gap) between the steel liner and the composite overwrap.

Case 4: A steel cylinder with a gap and a composite overwrap.

From an analysis of the experimental data and the finite element analysis of the steel cylinder, it was apparent that the gap was approximately 0.004 inch. Figure 7 shows the experimental results along with the computer modeling results. The composite material properties used in the computer model up to this time had been based on a fiber volume of 60 percent. An additional model with a 50 percent fiber volume was then examined to see if these results yielded a better fit to the experimental data. Typically, composites produced here have a fiber volume between 50 and 60 percent. We found the 50 percent fiber volume model represents the experimental data more closely than the 60 percent fiber volume model shown in the figure.

EXPERIMENTAL INVESTIGATION

Results from the testing of cylinders that were not thermally cycled were compared with those that were thermally cycled to determine if the thermal cycle affected the structure in terms of stress-strain response and burst pressure. Table III summarizes the results for the twelve cylinders tested. An unjacketed liner was tested to demonstrate that although the composite did not lend support to the liner in the early stages of pressurization, it did provide support and strengthen the structure as the pressure increased above 17,500 psi. The burst pressure for the liner only was 22,300 psi, while the burst pressure for a composite tube with no thermal cycling was approximately 44,100 psi. Figure 8 is a pressure versus strain plot for the as-cured cylinder denoted in Table III as

TABLE III. TEST RESULTS FROM THE PRESSURIZATION AND BURST TESTING
OF THE TWO-INCH INNER DIAMETER COMPOSITE CYLINDERS

Liner Number	Condition (Thermal Cycle)	Burst Pressure (Psi)	Ave. Burst Pressure (Psi)	Failure Strain (μ in./in.)	Pressure to Reach 150 μ in./in. (Psi)
2	Cured	43,800	44,200	-	17,500
3	Cured	44,500		-	-
4	650°F - 1 hr	41,800	43,200	-	-
5	650°F - 1 hr	44,500		-	-
7	650°F - 2 hr	41,300	41,900	11,600	17,500
9	650°F - 2 hr	42,500		-	18,500
6	650°F - 3 hr	41,100	41,700	10,600	18,000
11	650°F - 3 hr	42,300		10,600	19,300
8	750°F - 1 hr	36,800	37,900	8,300	19,500
10	750°F - 1 hr	39,000		9,800	20,100
13	Cured*	38,700	-	13,300	17,500
Liner Only		22,300	-	13,000†	1,300

*Curing process for this cylinder is different than the other 11.

†Used to calibrate the ceramic heater.

liner 13. This cylinder was cured by a different process, and thus shows a different burst pressure. However, it is a typical pressure versus strain plot in all other respects. The strain in this case actually goes negative (compression) before returning to "zero" at approximately 17,000 psi and then proceeds into tension up to failure. A gage mounted 180 degrees from the plotted gage would probably have gone slightly into tension before returning to zero and then, as in the other gage, returned to tension up to failure. This was seen in other cylinders and may indicate that the gap is not uniform or symmetric. A comparison of the other results, included in Table III, indicates a very slight deterioration in burst pressure as the time of the thermal cycle at 650°F increases from one hour to three hours. The strain-to-failure is also slightly affected, again in a negative way. There was also a slight increase in the pressure required to reach a tensile strain of 150 μ in./in. (This number was chosen because of the small compressive and tensile strains that were read and then these strains returned to zero before going in the proper tensile direction.) Figure 9 is a plot of pressure versus strain for a cylinder (liner 8) thermally cycled at 750°F for a period of one hour. The burst pressure, strain-to-failure, and the pressure at which the strain reaches 150 μ in./in. have all been significantly affected.

AUTOFRETTAGE

During the pressurization test of a cylinder thermally cycled at 650°F for two hours, the stroke from the pressure source reached its upper limit and we were required to return the pressure in the cylinder to zero. Figure 10a shows the pressure versus strain plot for the initial pressurization cycle and the fact that, at the OD of the composite, 4500 μ in./in. of tensile strain had been

retained. Figure 10b shows the subsequent pressurization cycle; the pressure versus strain plot now shows the strain on the OD of the composite responding immediately to the slightest internal pressure. The burst pressure does not appear to be negatively impacted by the prior pressurization cycle in which the pressure reached 35,500 psi or approximately 90 percent of final burst pressure.

CONCLUSIONS

While the original intention of the investigation was to measure the effect of thermal cycles on the stiffness strength of the composite structure, the discovery of the gap between the composite and the steel cylinder caused a change in the program. The following specific conclusions can be drawn from the data:

1. The outer diameter of the composite jacket registers little or no strain until the internal pressure in the cylinder reaches 17,000 to 19,000 psi. This effect can be modeled using a gap element in the ABAQUS program. Introducing a gap of 0.004 inch in the program predicts the experimental results very well.
2. Thermally cycling the cylinders at 650°F causes only minor changes in the strain-to-failure and the burst pressure of the cylinder.
3. Thermally cycling at 750°F appears to cause considerable deterioration in both the strain-to-failure and the burst pressure of the cylinder.
4. Hydraulic autofrettage of the steel cylinder can be conducted to remove the gap and leave circumferential tensile stresses in the composite. In the one case investigated, the burst pressure was apparently unaffected by the process.

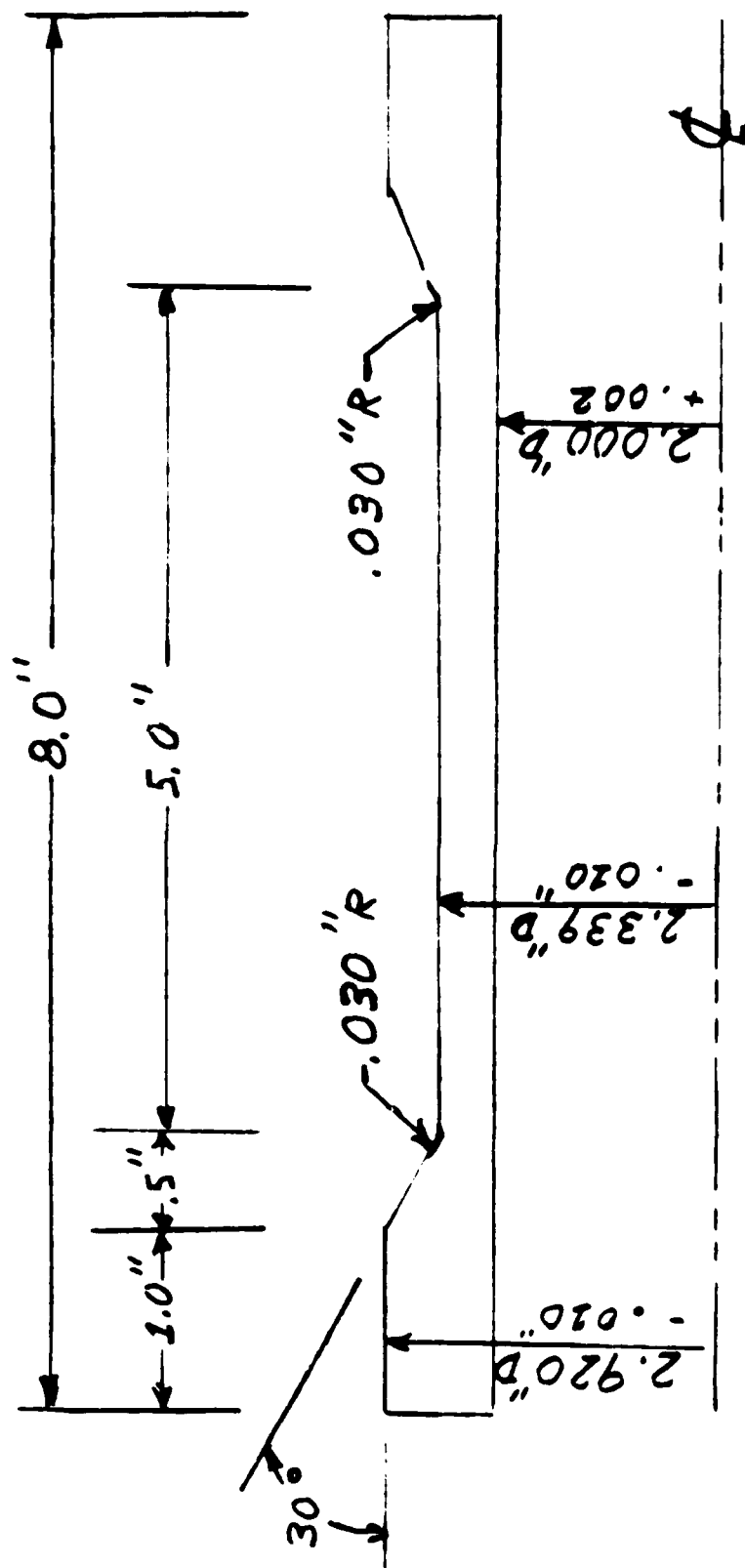


Figure 1. Steel liner details.

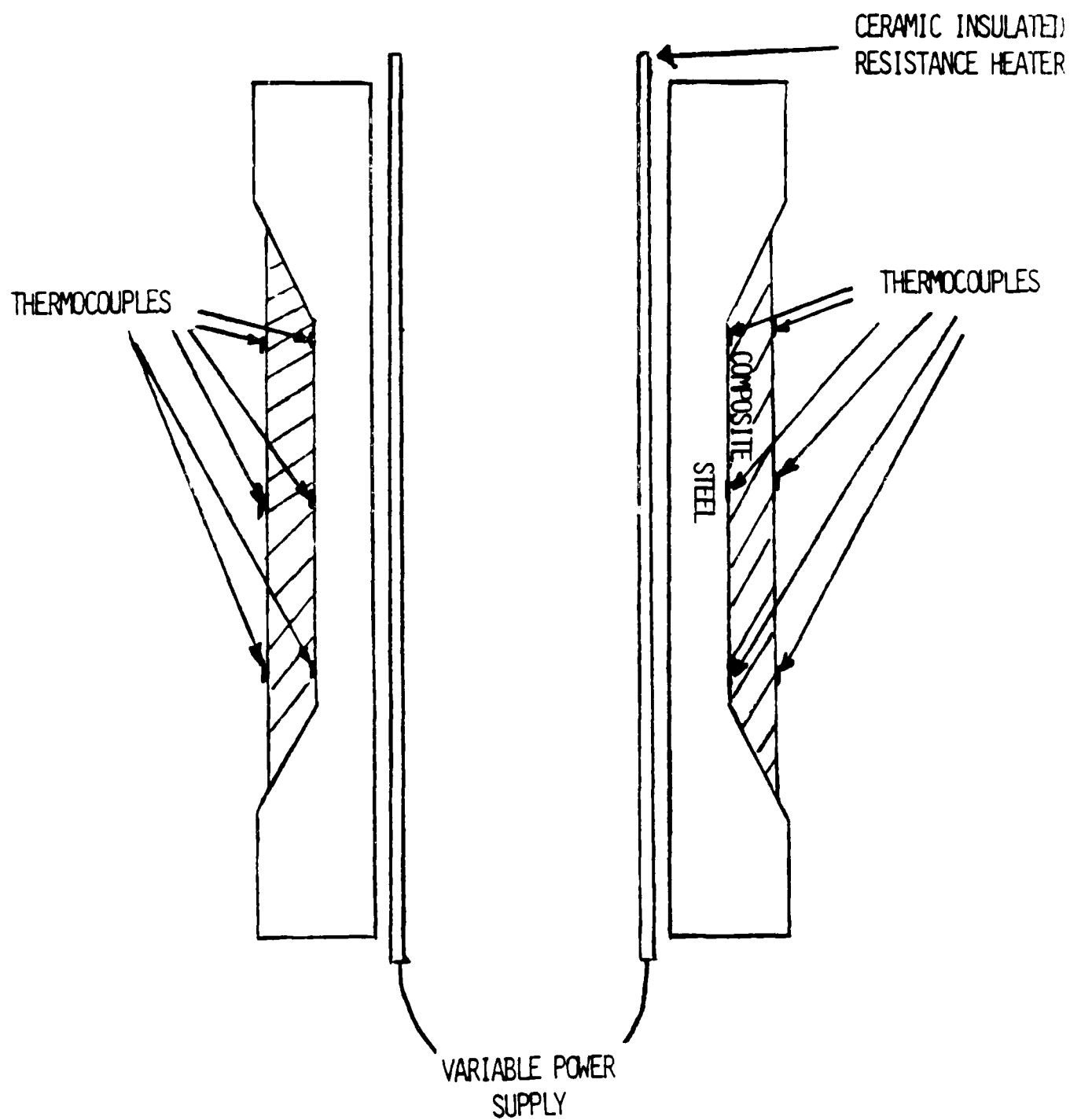


Figure 2. Schematic of the bore heating apparatus.

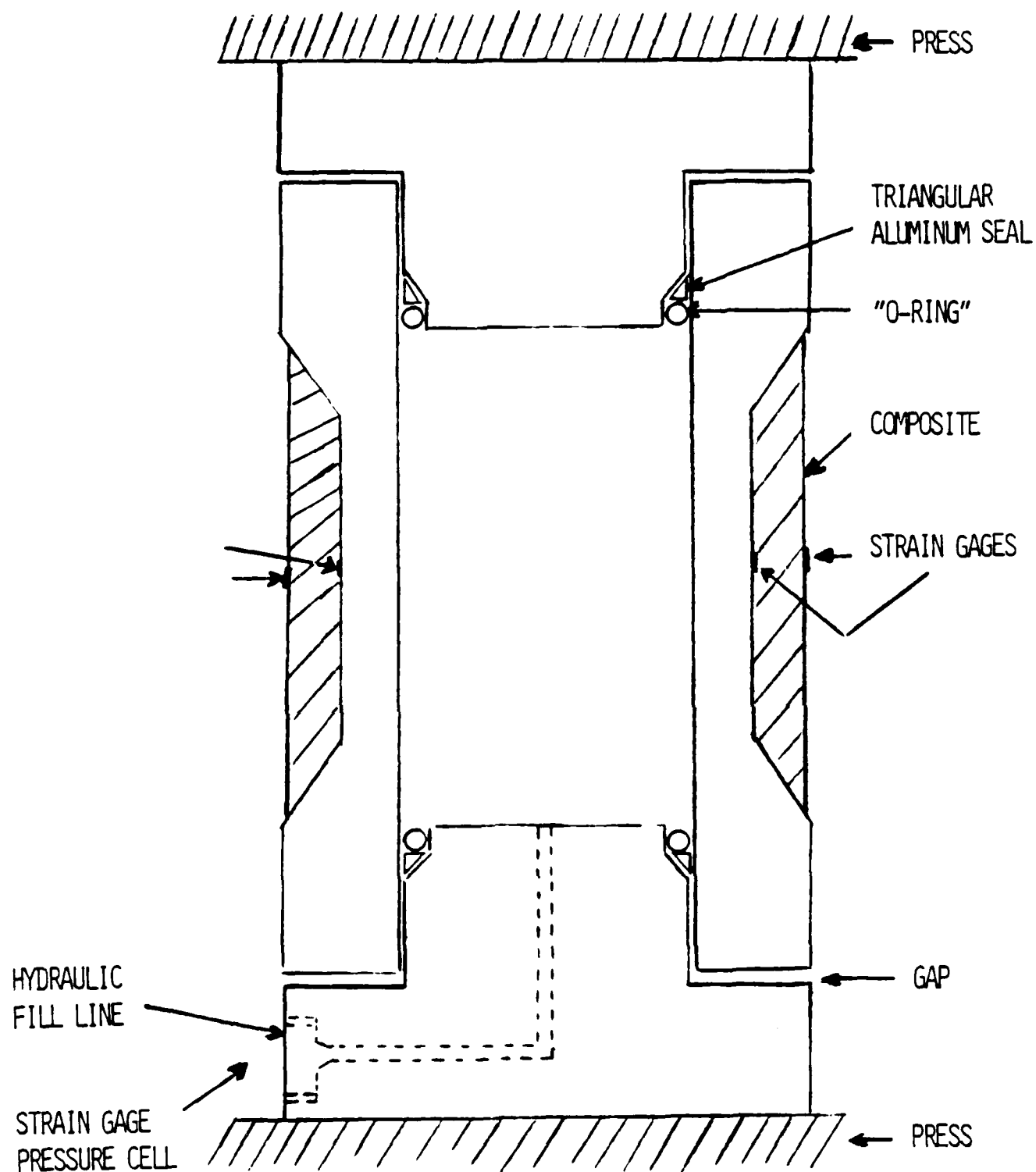


Figure 3. Schematic of the setup for pressurizing test specimens.

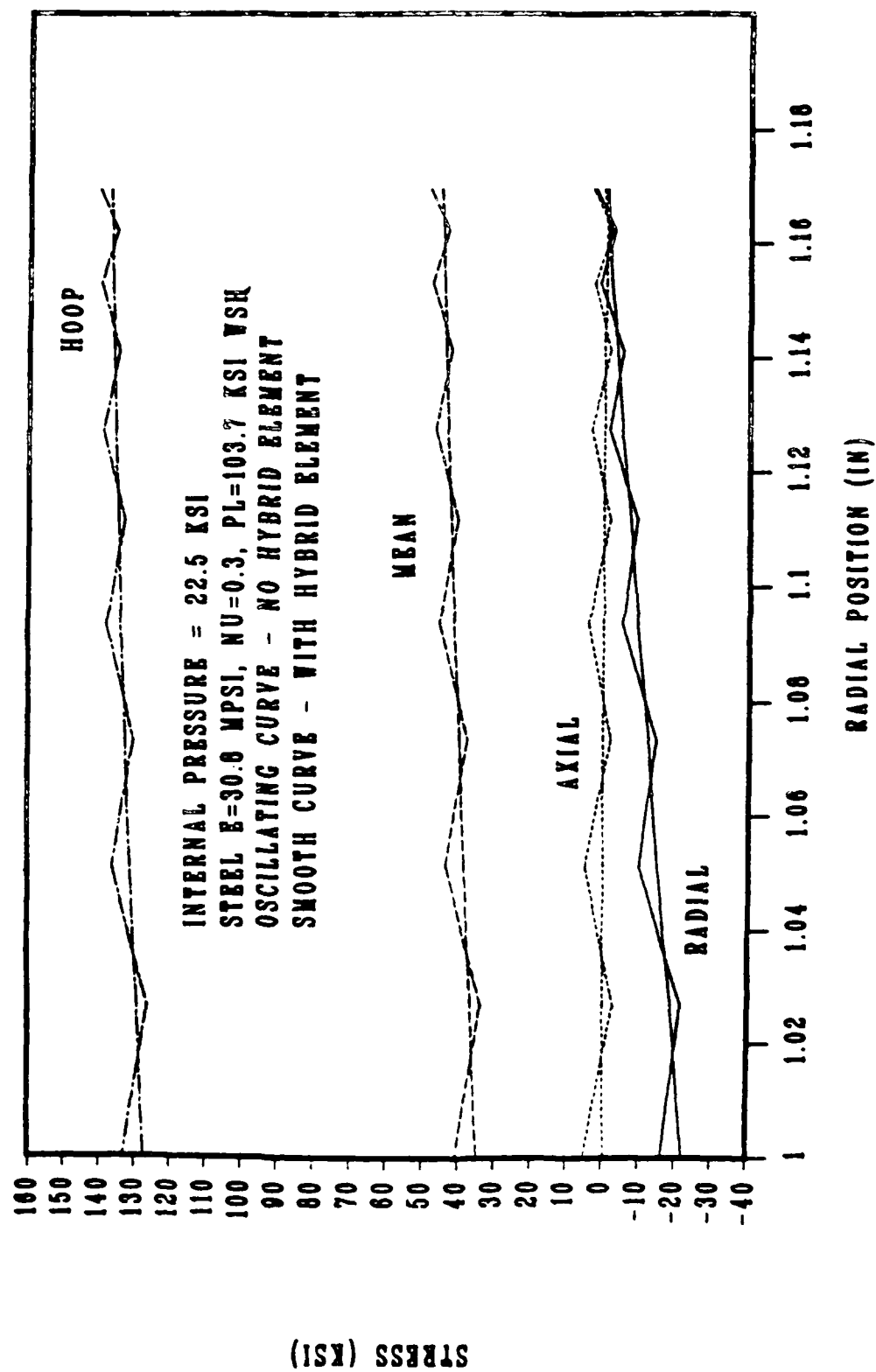


Figure 4. Plot of stress versus radial position in the steel liner for both the conventional and hybrid element.

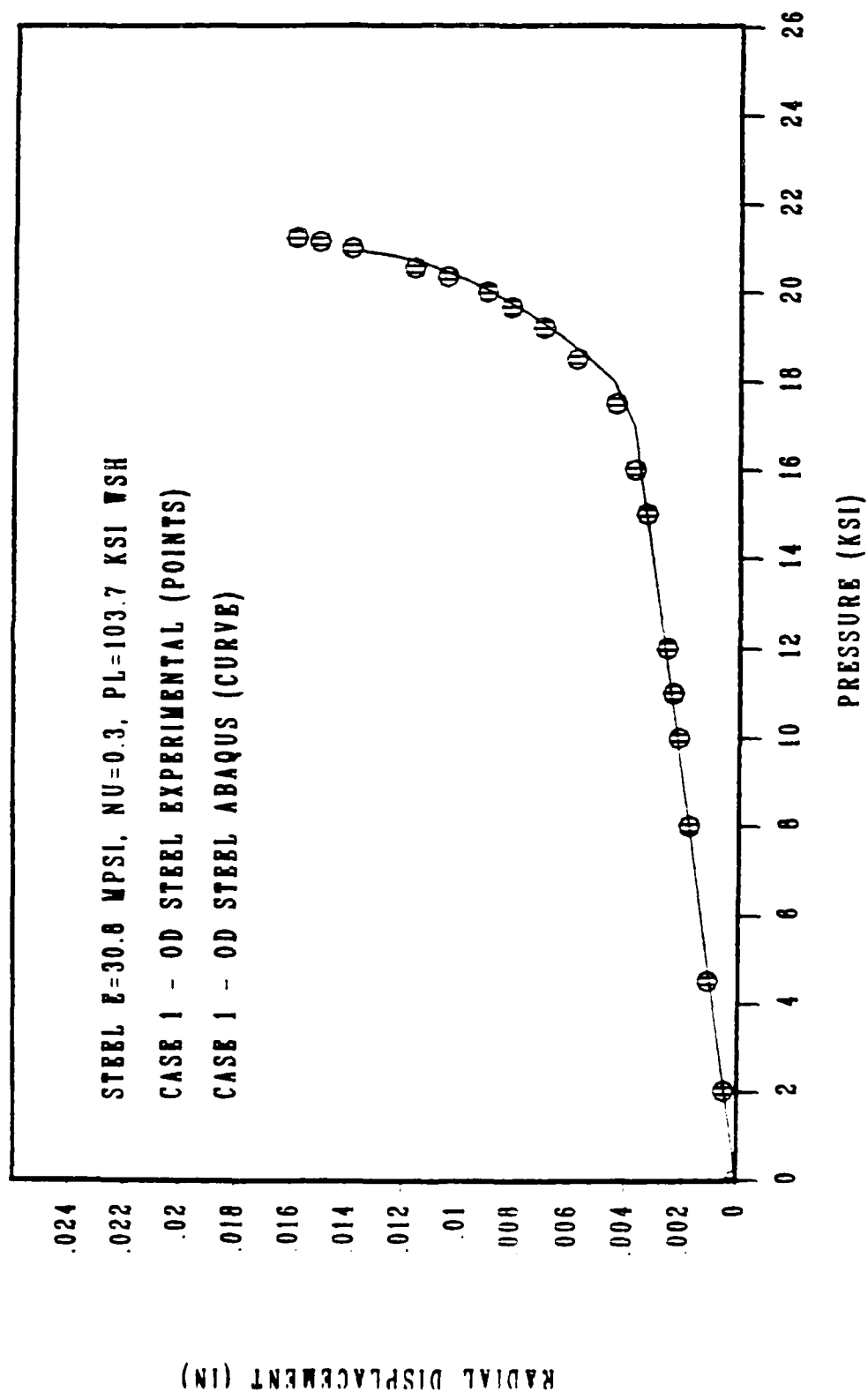


Figure 5. Experimental and theoretical radial displacement versus pressure results for the steel liner.

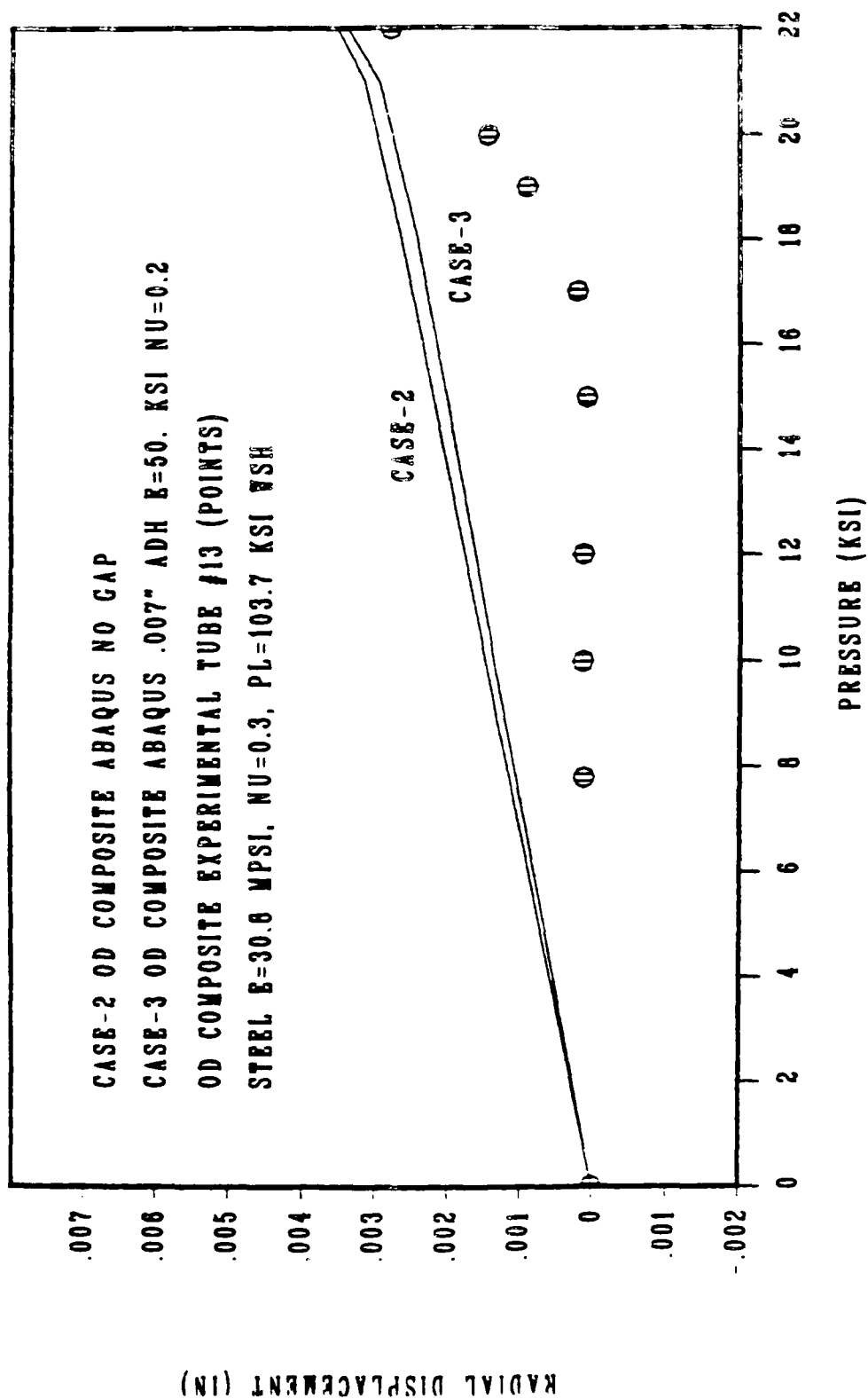


Figure 6. Theoretical results compared to experimental results for cases 2 and 3.

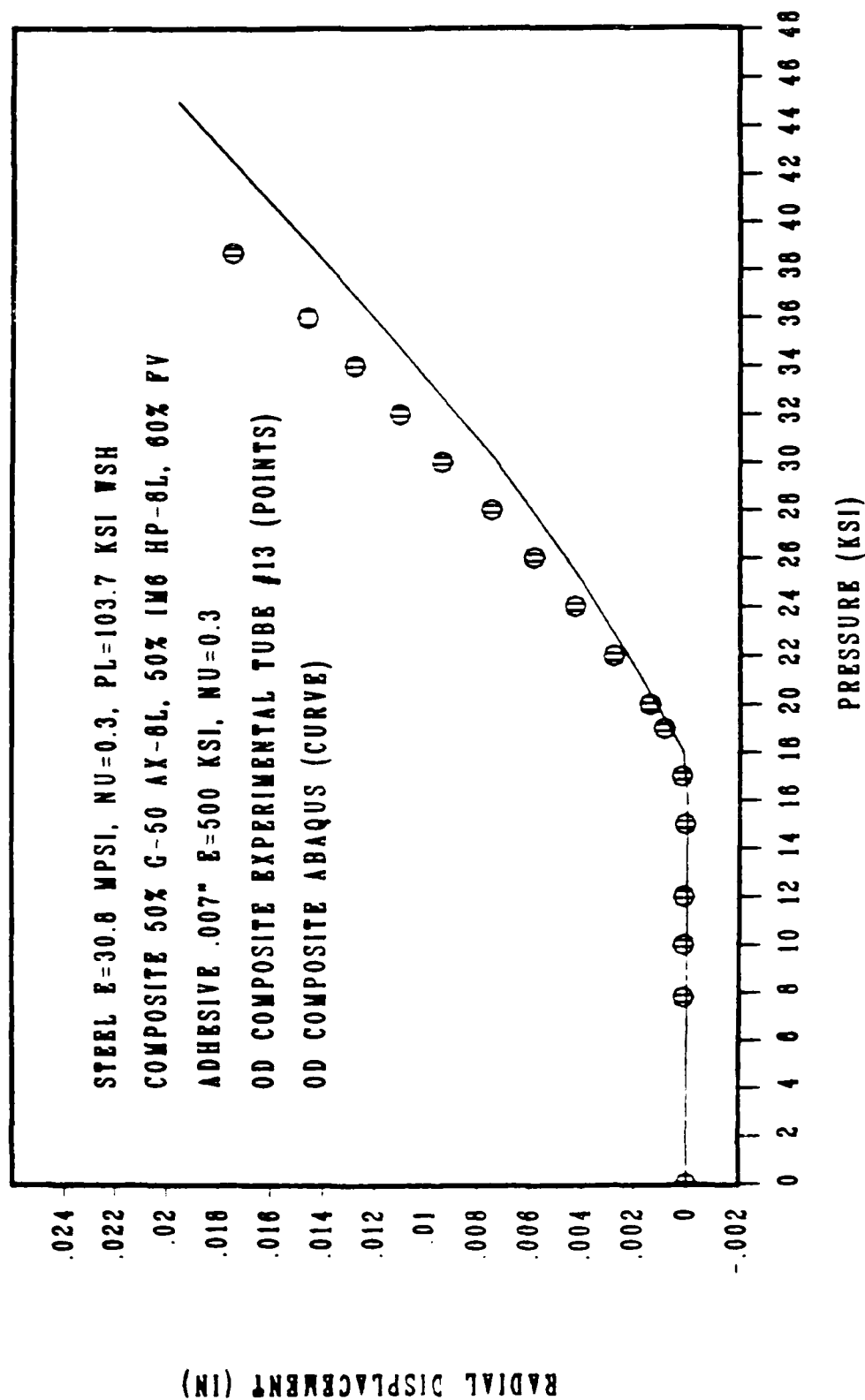


Figure 7. Theoretical results compared to experimental results for the case of a gap between the steel liner and the composite shell.

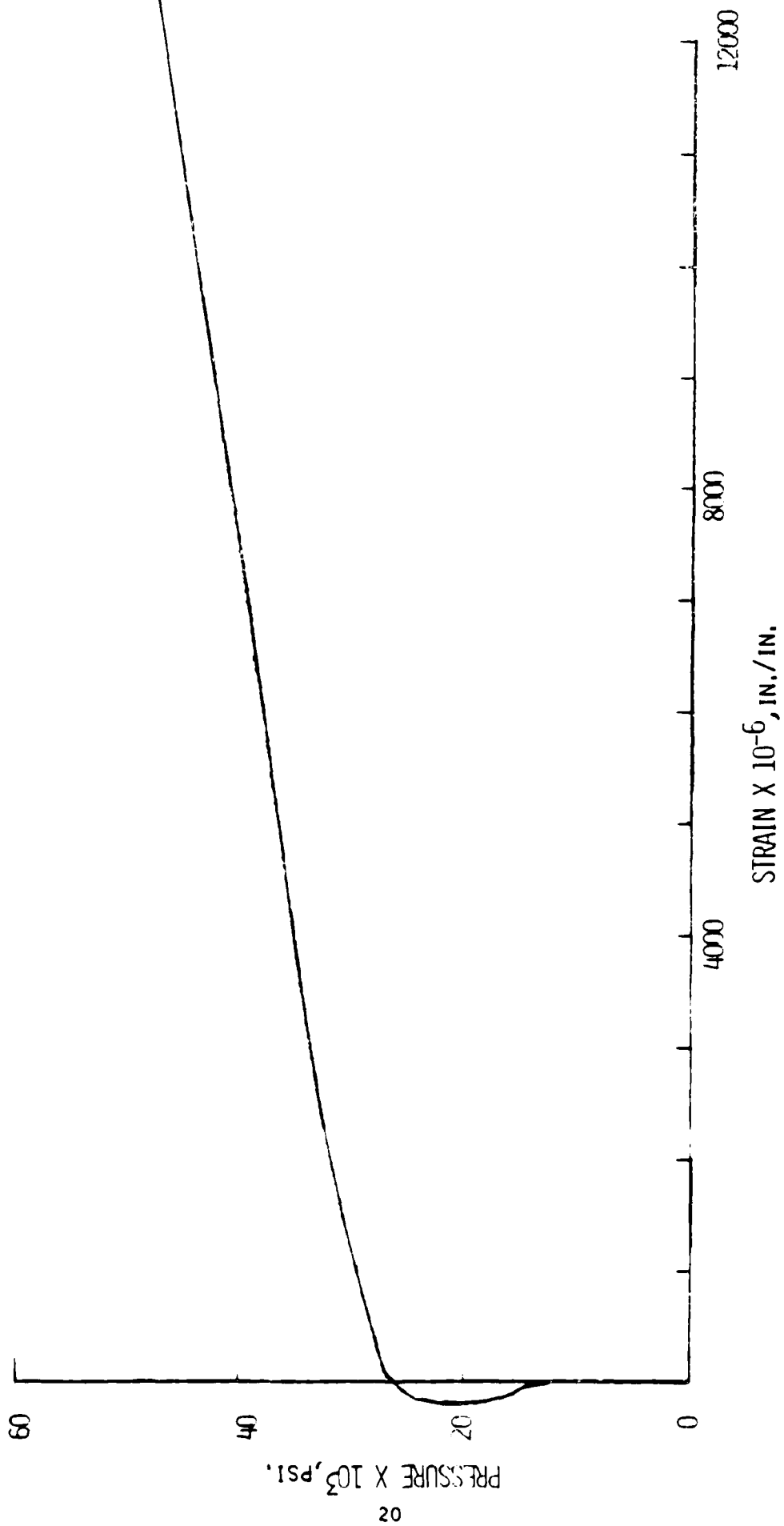


Figure 8. Typical internal pressure versus outer diameter strain for the composite cylinders tested.

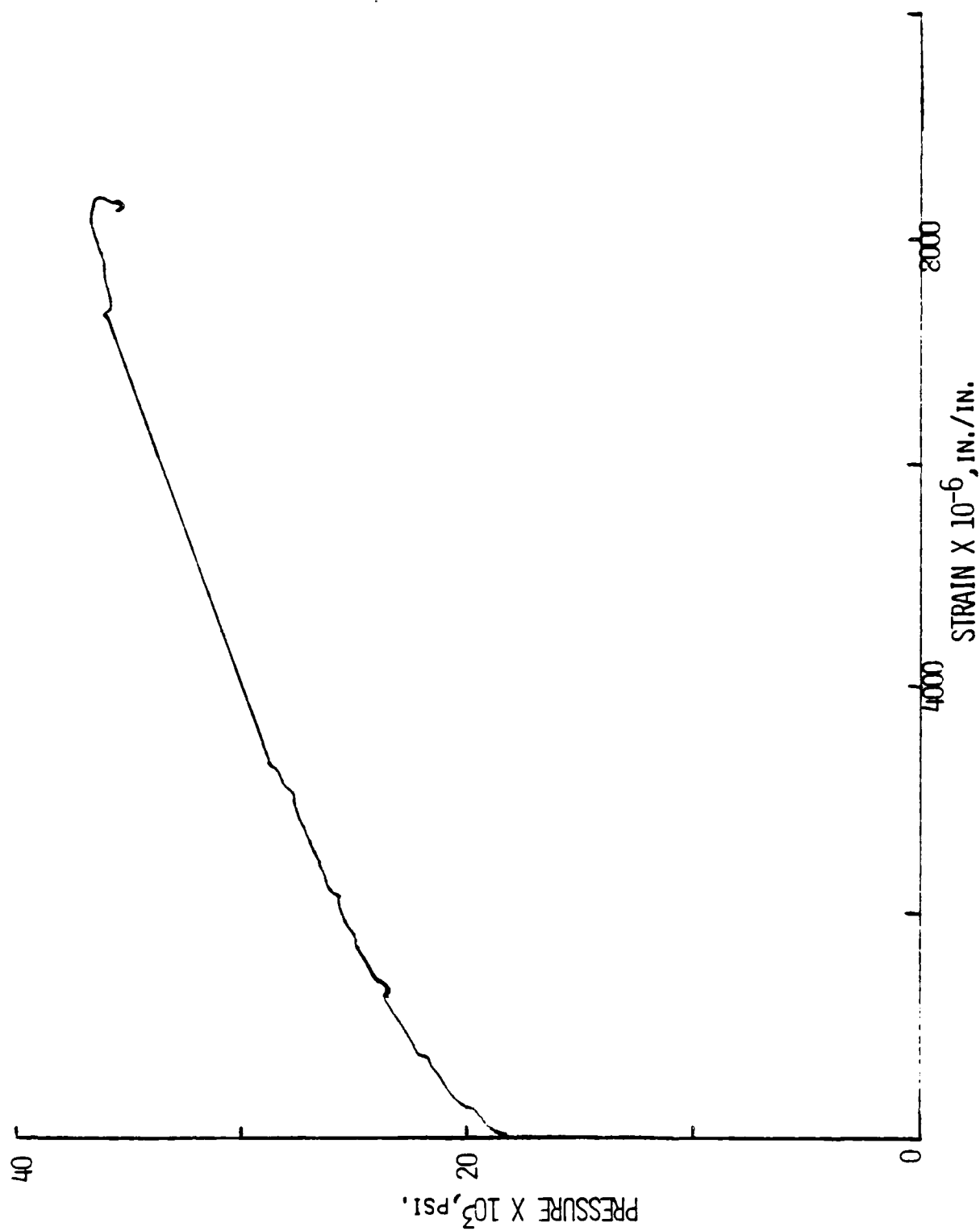


Figure 9. Internal pressure versus outer diameter strain for a composite cylinder which was thermally cycled at 750°F for one hour.

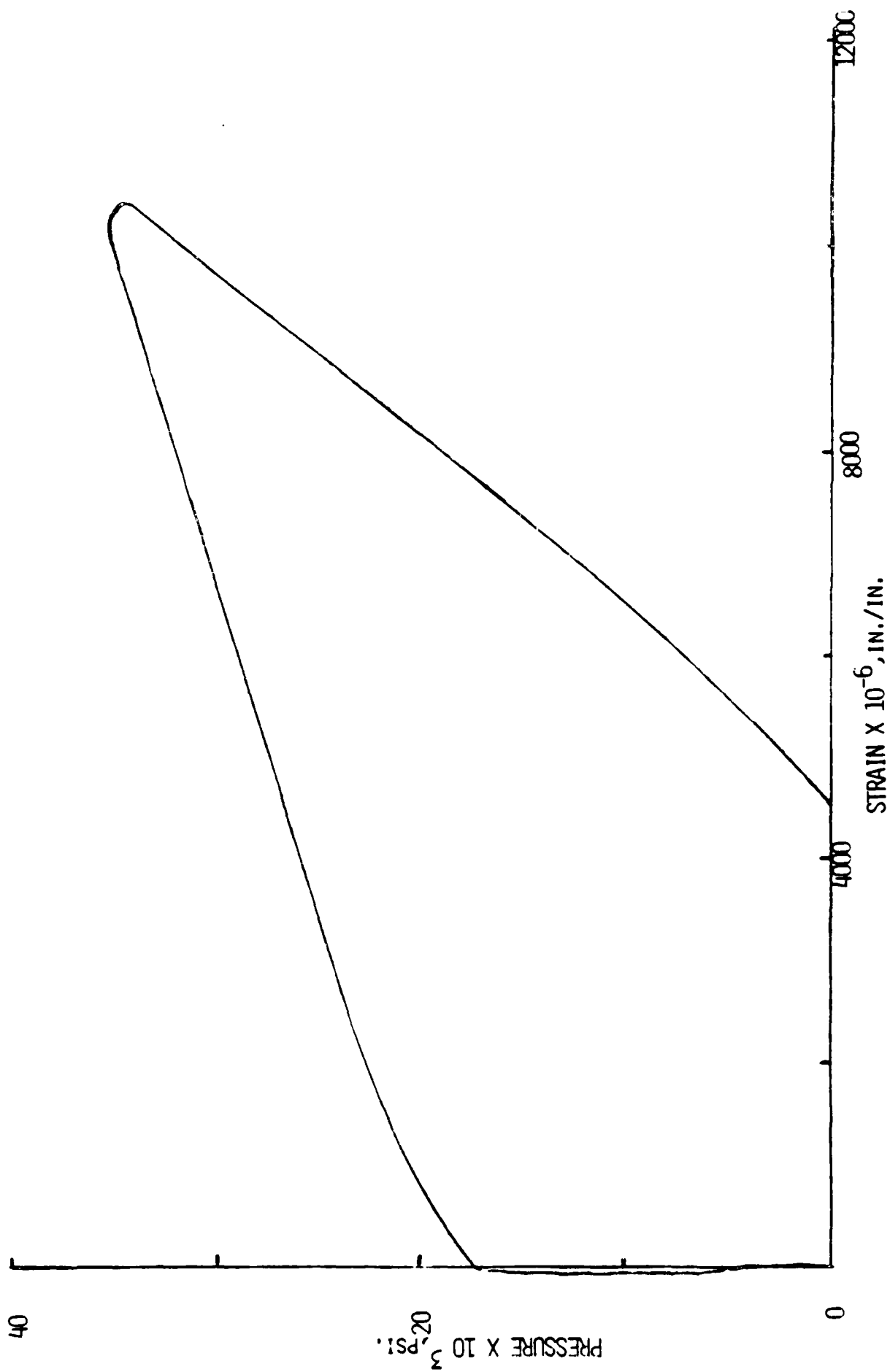


Figure 10a. Autofrettage of a composite tube which was thermally cycled at 650°F for two hours - Initial pressurization cycle.

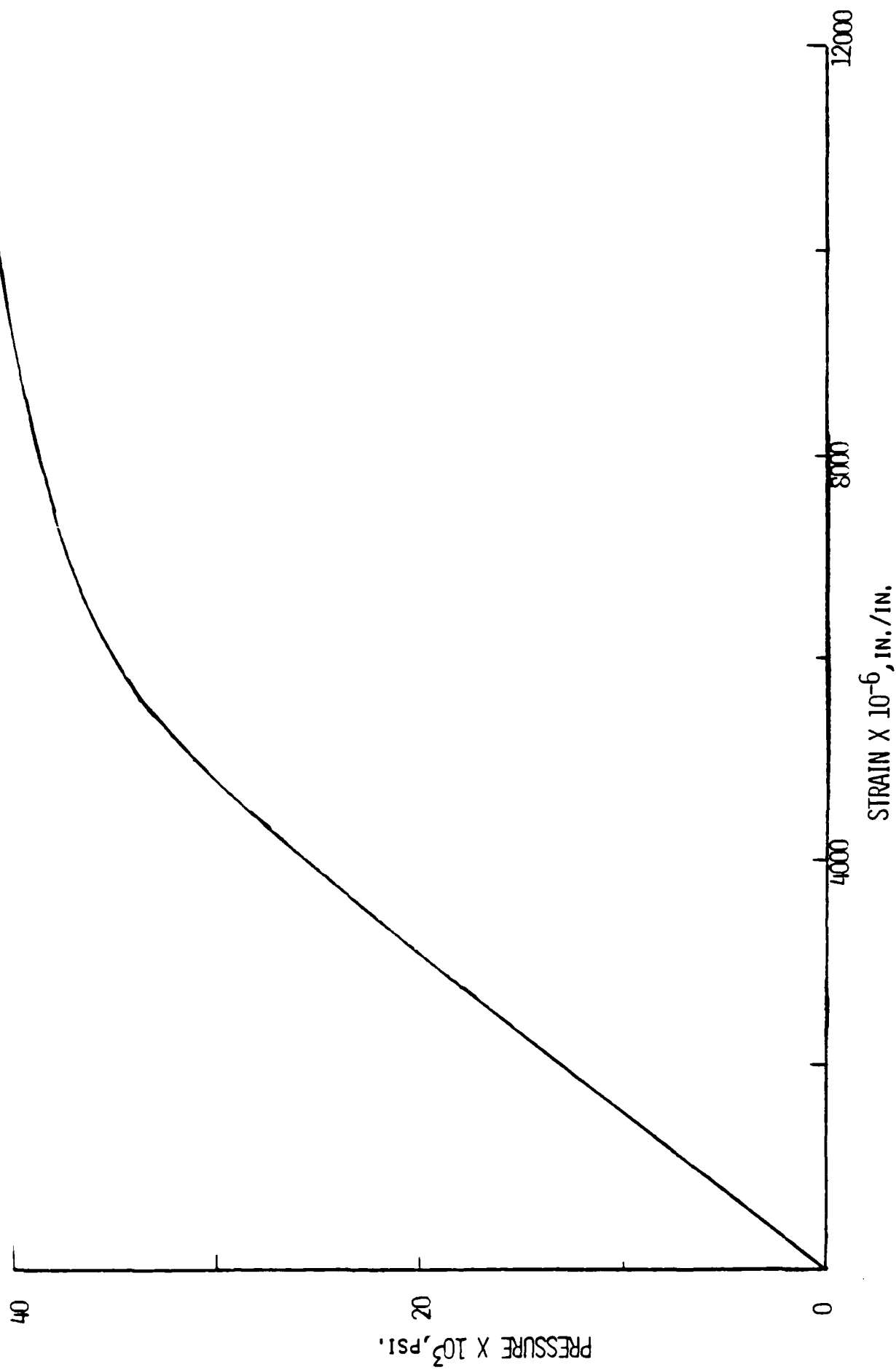


Figure 10b. Autofrettage of a composite tube which was thermally cycled at 650°F for two hours - Second pressurization cycle.

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