COMPRESSION TESTS OF WIRE-FILM CYLINDERS

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INTRODUCTION

Wire-film composites have many features that make them particularly attractive as a structural material for space applications. They can be fabricated into a variety of strong, extremely lightweight shapes and sizes that can be packaged into a small volume for launch. In space the material can be erected easily by inflating to the rigidification pressure. After the inflatant escapes, the rigidified unpressurized structure maintains its design shape. Among the potential applications of wire-film materials are passive communications satellites, decoys, and space vehicle camouflage systems.

One efficient structural element that can be made from wire-film material is a circular tube. A single tube could be used as a beam or a strut, or a number of tubes could be combined to make a truss. Preliminary analyses and in-house test programs at Goodyear Aerospace Corporation have demonstrated that extremely lightweight wire-film tubes with significant structural strength are practical. This paper offers information for the design of wire-film cylinders in compression by reporting a test program with the following objectives:

1. To establish the rigidification pressure that gives wire-film tubes the best structural characteristics
2. To determine the buckling coefficient for tubes loaded in compression
3. To determine the axial stiffness for tubes loaded in compression
4. To investigate the effects of packaging on the above properties

TEST SPECIMEN

A typical wire-film cylinder tested is shown in Figure 1. It consisted of a film to contain the pressure required for rigidification, equally spaced wires

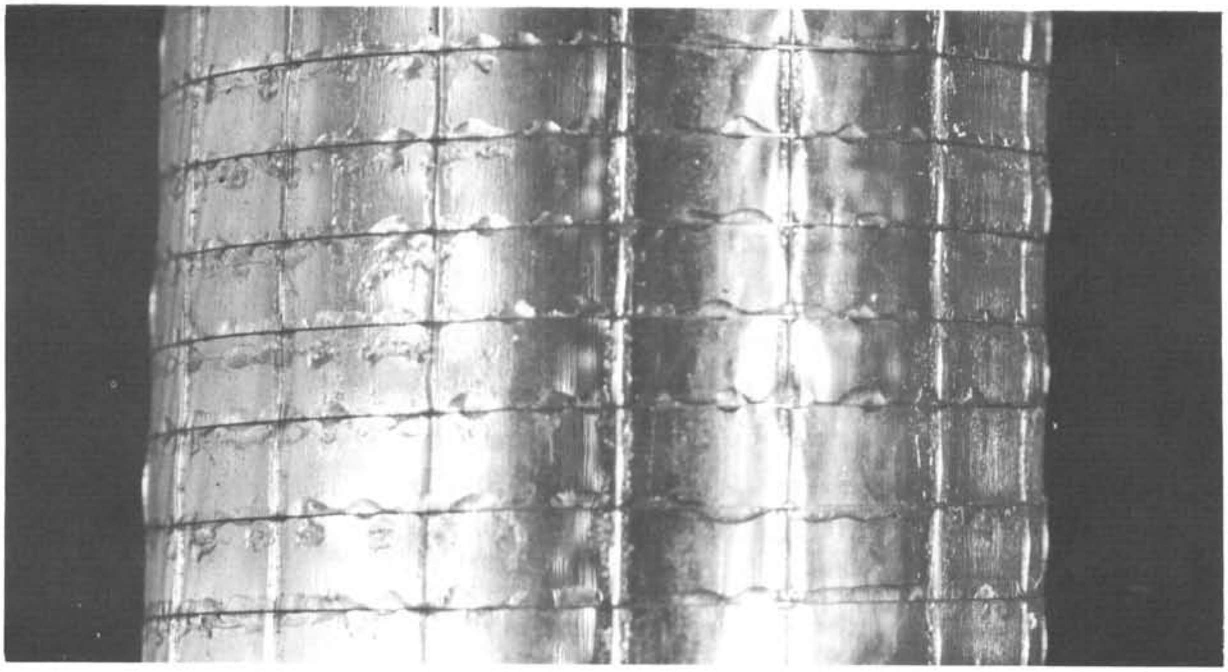

Figure 1 - Typical Wire-Film Cylinder

in the longitudinal direction, and wires wrapped continuously in the hoop direction. The diameters of the longitudinal and hoop wires were kept the same for a particular specimen, and the spacing of the hoop wires was one-half of the spacing of the longitudinal wires. The nomenclature used to describe the specimen is shown in Figure 2. Twenty eight specimens were fabricated, four each of seven types. In all cases the film was 1/4-mil Mylar, a practical minimum, to reduce the contribution of the film as much as possible. The other and more important variables were selected to cover as wide a range as practical. These included three wire materials (aluminum, stainless steel, and copper), three wire diameters (3, 5, and 10 mils), two spacings of the longitudinal wires (1/4 and 1/2 in.), and two cylinder diameters (3.000 and 1.273 in.). The data for the seven types of specimens are given in Table I.

The specimens were made in pairs on a mandrel using filament-winding techniques (see Figure 3). At each end of the mandrel was a special aluminum end cap containing a fitting to attach the pressure source and a micromanometer to measure the pressure. The fabrication procedure for the specimens was as follows.

1. A flat sheet of 1/4-mil Mylar lined with longitudinal wires was fabricated on a large-diameter mandrel.

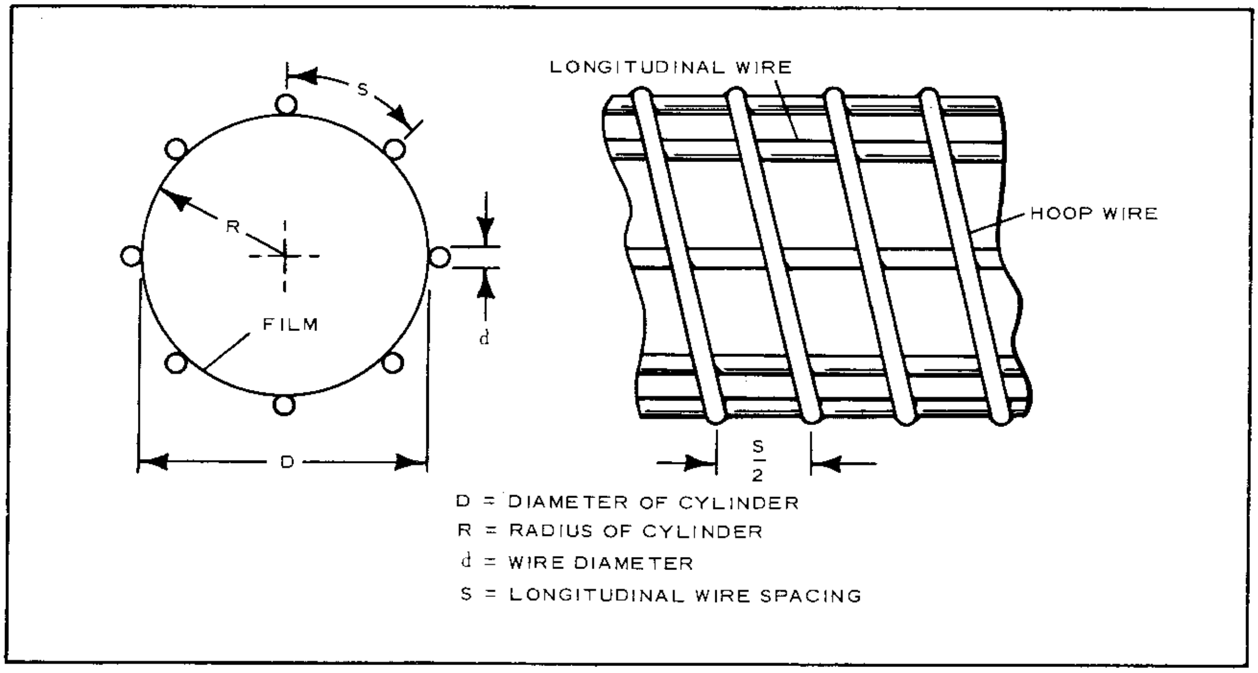

Figure 2 - Wire-Film Nomenclature

TABLE I - DESCRIPTION OF TEST CYLINDERS

Specimen type	Cylinder Length (in.)	Cylinder Diameter (in.)	Wire Material	Wire Diameter (mils)	S, from Figure 2 (in.)	Film
1	24.0	3.000	Stainless steel	3.1	0.500	1/4-mil Mylar
2	10.2	1.273	Stainless steel	3.1	0.250	1/4-mil Mylar
3	10.2	1.273	Stainless steel	5.1	0.250	1/-4 Mylar
4	10.2	1.273	Aluminum	5.0	0.250	1/4-mil Mylar
5	10.2	1.273	Aluminum	10.5	0.250	1/4-mil Mylar
6	10.2	1.273	Aluminum	10.5	0.500	1/4-mil Mylar
7	10.2	1.273	Copper	2.9	0.250	1/4-mil Mylar

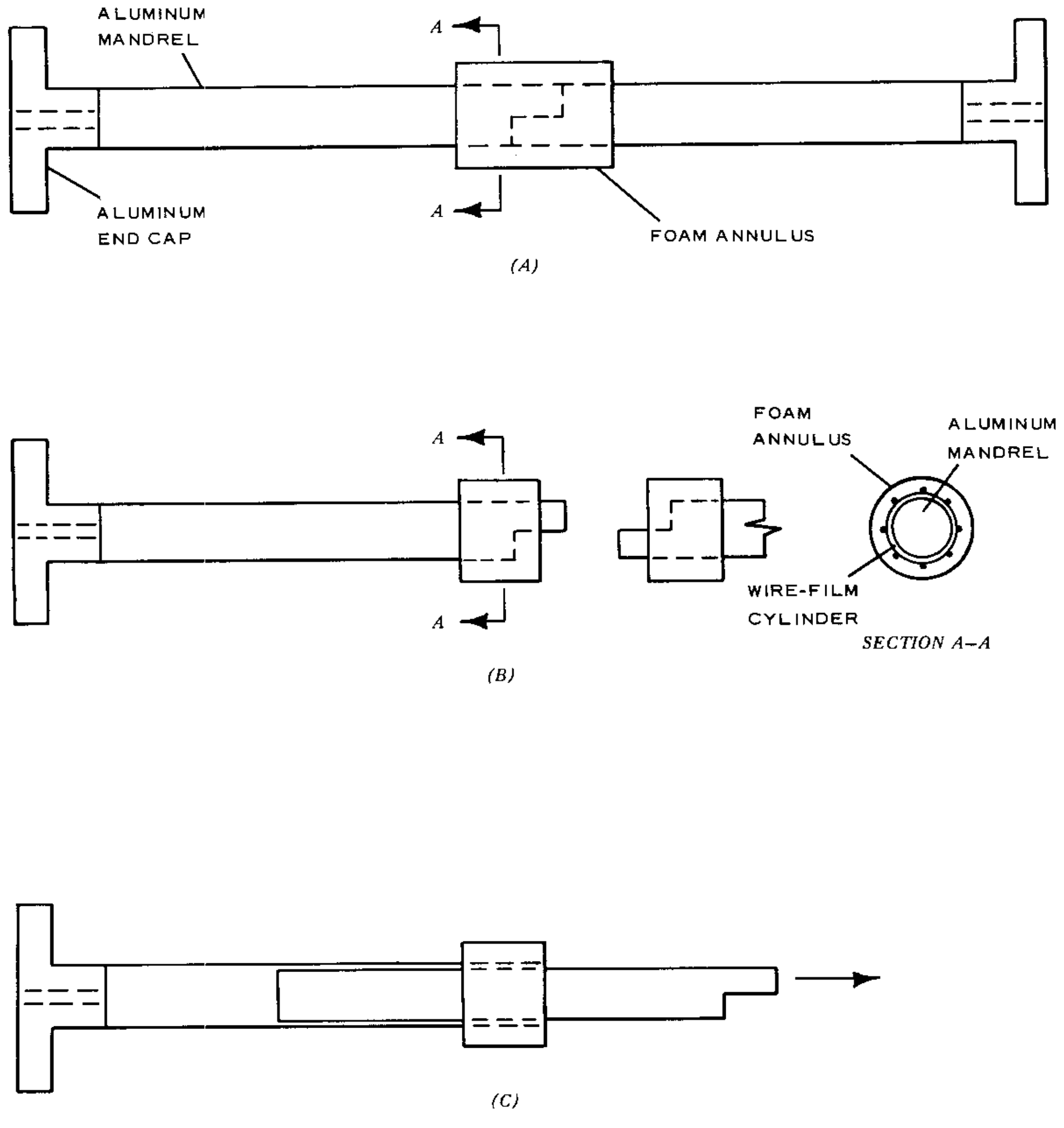

Figure 3 - Fabrication of Wire-Film Cylinders

2. The flat sheet was removed and wrapped around a mandrel and end caps of the desired cylinder diameter, with the longitudinal wires parallel to the mandrel axis. A longitudinal seam was made in the Mylar film, and the film was cemented to the end caps.
3. The hoop wires were wound on the wire-film cylinder while it was still on the mandrel.
4. A foam annulus was foamed around the cylinder at its midpoint (Figure 3A).
5. The annulus was machined to a specified diameter, thus making it concentric with the mandrel and cylinder center line.
6. The foam annulus and wire-film cylinder were diametrically cut at the midpoint of the cylinder's length. The mandrel had been made in two halves, and the halves were separated (Figure 3B).
7. The mandrel was removed from the cylinder halves with the aid of forced air, which was circulated between the mandrel and cylinder through small holes in the mandrel. (Figure 3C)
8. A foam plug was inserted and glued to the foam annulus.

TEST PROCEDURE

Compression was tested in an Instron machine, which automatically recorded the load-deflection curve. The aluminum end cap was attached to the crosshead of the Instron machine, as shown in Figure 4. A pressure differential, small compared to that required to develop the yield strength of the wires, was applied to the specimen. Then, the pressure differential was reduced to zero, the crosshead was run down, and the centering disk was located. This disk contained a centrally located button to ensure that the compression load was applied concentrically to the axis of the cylinder. A compression load-deflection curve was then obtained. By observing the record it was always possible to tell when the maximum load was attained.

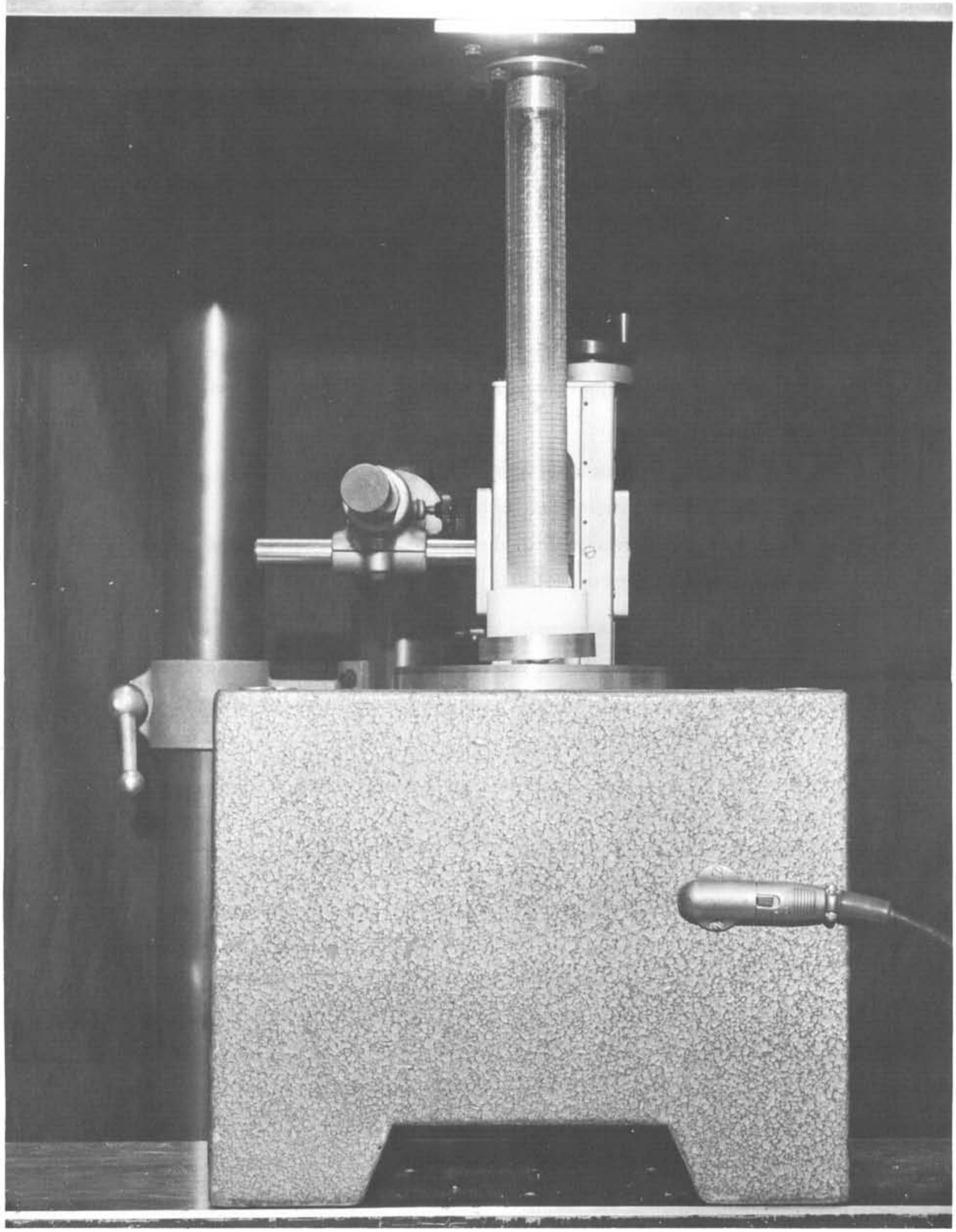

Figure 4 - Wire-Film Specimen Installed in Instron Machine

After the maximum compression load was reached, the crosshead was run up and the above procedure was repeated at successively higher inflation pressures until the maximum load began to decrease.

After the tests were completed, the same specimens were packaged. A double fold about one inch long was made at the center of the specimen, and a load was applied for 18 hours. This load was selected to give an average pressure on the fold of 5 psi. These specimens were then tested in the same manner as described above for the unpackaged cylinders.

RIGIDIFICATION PRESSURE

One of the objectives of the test was to determine the best rigidification pressure. To correlate this pressure with the specimen design, several key pressures were computed using methods developed at Goodyear Aerospace[a] and the stress-strain characteristics of the wire-film material. Stress-strain curves for the wire used to make the specimen were obtained (see Table II for the principal properties). The key pressures considered were:

p_p - the pressure at which the proportional limit stress of the longitudinal wires is attained under pressure,

p_y - the pressure at which the yield stress of the longitudinal wires is attained under pressure, and

TABLE II - WIRE PROPERTIES

Material	Diameter (mils)	Proportional limit (psi)	Yield stress (psi)	Modulus (psi)
Stainless steel	3.1	48,000	80,000	28×10^6
Stainless steel	5.1	28,000	41,000	28×10^6
Aluminum	5.0	3,000	5,500	10×10^6
Aluminum	10.5	3,000	6,000	10×10^6
Copper	2.9	12,100	24,000	16×10^6

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[a] Rottmayer, E.: Rigidization Analysis of Wire Film Materials. GER-11117. Akron, Ohio, Goodyear Aerospace Corporation, 20 May 1964.

p_L - the pressure at which the residual compressive stress of the longitudinal wire is equal to the buckling stress. The buckling stress is computed as if the longitudinal wires were a pin-ended column with a length equal to the spacing of the hoop wires

The effect of the rigidification pressure on both the buckling strength and the axial stiffness of the cylinders was similar. In general, both these properties increased with increasing pressure to a maximum value and then began to decrease. A curve of the buckling load versus rigidification pressure for the four Type 1 specimens is shown in Figure 5. Spotted along the abscissa are the three key calculated rigidification pressures. In this instance it is apparent that maximum load is obtained at a rigidification pressure slightly lower than key pressure p_y.

A rigidification pressure summary is given in Table III. In addition to listing the calculated key pressures for the seven types of cylinders, the table gives the rigidification pressure at which the maximum load and maximum stiffness were obtained. It is evident from Table III that the rigidification pressure should be greater than p_p. Comparing p_y and p_L to the optimum test pressures, it is concluded that the rigidification pressure should be either p_y or p_L, whichever is smaller.

BUCKLING STRESS

The buckling stress considered here is not one of general column instability but one of local instability involving both the longitudinal and hoop wires. A typical failure is shown in Figure 6. The problem of buckling of wire-film cylinders is similar to that of circular cylinders stiffened by ring-stringer combinations (a problem treated in Becker's Handbook of Structural Stability[a]). This problem is similar to that of the wire-film cylinder, where the hoop wires can be considered the rings and the longitudinal wires as the stringers. Using this approach and rewriting the equation in terms of the wire-film cylinder, the buckling stress (σ_{cr}) is given by

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[a] Becker, H.: Handbook of Structural Stability, Part VI - Strength of Stiffened Curved Plates and Shells. T.N. No. 3786, NACA, July 1958.

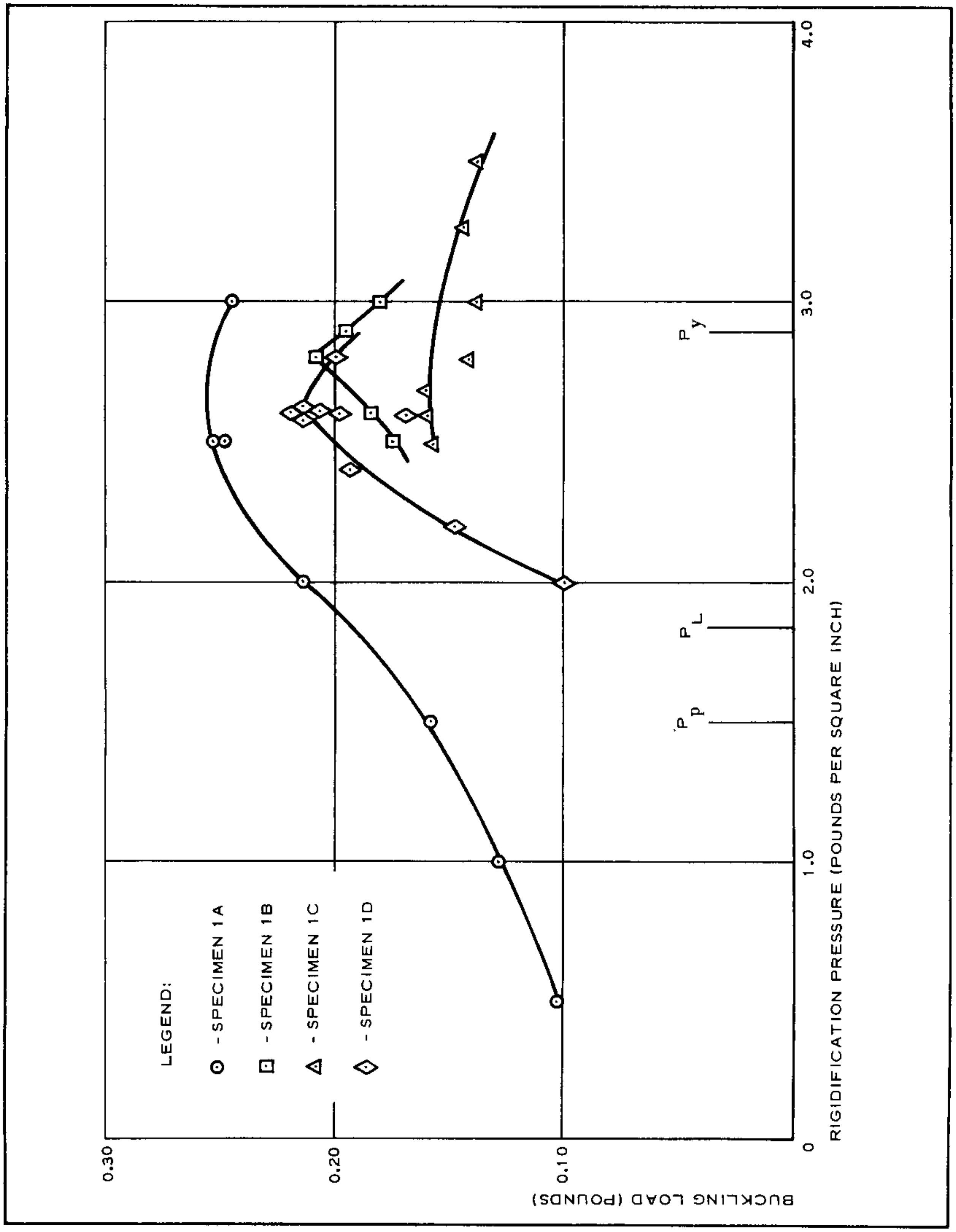

Figure 5 - Buckling Load versus Rigidification Pressure

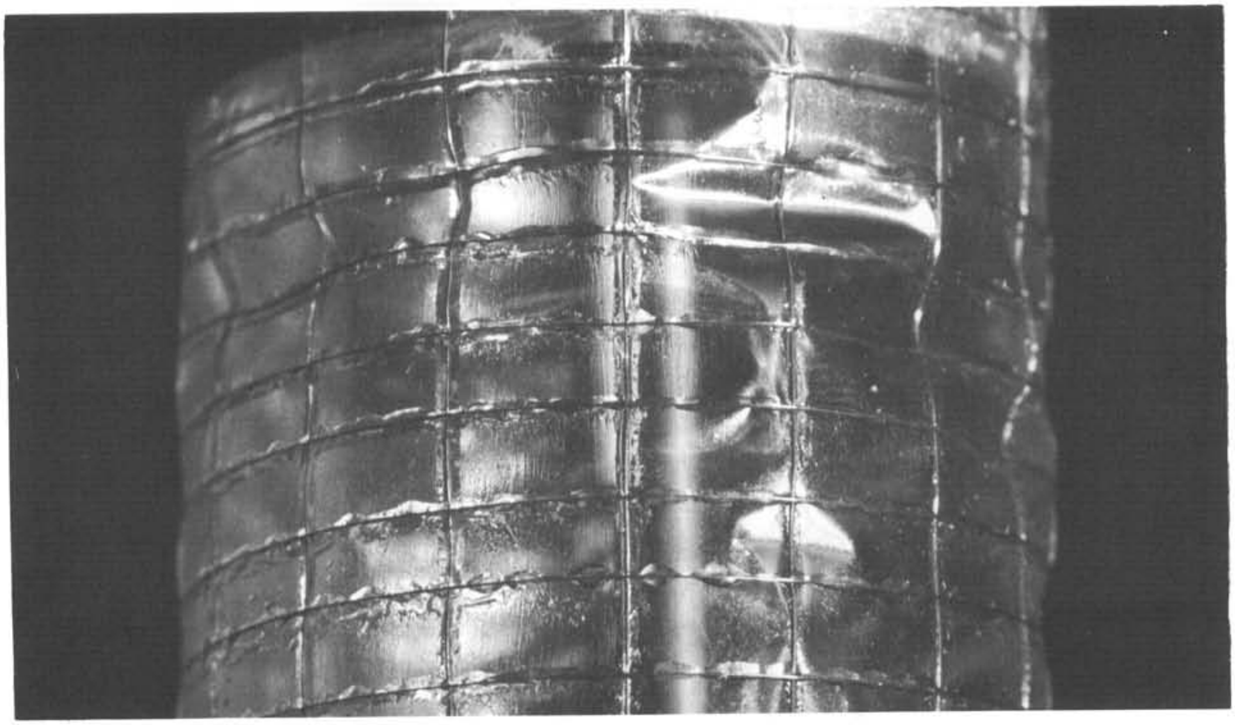

Figure 6 - Typical Compression Buckling Failure

TABLE III - RIGIDIFICATION PRESSURE SUMMARY

Specimen type	Key calculated pressures (psi)			Optimum test pressures (psi)	
	p_p	p_y	p_L	Maximum load	Maximum stiffness
1	1.5	2.9	1.9	2.6	2.0
2	5.9	12.0	10.1	7.0	7.0
3	7.9	13.4	19.0	14.0	13.0
4	1.0	3.5	4.5	4.0	3.0
5	3.5	8.4	High	8.0	9.0
6	1.8	5.3	10.0	8.5	8.0
7	1.5	6.0	3.1	3.0	2.5

$$\sigma_{cr} = C\eta EQ \, , \qquad (1)$$

where

C = empirical constant to be determined,

η = plasticity reduction factor,

E = modulus of elasticity of wires, and

$$Q = \frac{d^{3/2}}{6.72 \, RS^{1/2}} \, , \qquad (2)$$

where d, R, and S are defined in Figure 2.

The cross-sectional area of the longitudinal wires is given by

$$A = (2\pi R) \frac{\pi d^2}{4S}$$

$$= \frac{\pi^2 R d^2}{2S} \, . \qquad (3)$$

The selection of the specimen types was based primarily on the desire to cover a wide range of the parameter Q, in order to establish the empirical constant C in Equation 1. The range covered was from 0.242×10^{-4} to 5.031×10^{-4}. The values of Q for each specimen are given in Table IV, along with the cross-sectional area A and the maximum load obtained on each specimen.

TABLE IV - SPECIMEN DATA

Specimen type	$Q \times 10^4$	$A \times 10^4$ (sq in.)	Maximum compression load (lb)			
			A	B	C	D
1	0.242	1.42	0.255	0.218	0.161	0.219
2	0.807	1.21	0.642	0.488	0.456	0.540
3	1.703	3.27	1.76	2.33	3.22	1.88
4	1.653	3.15	0.550	0.580	0.750	0.710
5	5.031	13.86	6.16	6.24	5.42	6.80
6	3.557	6.93	1.32	2.25	0.845	0.960
7	0.730	1.06	0.244	0.182	0.264	0.236

C was determined by plotting $\sigma_{cr}/\eta E$ against Q. The value of σ_{cr} was determined by dividing the maximum load on each specimen by the cross-sectional area of the longitudinal wires. All specimens except those of Type 5 failed in the elastic range, so the plasticity relation factor was unity, with the one exception. For Type 5 specimens the secant modulus of the wire material was used (see Figure 7). The three straight lines in the figure correspond to values of C of 1.0, 1.5, and 2.0 (shown for reference).

The data are consistent for all specimens, except for those of Type 6. This type had a large wire spacing, in relation to cylinder diameter, which resulted in a large helical angle for the hoop wires. Such a large helical angle is apparently undesirable and should be avoided. For this reason these points should be ignored in selecting C. The remaining points have a fair amount of scatter, but this is to be expected in any buckling test of thin cylinders. A value of C equal to 1 is certainly conservative because all data points are above this line. A value of 1.5 is more realistic, however, and is recommended for design purposes at this time.

AXIAL STIFFNESS

The axial stiffness (EA) is defined by

$$EA = \frac{P\ell}{\delta}, \tag{4}$$

where

ℓ = length of member,

P = applied axial load, and

δ = deflection associated with load P.

Usually, the axial stiffness can be predicted accurately by multiplying the modulus of elasticity by the cross-sectional area of the member, which in this case would be the area of the longitudinal wires. If the member is not straight, the axial stiffness is considerably reduced, depending on the amount of initial eccentricity. The axial stiffness can be computed in this case if the deviation of the member from a straight line is known.

During rigidification the longitudinal wires are subjected to a combination of

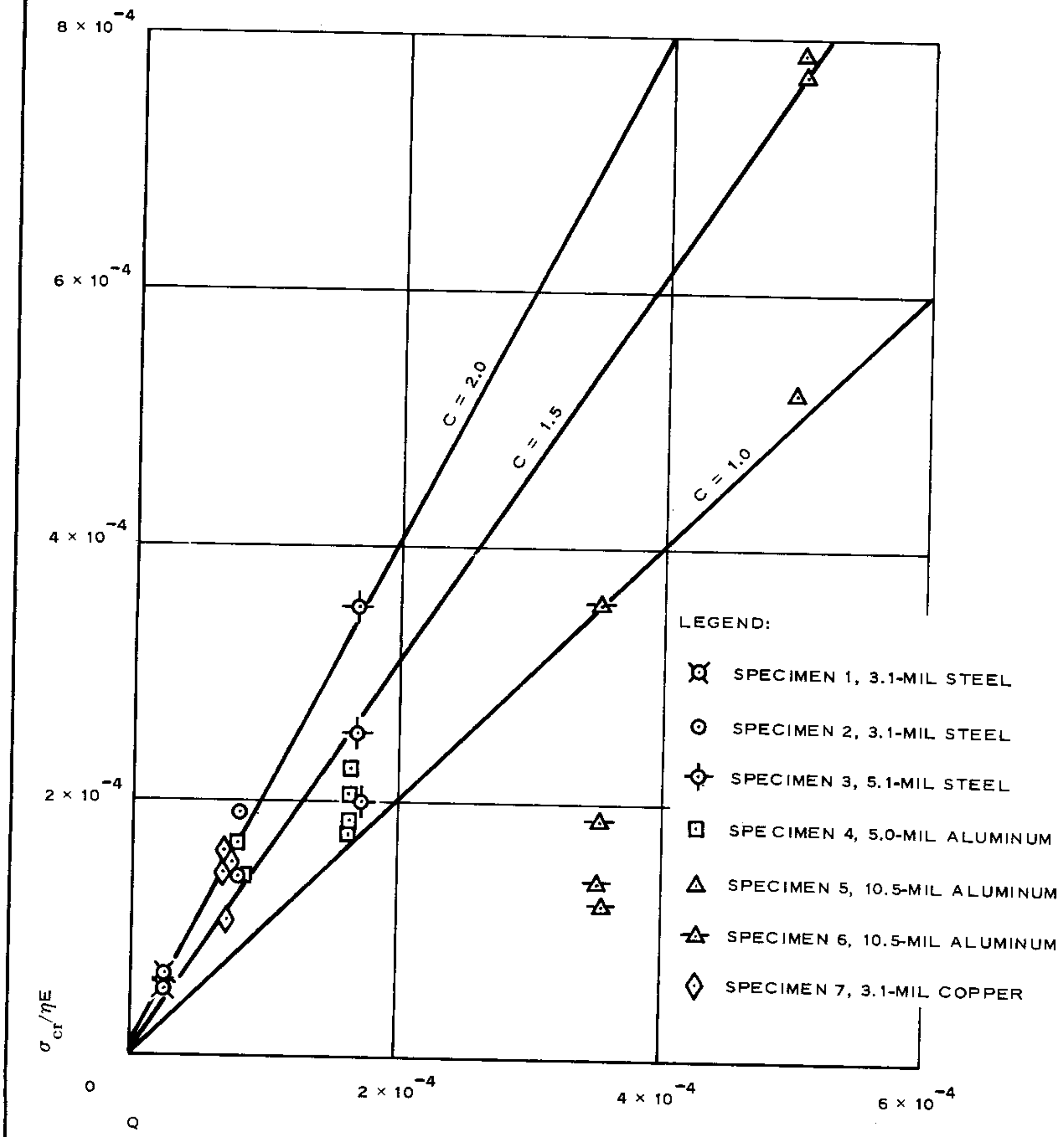

Figure 7 - $\sigma_{cr}/\eta E$ versus Q

tension and bending stresses, and permanent deformations are to be expected at the higher inflation pressures. It was beyond the scope of this program to attempt to predict the deformation of the longitudinal wires as a function of pressure.

The axial stiffness of the specimen was obtained by test. The initial slope of the load-deflection curve automatically recorded by the Instron machine established the ratio P/δ required in Equation 4 to compute the axial stiffness. This was found to be a function of pressure, just as the maximum load was.

The maximum values of EA determined by test are given in Table V. Also given for comparison is a basic calculated value determined simply by multiplying the modulus of elasticity of the longitudinal wire by its cross-sectional area. The ratios of the test values to the theoretical values are listed in the last column.

It is evident that the effective stiffness of the wire-film cylinder is considerably less than the calculated value. The minimum value (21.1 percent) was obtained on Type 1 specimens; the maximum (52.5 percent), on those of Type 3. No attempt is being made at this time to predict the stiffness, so a detailed discussion of the results is not warranted. The most important point, perhaps, is that if stiffness is the governing criterion, an effective stiffness of 50 percent of the basic calculated stiffness can probably be attained.

TABLE V - AXIAL STIFFNESS

Specimen type	EA_w (calculated)	EA_w (test)	Calculated/-test
1	3,980	840	0.211
2	3,390	928	0.273
3	9,150	4810	0.525
4	3,150	1400	0.445
5	13,860	6530	0.475
6	6,930	2320	0.333
7	1,700	611	0.360

PACKAGING

The effects of packaging are illustrated by plotting unpackaged data against packaged data. The buckling loads are shown in Figure 8; the effective modulus, in Figure 9. In both figures the packaged values are less than the unpackaged values. The test points scatter about the line labeled 0.8, which corresponds to a 20-percent reduction.

It should be emphasized that the packaged specimens were the same specimens that were tested originally as unpackaged specimens. While unpackaged, they were tested many times and subjected to inflation pressures greater than the optimum pressure. Therefore, it is reasonable to anticipate that the packaged values would be less than the unpackaged values. For these reasons it is concluded that packaging has little or no effect on the properties of the cylinder.

CONCLUSIONS

The following conclusions have been reached:

1. The optimum rigidification pressure is the one that produces yield stress of the wire or buckling of the wire, whichever is smaller.
2. The value of the local buckling constant is 1.5.
3. An effective axial stiffness of 50 percent of the basic calculated value can be achieved.
4. Packaging has little effect on the axial stiffness or buckling load.

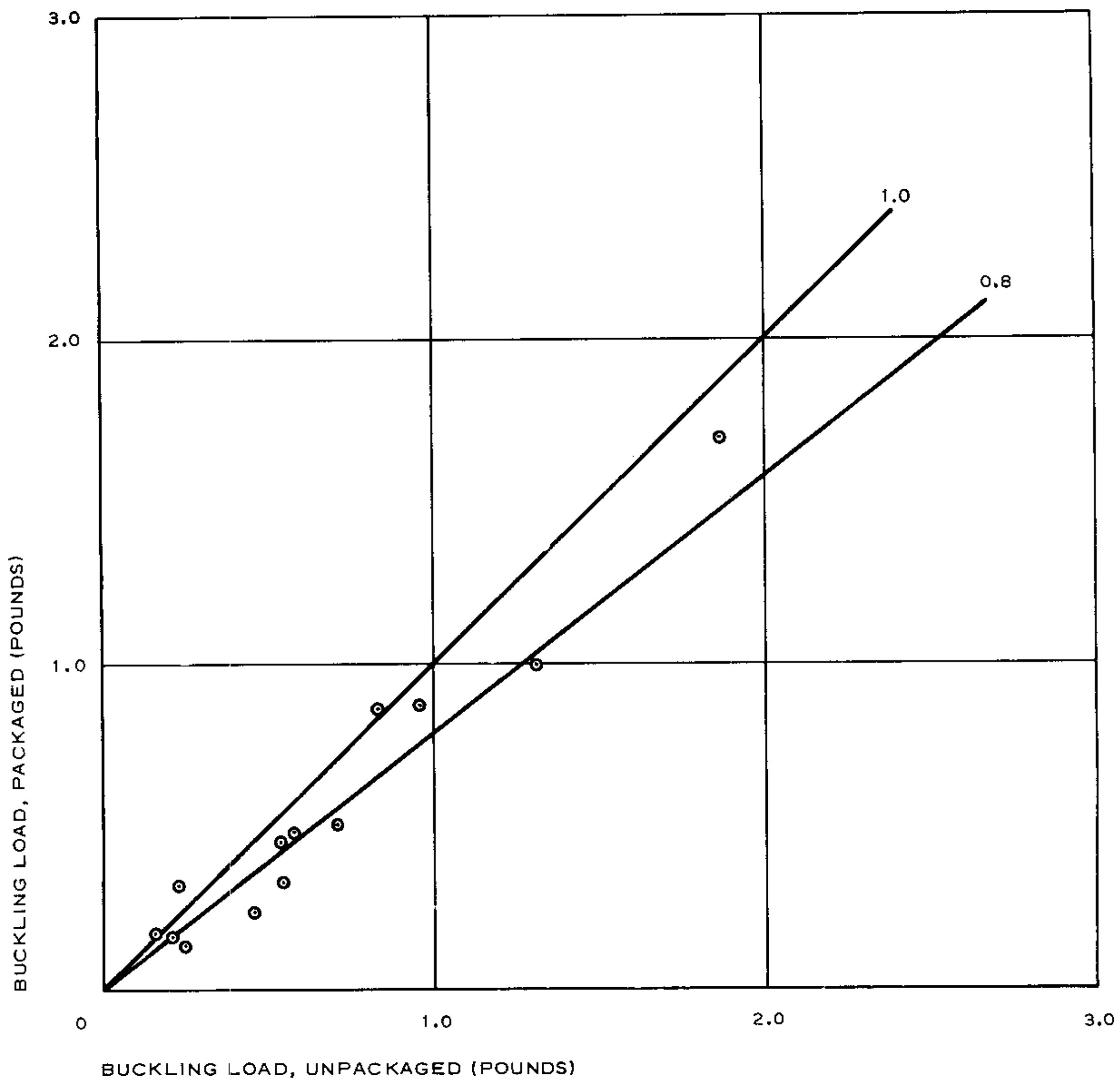

Figure 8 - Buckling Loads; Packaged versus Unpackaged

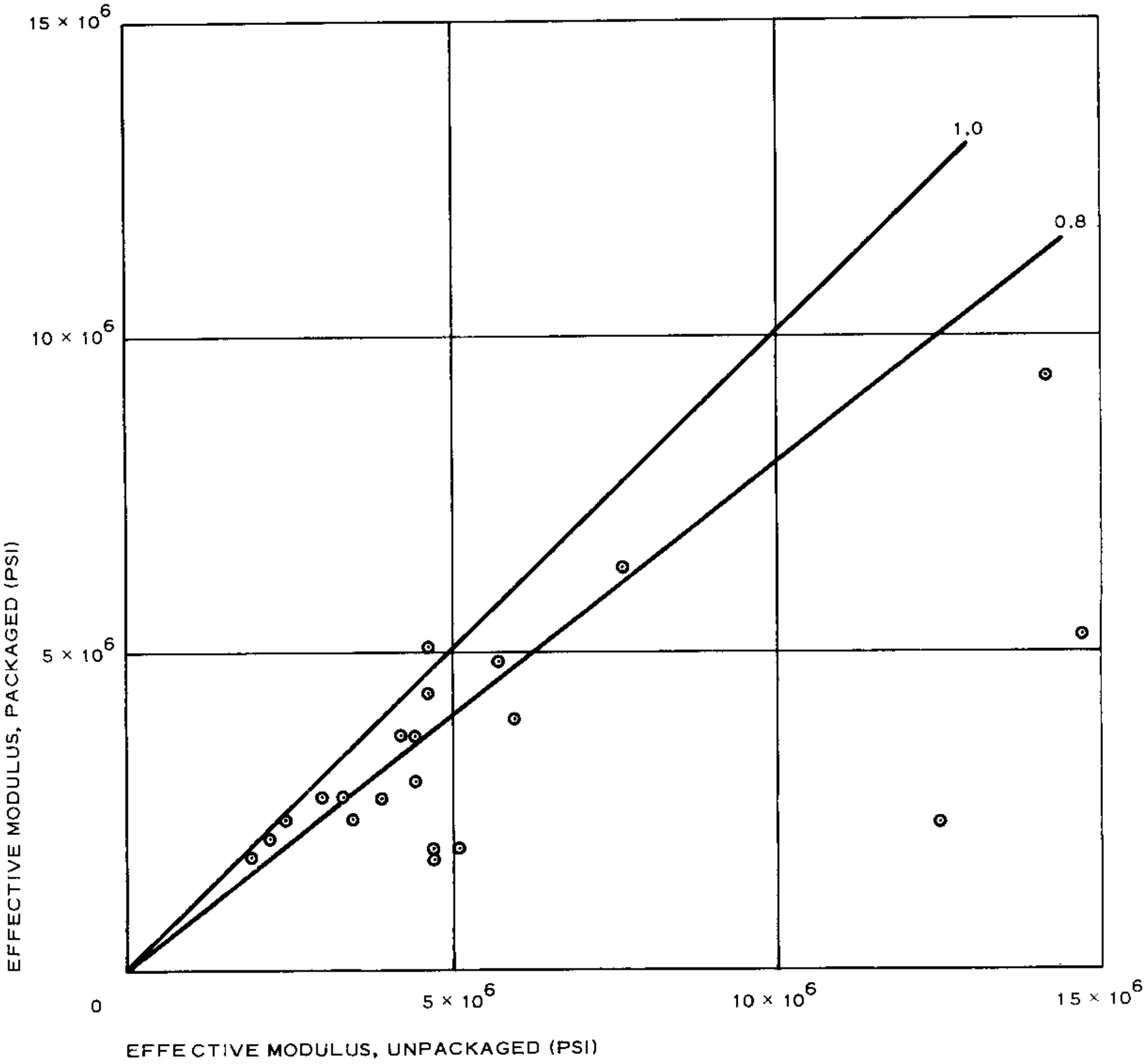

Figure 9 - Effective Modulus; Packaged versus Unpackaged