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ROOM TEMPERATURE MECHANICAL PROPERTIES OF SHUTTLE THERMAL PROTECTION SYSTEM MATERIALS

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Summary

Tests have been conducted at room temperature to determine the mechanical properties and behavior of materials used for the thermal protection system of the Space Shuttle. The materials investigated include the LI-900 RSI tiles, the RTV-560 adhesive and the .41cm (.16 thick) strain isolator pad (SIP). Tensile and compression cyclic loading tests have been conducted on the SIP material and stress-strain curves obtained for various proof loads and load cycle conditioning. Ultimate tensile and shear tests have been conducted on the RSI, RTV, and SIP materials. The SIP material exhibits highly nonlinear stress-strain behavior, increased tangent modulus and ultimate tensile strength with increased loading rate, and large short time load relaxation and moderate creep behavior. Proof and cyclic load conditioning of the SIP results in permanent deformation of the material, hysteresis effects, and much higher tensile tangent modulus values at large strains. Due to hysteresis effects, a family of applicable stress-strain curves are possible and curves bounding the family have been obtained for the SIP material. The ultimate shear strength of the RSI, and RTV was equal to or greater than published results. The measured ultimate tensile strength of the SIP was in agreement with the published results for the higher load rate tests but was 20 percent lower for the low displacement rate tests.

Introduction

Tests have been conducted to determine the mechanical properties and behavior of materials used for the thermal protection system of the Space Shuttle. The materials investigated include the LI-900 RSI tiles, the 560 RTV adhesive and the .41 cm (.160 thick) strain isolator pad (SIP). Tensile and compression cyclic loading tests have been conducted on the SIP material. Tensile tests have been conducted on the RSI material and the RSI-RTV-SIP system. Shear tests have been conducted on the RSI, RTV, and SIP materials. Stress-strain curves, as well as ultimate strength, have been obtained from the tension-compression tests and ultimate shear values were obtained from the shear tests.

Specimens and Tests

Specimens

Materials: The materials considered in this investigation include LI-900 RSI tiles, .41 cm (.160 inch) thick SIP, and RTV-560 adhesive. These materials form the basis of the thermal protection system used for the shuttle orbiter. The LI-900 RSI tiles are made from rigidized silica fibers, weigh about 145 kg/m^3 (9 lb/ft^3), and insulate the primary air frame from the entry heat pulse. The SIP is a needled (non-woven) Nomex felt and is used as a strain isolator pad (SIP) between the RSI tiles and the aluminum primary structure of the vehicle. The RTV-560 is a silicone rubber adhesive which cures at room temperature. It is used to bond the RSI tile to the SIP and the SIP to the skin of the vehicle. The tile and SIP material was obtained from the same supply as that for the Shuttle. Fresh RTV-560 was obtained from the manufacturer to insure that the shelf life had not been exceeded. All specimen support fixtures were made from 2024-T4 aluminum. Aluminum fixture surfaces that were to be bonded to test specimens were chemically etched, sprayed with a protective primer (Koropon), and vacuum baked to remove all volatiles. The bonding procedure used to make the specimens is a very close duplicate of that used on the actual shuttle. The bonding and quality control personnel received special training at the JFK Center to insure that the correct procedure was used in making the specimens. Care was taken to insure that the RTV had cured to a Shore hardness of 50 or greater before testing the specimen.

Configurations: Poker-chip, napkin ring tension, and thick adherend shear specimens were used in this investigation. Detail dimensions of the poker-chip specimens with SIP, RSI, and combined SIP-RSI test materials are shown in figures 1(a), 1(b), and 1(c), respectively. The test materials are bonded between two aluminum blanks 5.72 cm (2.25 inches) in diameter with a .8 cm (.3 inch) diameter alignment pin hole through the center. The test materials were bonded to the aluminum blanks using a .018 cm (.007 inch) thick layer of RTV-560 adhesive. An alignment pin is inserted through the center of the aluminum blank and the test material while bonding and during the cure of the adhesive, but is removed before testing the specimen.

Details of the napkin ring tensile specimen are shown in figure 2. The specimen consisted of two aluminum rings bonded together with the test material between the rings. A 0.018 cm (.007 inch) thick layer of 560 RTV adhesive is used to bond each side of the test material to the ring. The rings have an inner diameter of 2.54 cm (1.00 inch) and an outer diameter of 3.8 (1.50 inches) which gives a wall thickness of .64 cm (.25 inches). The specimens are aligned in a V-groove bonding fixture until the adhesive cures.

The detail dimensions of the thick adherend specimens are given in figure 3. The specimen consists of two thick aluminum bars overlapped and fastened together with the test material. The test material has a width of 2.54 cm (1.00 inches) and an overlap length of 1.27 cm (.50 inches). The RTV specimen (figure 3(a)) has a thickness of .018 cm (.007 inches). The specimens are clamped to a flat surface until the adhesive has cured.

Tests

All tests were conducted on a hydraulically actuated test machine that can be operated in either the load or displacement control mode. A 890 newton (200 lb) tension-compression load cell was used to measure the load applied to the specimen and to control the test machine when in the load control mode. For most testing, specimen displacement was measured using an LDVT which measured testing machine head motion. Data were recorded using a digital data acquisition system and a x-y recorder.

For the first few poker-chip tests with SIP, three LDVT's were equally spaced around the periphery of the test blocks (see figure 4) to correlate head motion and specimen displacement and to determine the amount of bending present due to mis-alignment. These tests demonstrated that because of the high relative stiffness of the test fixture compared to the SIP material that the displacement of the SIP material could be determined by measuring the displacement of the moveable head on the testing machine. The tests also indicated a maximum bending of approximately 5 percent but with 2 to 3 percent bending typical for most of the tests. The LDVT's were removed for subsequent tests.

The test setup used for the poker-chip test is shown in figure 4. The procedure followed in setting up a typical test is as follows: The load cell is zeroed with the upper half of a typical specimen attached to the load cell. The specimen is then installed with the test machine in the displacement control mode. The test machine control mode is then switched to load control which removes any residual setup loads that were applied to the SIP. (Note that although the specimen is installed very carefully, some small setup loads are always present). The x-y recorder is then set up and the load and displacements both taken as zero.

The poker-chip specimens were used to test the SIP material under various load conditions some of which are typical of those that it would experience on the Shuttle during the first flight. Typical load cycles that were applied to the SIP material are shown in figure 5. First, the specimen is subjected to a static proof load to simulate the proof tests performed on the vehicle. The proof load is applied and removed at the rate of (.5 psi) per second. Two holds for 30 seconds each are made at (1 psi) and (2 psi) below the maximum tensile proof load. A hold of 60 seconds is made at the maximum tensile load and for 30 seconds at the maximum compression load. After the proof load, the specimen is cycled to 80% of the proof load at the rate of 1 cycle per second for at least 100 cycles. This cyclic load conditioning is applied to simulate launch loads.

In addition to the proof and cyclic loading tests, other poker-chip tests were conducted where either or both the proof and cyclic loading conditions were not applied to the specimen. The napkin ring tension and thick adherend shear tests were conducted without any proof or cyclic loading pre-conditioning.

Results and Discussion

SIP Tension - Compression Tests

Proof and Cyclic Load - The effect that a typical proof load of 69 kPa (10 psi) and a 55 kPa (8 psi) cyclic load condition has on the stress-strain curve for a SIP specimen is shown in figure 5. The constant load intervals during the proof loadings results in considerable creep of the material in tension, but very little creep in compression. Note that removing the proof load does not return the specimen to its original condition but results in it being permanently strained by .15. The first load cycle does not result in any additional straining of the specimen. However, after 100 load cycles, the tension part of the cycle results in higher strains than that obtained with the proof load and the permanent strain of the specimen has increased to approximately .23. The compression part of the curve is almost identical for the first and 100th cycle.

A comparison of the stress-strain curves for the virgin material, and for the material during the first and 100th cycle after the proof, can be made in figure 6 where the stress-strain curves have been shifted to a common zero. Although all curves show a nonlinear behavior, the virgin material before proof is more nearly linear and behaves considerably different than the proofed material. The stress-strain curves for the first and 100th cycle show very similar nonlinear results. Unpublished results from tension tests on a 12.70 by 12.70 cm (5 by 5 inch) piece of SIP attached to a tile is shown by the dashed curve in figure 6. The agreement is relatively good with the stress-strain curve for the virgin material.

The effect that the proof and cyclic loading has on the tensile tangent modulus of the SIP is shown in figure 7 where the modulus is given as a function of the stress (fig. 7a) and as a function of strain (fig. 7b). The tangent modulus for the virgin SIP material is low for low strains but increases almost linearly with strain (fig. 7b). For strains greater than .35, the SIP material that has had the proof load or proof and cyclic conditioning applied has much higher tangent modulus values than the virgin material. Cyclic loading of the material after it has been proof loaded significantly increases variation in tangent modulus with stress (fig. 7a). Note the difficulty of determining a single elastic modulus value to use if a linear analysis is to be performed.

The effect that other proof and cyclic load conditions have on the stress-strain curves are shown in figure 8. A 41 kPa (6 psi) proof with a 28 kPa (4 psi) cyclic load is shown in figure 8a, and a 41 kPa (6 psi) cyclic load without a proof load is shown in figure 8b. After a 41 kPa (6 psi) proof load, additional cycling at 28 kPa (4 psi) has little effect on the resulting stress-strain curves. However, a cyclic load of 41 kPa (6 psi) without a proof load results in larger tension strains dur ng each cycle but little change in the compression portion of the stress-strain curves. Note that some growth in the thickness of the SIP (zero shift) occurs in both cases.

<u>Load Rate</u> - Stress-strain curves for typical specimens with various load or displacement rates are shown in figure 9. The lower curve was obtained with a displacement rate of .13 cm/min (.05 in/min). The middle curve was obtained with a load rate of 111 N/m (25 lbs/min) and the upper curve with a rate of 1110 N/m (250 lbs/min). Increasing the load rate results in the stress-strain curve having a higher slope and thus a higher modulus. The 111 N/m (25 lbs/min) load controlled test, and the displacement controlled test are loading at approximately the same head motion rate over much of the range shown. Thus,

running the tests in load control and increasing the load rate both increase the indicated material tensile modulus and ultimate strength of the material. Additional effects of load rate on ultimate tensile strength are shown in Table I and confirm the results already noted. A tenfold increase in the load or displacement rate increases the ultimate tensile strength by approximately 20 percent. The increasing strength of the SIP with increasing strain rate is also consistent with unpublished data, (C. Kistler, Battelle Institute) where tensile strengths increase from an average of 184 kPa (26.7 psi) at .08 cm/min (.03 in/min) to an average of 346 kPa (50.2 psi) at 1524 cm/min (600 in/min). The tabulated results also show that the 69 kPa (10 psi) proof and 55 kPa (8 psi) cyclic loading slightly decreases the ultimate tensile strength of the material. The tensile ultimate strength values given in Table I are in general agreement with the average value of 290 kPa (42 psi) given in reference 1. However, at the lower load and displacement rates, the average ultimate values are lower than the published results (by as much as 20% for the .13 cm/min (.05 in/min) displacement rate tests).

Creep and Relaxation - Short time relaxation and creep response for the SIP is shown in figure 10a and 10b respectively. The relaxation curve was obtained by loading the specimen at a constant strain rate of .05 in/min. and by holding the strain constant at several points until there was no noticeable additional relaxation of the stress. The hold times varied from 360 seconds at the lowest strain to 1060 seconds at the highest strain. The stress relaxation becomes progressively larger for larger stresses or strains.

The creep curve was obtained by loading the specimen at a constant load rate of 25 lbs/min. and by holding the load constant at several points for 30 seconds. For the short time observed, there was noticeable creeping of the material even at low stresses or strains. Additional creep would be expected for longer hold time intervals, as it was not demonstrated that creep had stopped in the short time observed.

Stress-Strain Curves - Typical stress-strain curves were shown in figure 5 for a SIP specimen proof loaded at 10 psi and cyclic loaded for 100 cycles at 80 percent of the proof load. Note that due to hysteresis effects, the stress-strain curves indicate that the material can have zero stress at two different states of strain. One strain level (marked A in figure 5) is obtained when returning from a compression load and the other (marked B in figure 5) when returning from a tensile load. Thus, the unloaded material could be at either strain state A or B or any point in between. Since in an actual design-analysis application the strain state is unknown, the best one can do is to have the bounding stress-strain curves.

The tension and compression load curves from figure 5 after the proof load and cyclic load conditioning are shown repeated in figure 11. The other stress-strain curves required to complete the boundaries were obtained on the specimen and are also shown in figure 11. The area enclosed by the two curves (shown shaded) represents the stress-strain curve bounds for the material. Note that the curves have a discontinuity in slope at the zero stress levels (points A and B).

The stress-strain boundaries presented in figure 11 were for the SIP material proofed at 69 kPa (10 psi) and subjected to a cyclic loading of 80% of the proof for 100 cycles. Similar curves for proof loads of 41, 48, 55, 62, 69, and 103 kPa (6, 7, 8, 9, and 15 psi) are presented in figure 12a, 12b, 12c, 12d, and 12e respectively. The correct boundaries to use for design-analysis purposes would be chosen depending on the previous history of the material. The data presented herein should not be considered as adequate for TPS design purposes since each of the stress-strain boundaries presented were obtained from one or at most three specimens taken from the same lot of .41 cm (.16 inch) thick SIP.

Specimen Size Effects - Stress-strain curves obtained using the poker chip specimen and the napkin ring tension specimen are shown compared in figure 13. The differences are considerable, especially the ultimate stress values. The napkin ring specimen failed at approximately 55 kPa (8 psi) (See Table II for additional test results) whereas the ultimate strength using the poker-chip specimen was over 207 kPa (30 psi). The difference is thought to be due to the small width .64 cm (.25 inches) of the SIP in the napkin ring specimen. These cursory tests of size effect on strength suggest that more testing should be conducted to define a minimum width for the SIP for which its apparent properties are not degraded.

SIP-RSI System Tension Tests

Tension test results for the SIP-RSI system are tabulated in Table III. The average ultimate tensile strength is 87 kPa (12.6 psi) for the three specimens tested. The failure occurs at the SIP-tile interface but at a stress much below the ultimate strength of the SIP, the RTV adhesive, or the RSI-tile. Small particles of RSI remained attached to the RTV adhesive holding the specimen together. No adhesive material was evident clinging to the RSI tile.

Thick Adherend Shear Tests

RTV-Adhesive - Shear test results for the RTV-adhesive are tabulated in Table IV. Tests were conducted at displacement controlled rates of .13, .64 and 1.27 cm/min (.05 to .50 in/min). No change was noted for an additional increase in load rate. In all cases, the shear values are above the average values listed in reference 1.

SIP - Ultimate shear results for the .41 cm (.16 inch) thick SIP is shown in Table V. Tests were ran for displacement control rates of .13 and .64 cm/min (.05 and .25 in/min) and for the shear load applied in both the roll and cross-roll direction. The increase in displacement rate increased the average ultimate shear by approximately 20 percent. The roll and cross-roll directions gave approximately the same shear results. This is in contrast with the results presented in reference 1 which showed higher values in the roll direction than in the cross-roll direction. The shear strength results listed in reference 1 are 25 to 70 percent higher than those obtained in the present investigation. Note the large scatter between tests in the present investigation makes the test results questionable.

RSI - Ultimate shear strength results for the LI-900 RSI tile material is presented in Table VI. Tests were conducted at load control rates of 111 and 1110 N/min. (25 to 250 lbs/min). The tenfold increase in load rate results in approximately a 35 percent increase in ultimate shear strength. The measured shear values for both load rates are above the average values listed in reference 1.

Concluding Remarks

Tests have been conducted at room temperature to determine the mechanical properties and behavior of materials used for the thermal protection system of the Space Shuttle. The materials investigated include the LI-900 RSI tiles, the RTV-560 adhesive and the .4 cm (.16 thick) strain isolator pad (SIP). Tensile and compression cyclic loading tests have been conducted on the SIP material. Tensile tests have been conducted on the RSI material and the RSI-RTV-SIP system. Shear tests have been conducted on the RSI, RTV, and SIP materials. Stress-strain curves, as well as ultimate strength, has been obtained by the tension-compression tests and ultimate shear values were obtained from the shear tests.

The test results show the following:

1. The indicated tangent modulus and ultimate tensile strength of SIP increases with loading rate.
2. The SIP material exhibits large short time load relaxation and moderate creep behavior.
3. Proof and cyclic load conditioning of the SIP results in permanent deformation of the material and much higher tensile tangent modulus values at large strains.
4. The SIP material exhibits highly nonlinear stress strain behavior.
5. Due to hysteresis effects, a family of applicable stress-strain curves are possible for the SIP material. Stress-strain curves bounding the family are obtained for various proof loads and load cycle conditioning.
6. The ultimate shear strength of the RSI, and RTV was equal to or greater than published results. The measured ultimate tensile strength of the SIP was in agreement with the published results for the higher load rate tests but was 20 percent lower for the low displacement rate tests.

References

Materials Properties Manual, Vol. 3, Thermal Protection System Materials Data, Rockwell International Publication, May 1979.

TABLE I - EFFECT OF LOAD RATE ON TENSILE ULTIMATE STRENGTH OF .41 CM (.16 INCH) THICK SIP

DISPLACEMENT CONTROLLED			LOAD CONTROLLED					
TEST NO.	RATE	σ_{ult} kPa (psi) VIRGIN MATERIAL	TEST NO.	RATE	σ_{ult} kPa (psi) VIRGIN MATERIAL	TEST NO.	RATE	σ_{ult} kPa (psi) PROOF ±68.9 (10) CONDITIONED-55.1 (8)
2	.13 cm/min (.05 in/min)	238 (34.5)	12	111 N/min (25 lb/min)	259 (37.6)	22	111 N/min (25 lb/min)	235 (34.1)
3		232 (33.7)	13		271 (39.3)	33		283 (41.1)
4		241 (35.0)	14		323 (46.8)	34		285 (41.4)
5		201 (29.1)	16		267 (38.7)	43		225 (32.6)
		AVG = 229 (33.2)			280 (40.6)	46		286 (41.5)
6	.64 cm/min (.25 in/min)	305 (44.3)	15	1110 N/min (250 lb/min)	335 (48.6)	57		225 (32.6)
7		256 (37.2)						AVG = 256 (37.2)
8		271 (39.3)				36	1110 N/min (250 lb/min)	301 (43.7)
9		279 (40.4)				37		307 (44.5)
10		265 (38.5)				38		339 (49.1)
		275 (39.9)				45		288 (41.7)
								310 (44.9)

TABLE II - NAPKIN RING TENSION TEST OF .41 CM (.16 INCH) THICK SIP. DISPLACEMENT RATE = .13 CM/MIN (.05 IN/MIN)

TEST NO.	ULTIMATE TENSILE STRENGTH, kPa(psi)
1	59.3 (8.6)
2	55.2 (8.0)
3	59.3 (8.6)
4	60.0 (8.7)

TABLE III - RSI-SIP SYSTEM ULTIMATE TENSILE RESULTS

SPECIMEN NO.	σ_{ult} kPa (psi)
1	83.4 (12.1)
2	82.0 (11.9)
3	92.4 (13.4)
AVERAGE σ_{ult} = 89.3 (12.61)	

NOTES:

1. SPECIMENS WERE NOT PROOFED OR CONDITIONED.
2. TESTS WERE LOADED AT THE RATE OF 111 N/min (25 lb/min).
3. FAILURE OCCURRED AT THE RSI-SIP INTERFACE.

TABLE IV - ULTIMATE SHEAR STRENGTH OF RTV-560

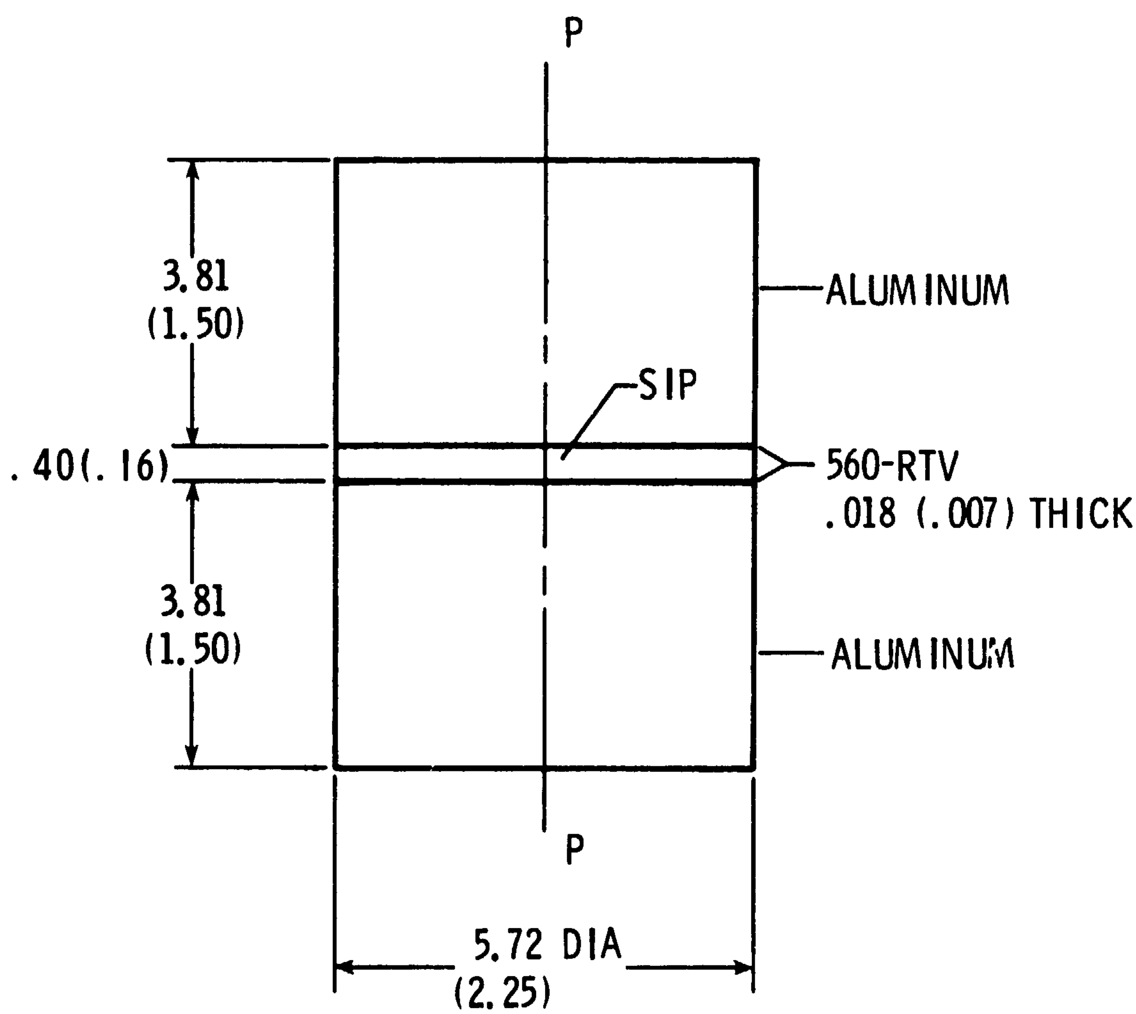
TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)	TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)	TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)
1	.13 cm/min	4780 (694)	6	.64 cm/min	5780 (838)	11	1.27 cm/min	6120 (888)
2	(.05 in/min)	5000 (726)	7	(.25 in/min)	5670 (822)	12	(.5 in/min)	6440 (934)
3		4720 (684)	8		6340 (920)	13		5560 (806)
4		4230 (614)	9		5160 (748)	14		5200 (754)
5		4290 (622)	10		6120 (888)	15		6160 (894)
						16		5930 (860)
AVERAGE SHEAR		4610 (668)			5810 (843)			5900 (856)

TABLE V - ULTIMATE SHEAR STRENGTH OF .41 CM (.16 INCH) THICK SIP

ROLL DIRECTION			CROSS-ROLL DIRECTION		
TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)	TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)
1	.13 cm/min	350 (50.7)	11	.13 cm/min	370 (53.7)
2	(.05 in/min)	193 (28.0)	12	(.05 in/min)	232 (33.6)
3		186 (27.0)	13		305 (44.3)
4		289 (41.9)	14		225 (32.7)
5		375 (54.4)	15		240 (34.8)
AVERAGE SHEAR		279 (40.4)	AVERAGE SHEAR		274 (39.8)
6	.64 cm/min	424 (61.5)	16	.64 cm/min	--
7	(.25 in/min)	305 (44.2)	17	(.25 in/min)	--
8		272 (39.4)	18		388 (56.3)
9		285 (41.4)	19		303 (47.4)
10		342 (49.6)	20		269 (39.0)
AVERAGE SHEAR		339 (49.2)	AVERAGE SHEAR		330 (47.6)

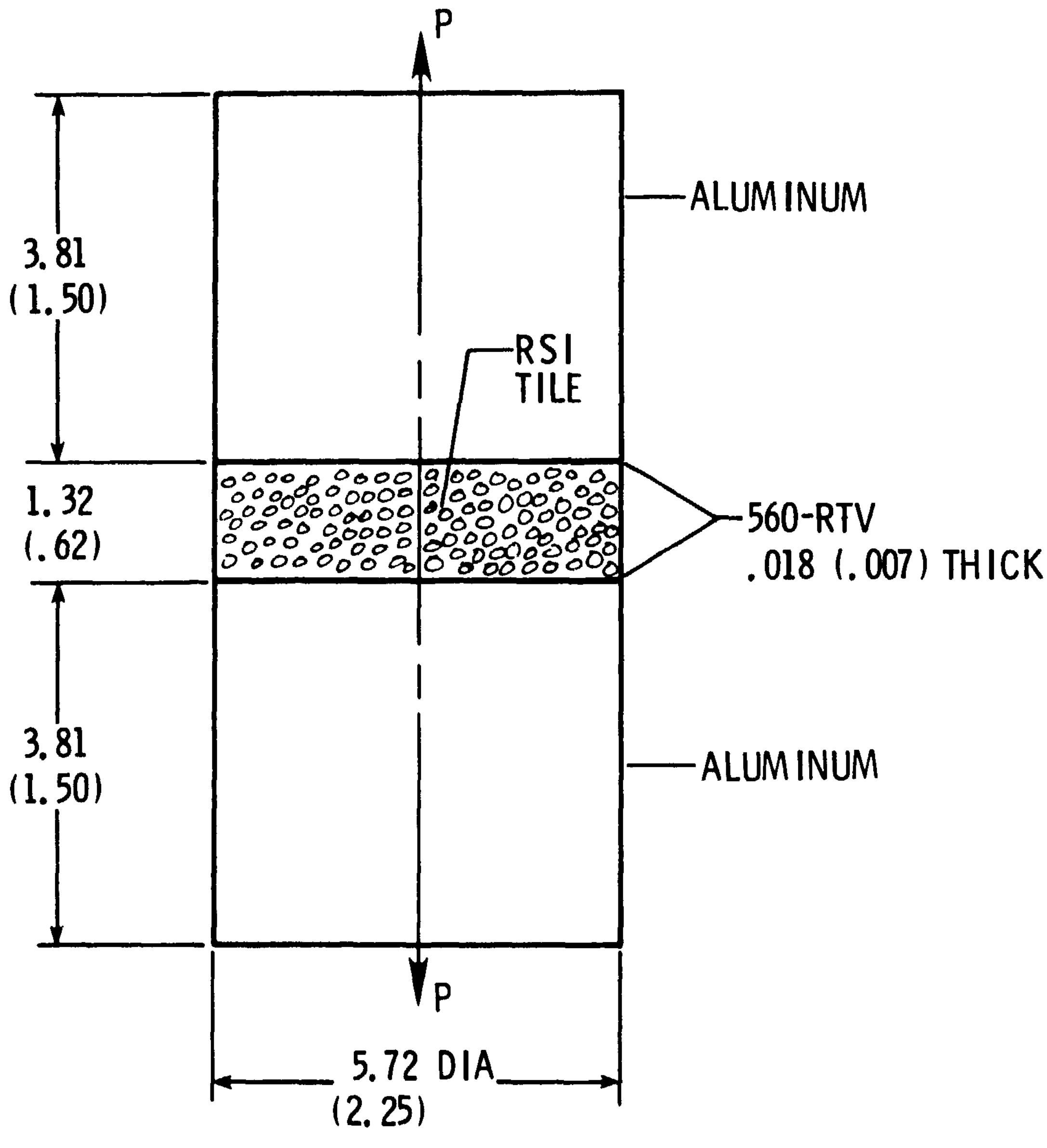
TABLE VI - ULTIMATE SHEAR STRENGTH OF LI-900 RSI TILE

TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)	TEST NO.	LOAD RATE	ULTIMATE SHEAR kPa (psi)
1	111 N/min	167 (24.2)	6	1110 N/min	208 (30.2)
2	(25 lb/min)	168 (24.4)	7	(250 lb/min)	210 (30.4)
3		175 (25.4)	8		222 (32.2)
4		183 (26.5)	9		236 (34.3)
5		124 (18.0)	10		234 (34.0)
AVERAGE SHEAR		163 (23.7)			222 (32.2)



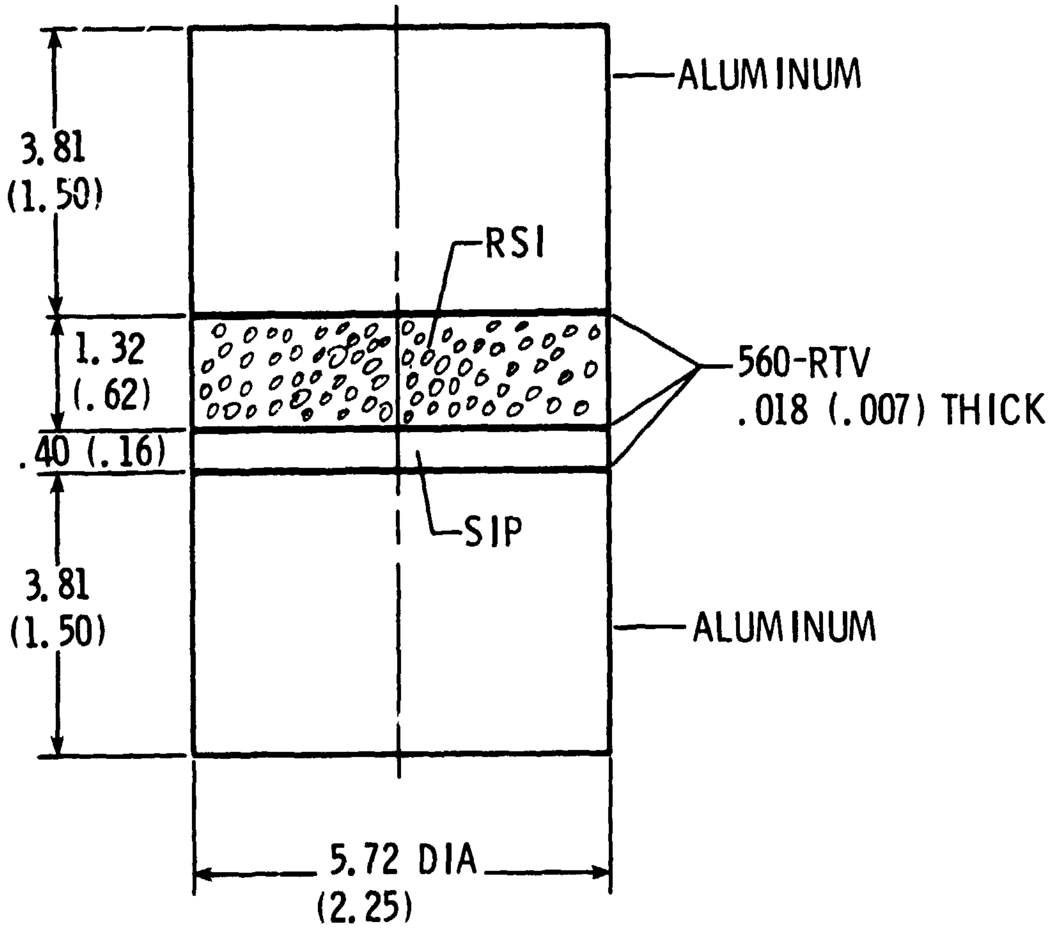
(a) SIP specimen

Figure 1 - Detail of poker-chip test specimens. Dimensions given in cm (inches).



(b) RSI tile specimen

Figure 1 - Continued.



(c) RSI-SIP system specimen

Figure 1 - Concluded.

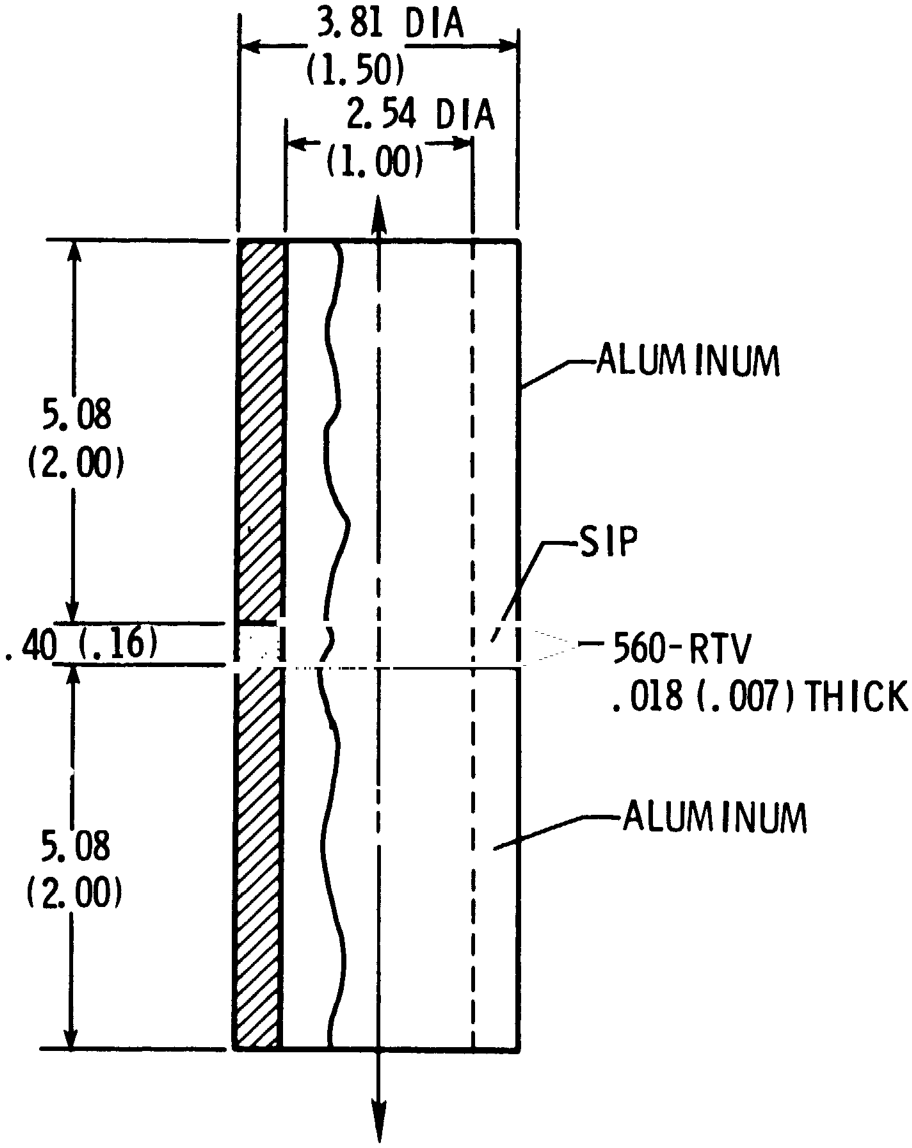


Figure 2 - Details of napkin ring test specimen. Dimensions given in cm (inches).

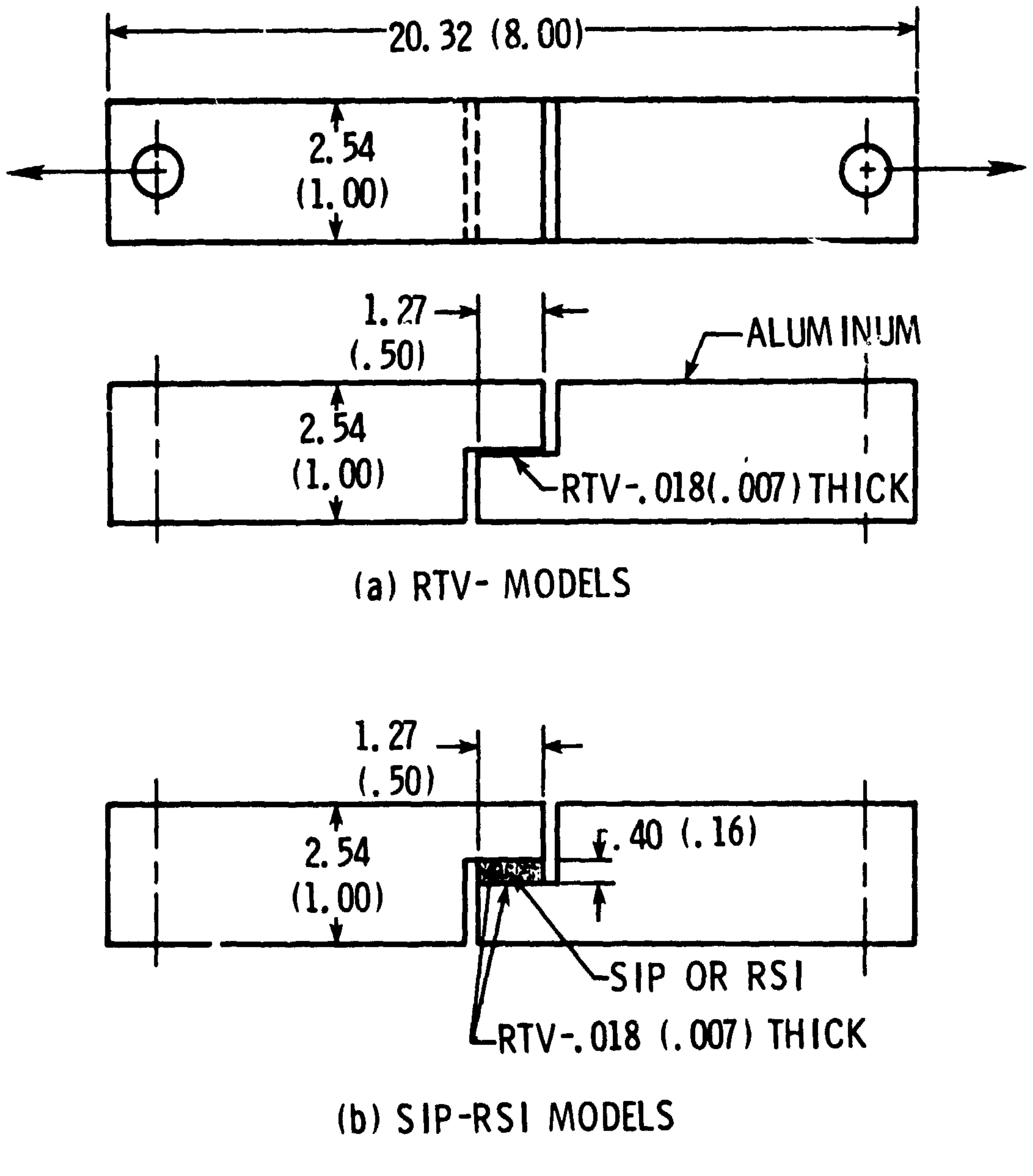


Figure 3 - Detail dimensions of thick adherend test specimen. Dimensions given in cm (inches).

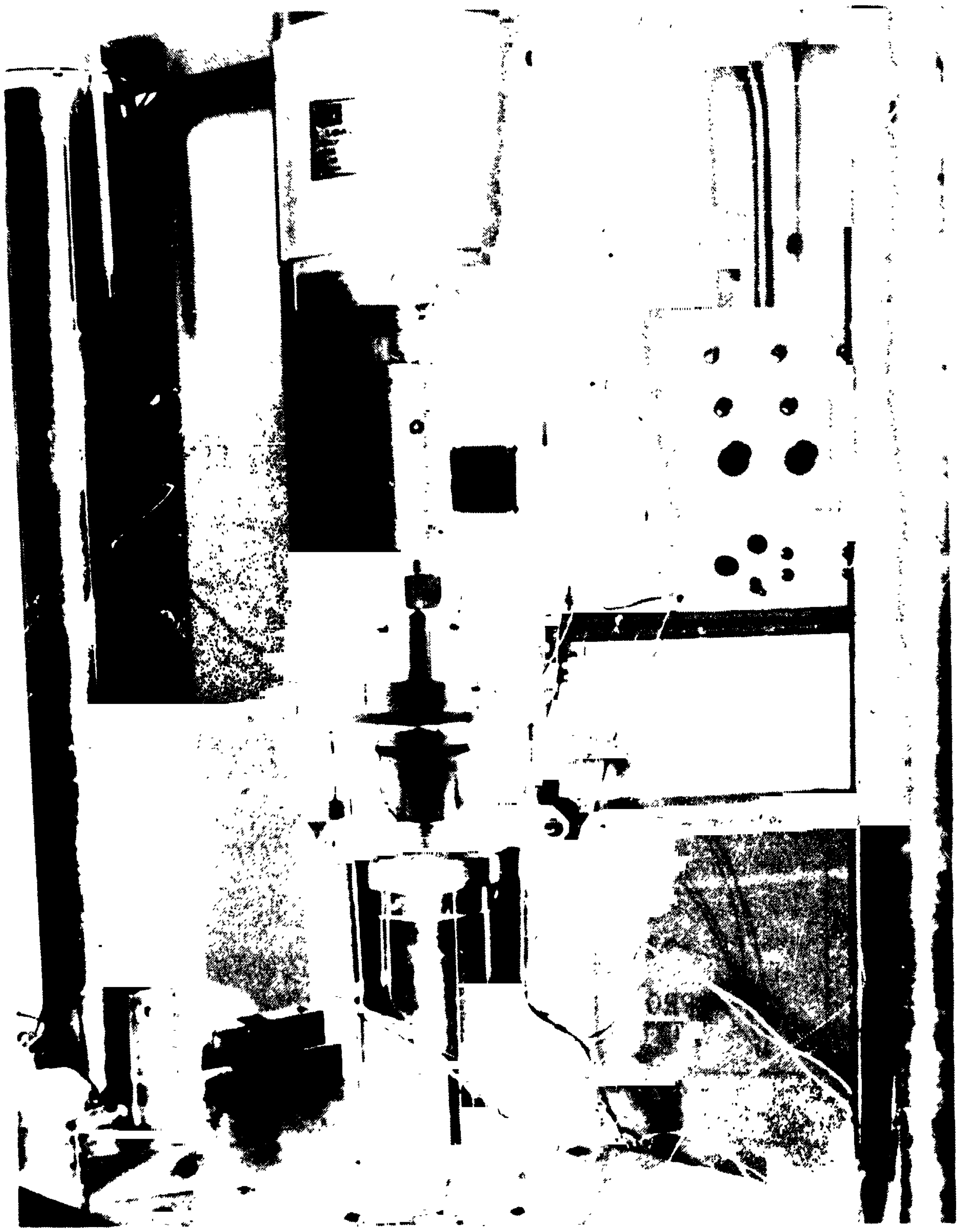


Figure 4 - Photograph of poker-chip test setup.

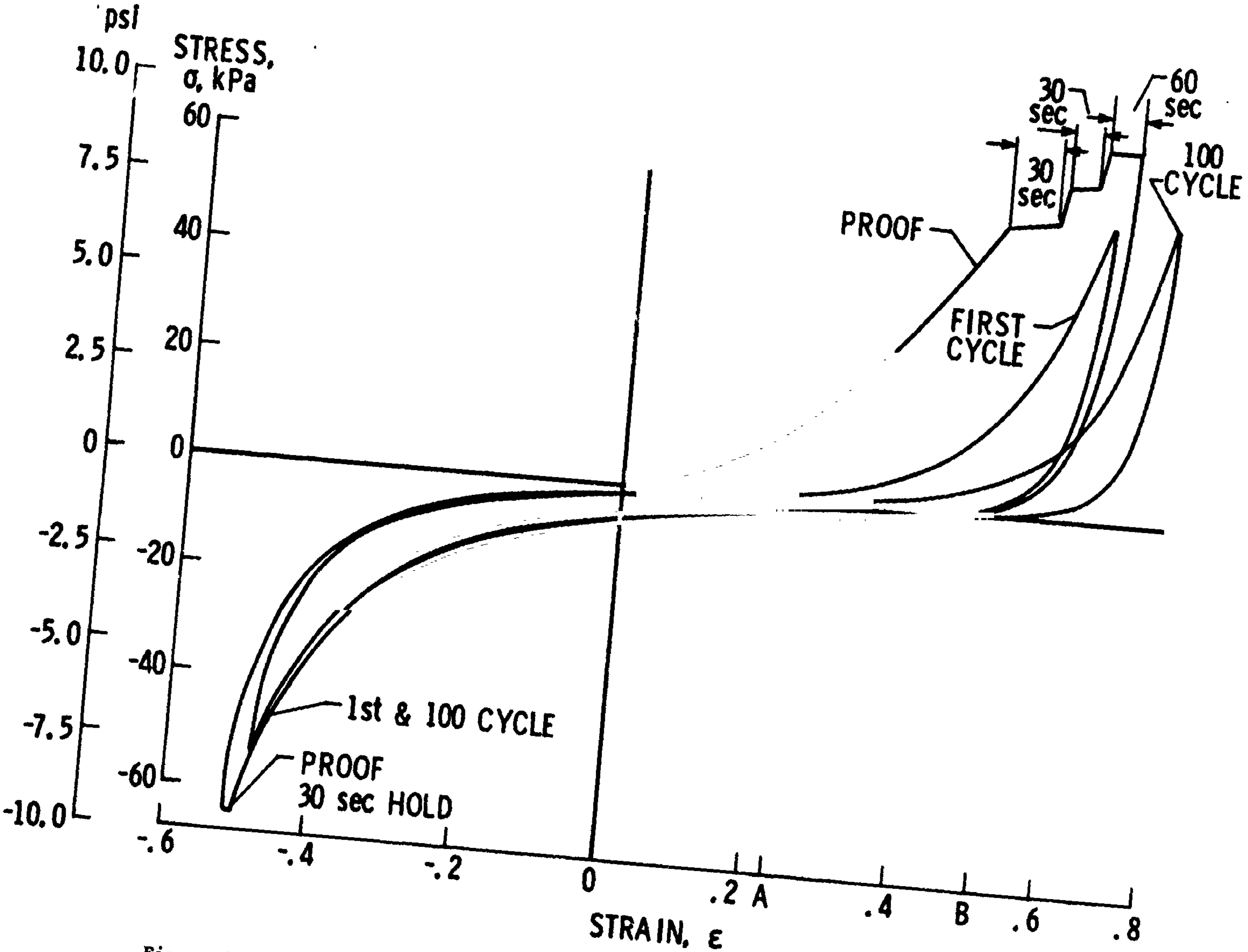


Figure 5 - Typical proof and load conditioning curves. Proof load is 69 kPa (10 psi) and conditioning load is 80 percent of proof load.

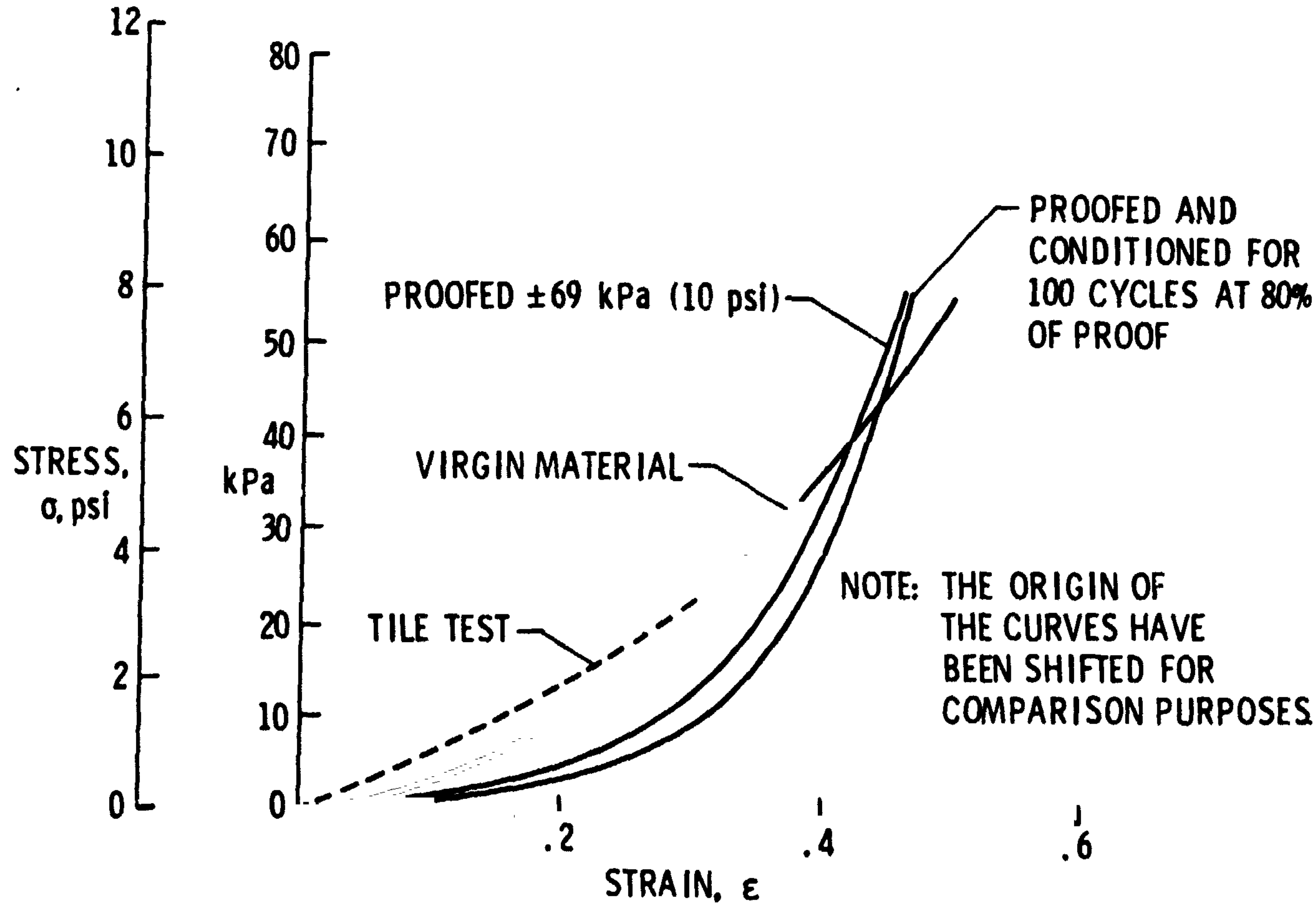
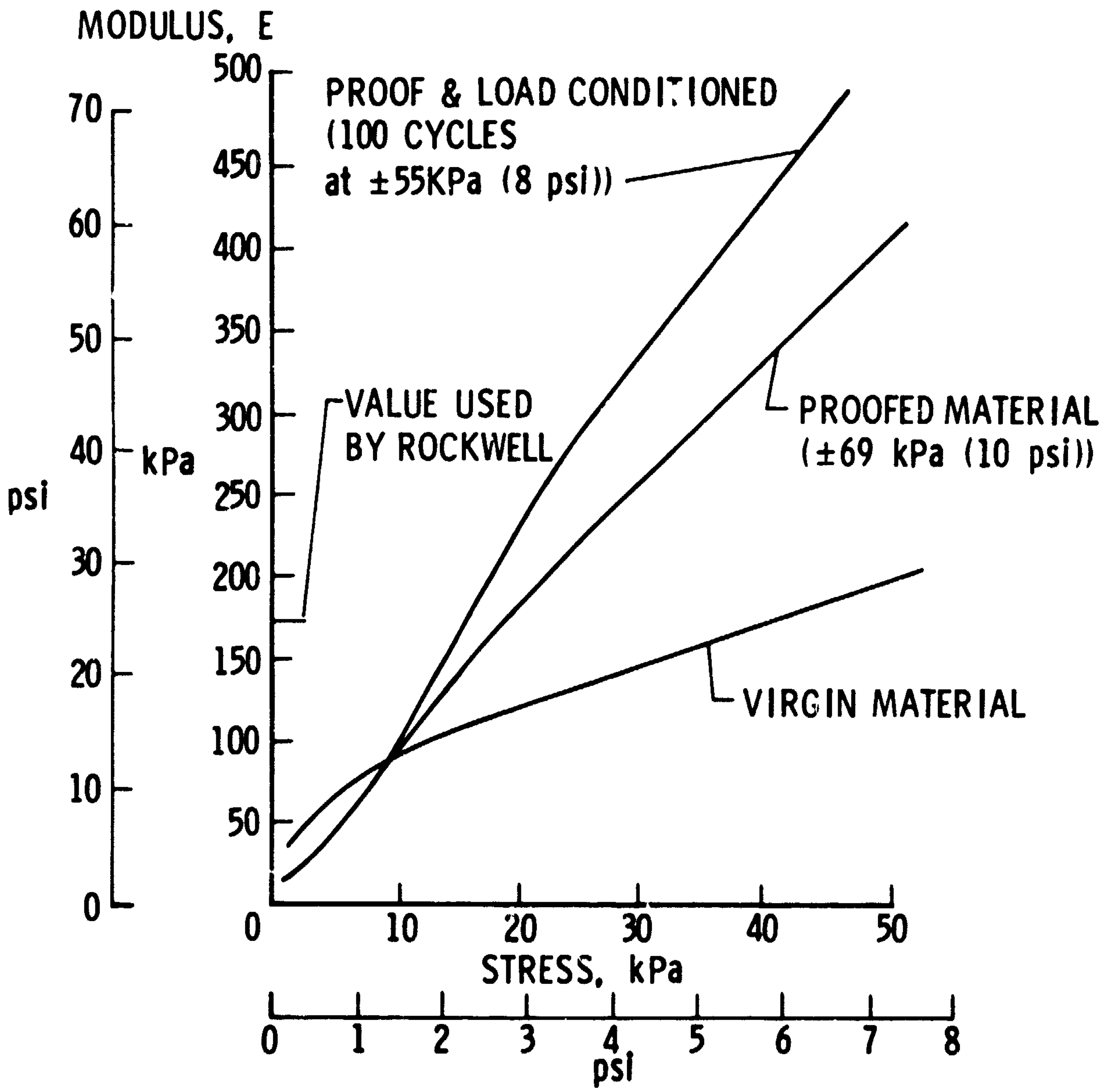
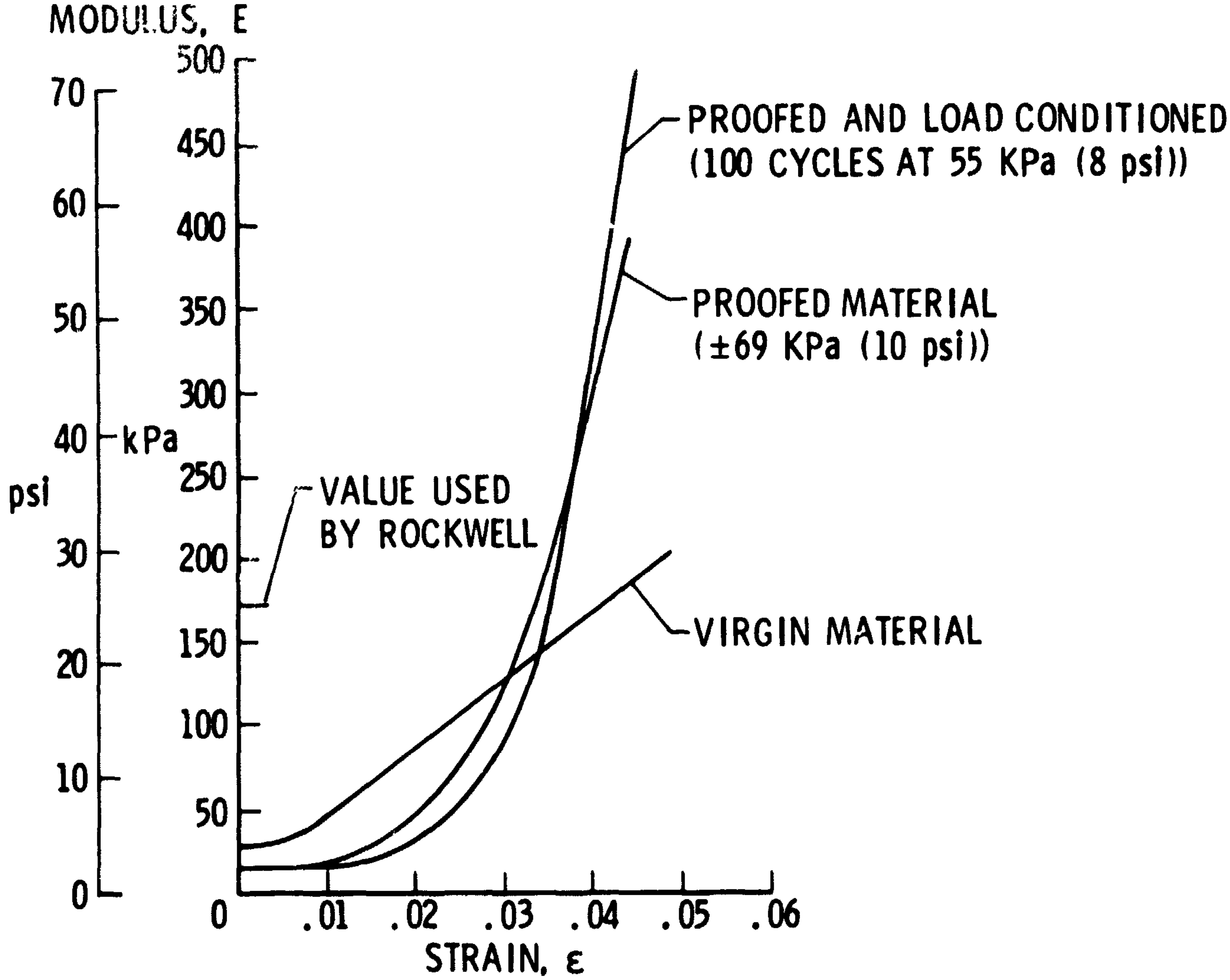


Figure 6 - Typical tension stress-strain behavior for virgin, proofed, and load conditioned .41 cm (.16 inch) thick SIP.



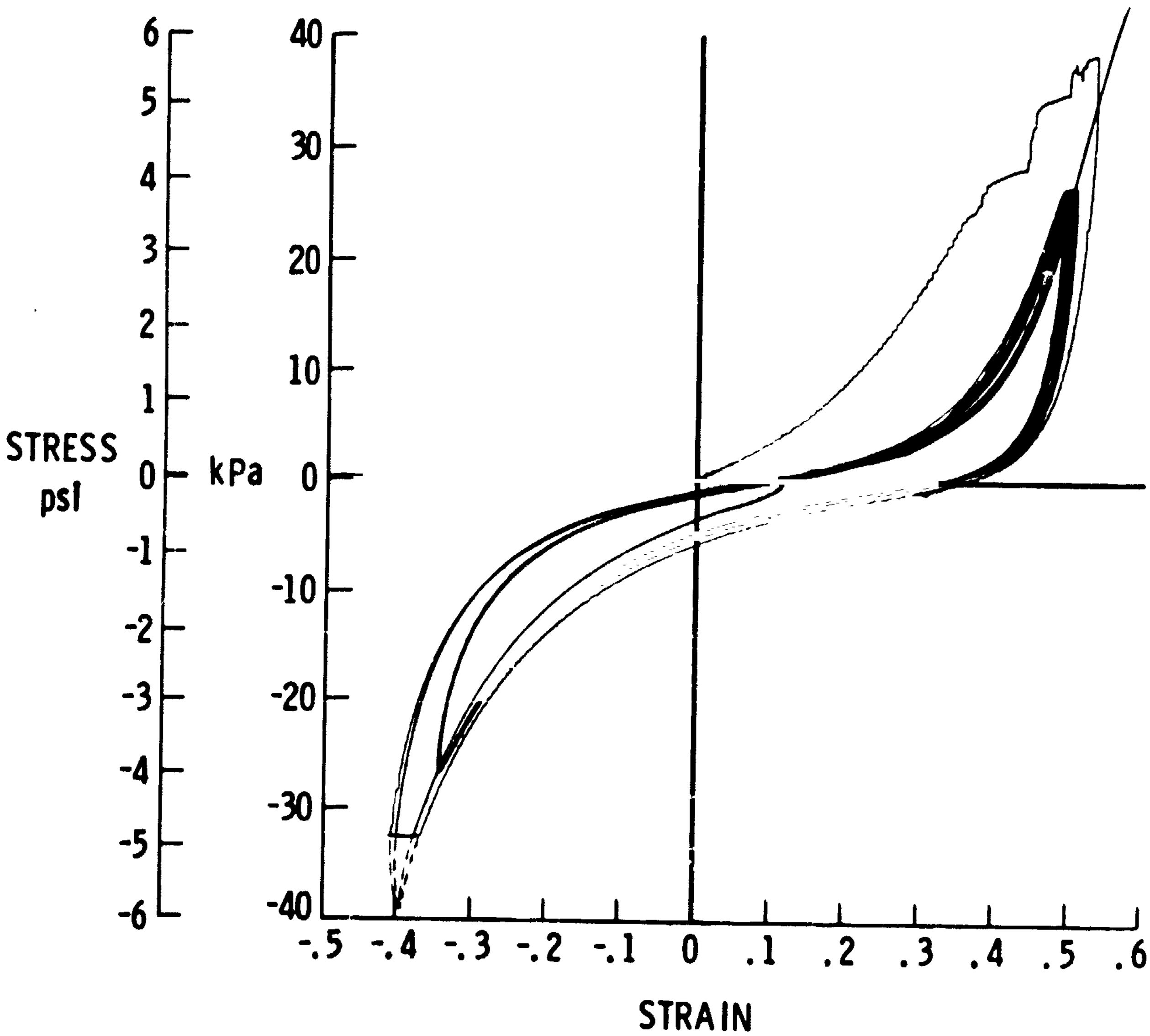
(a) Variation with stress

Figure 7 - Effect of proof cycle and load conditioning on tensile tangent modulus of .41 cm (.16 inch) thick SIP.



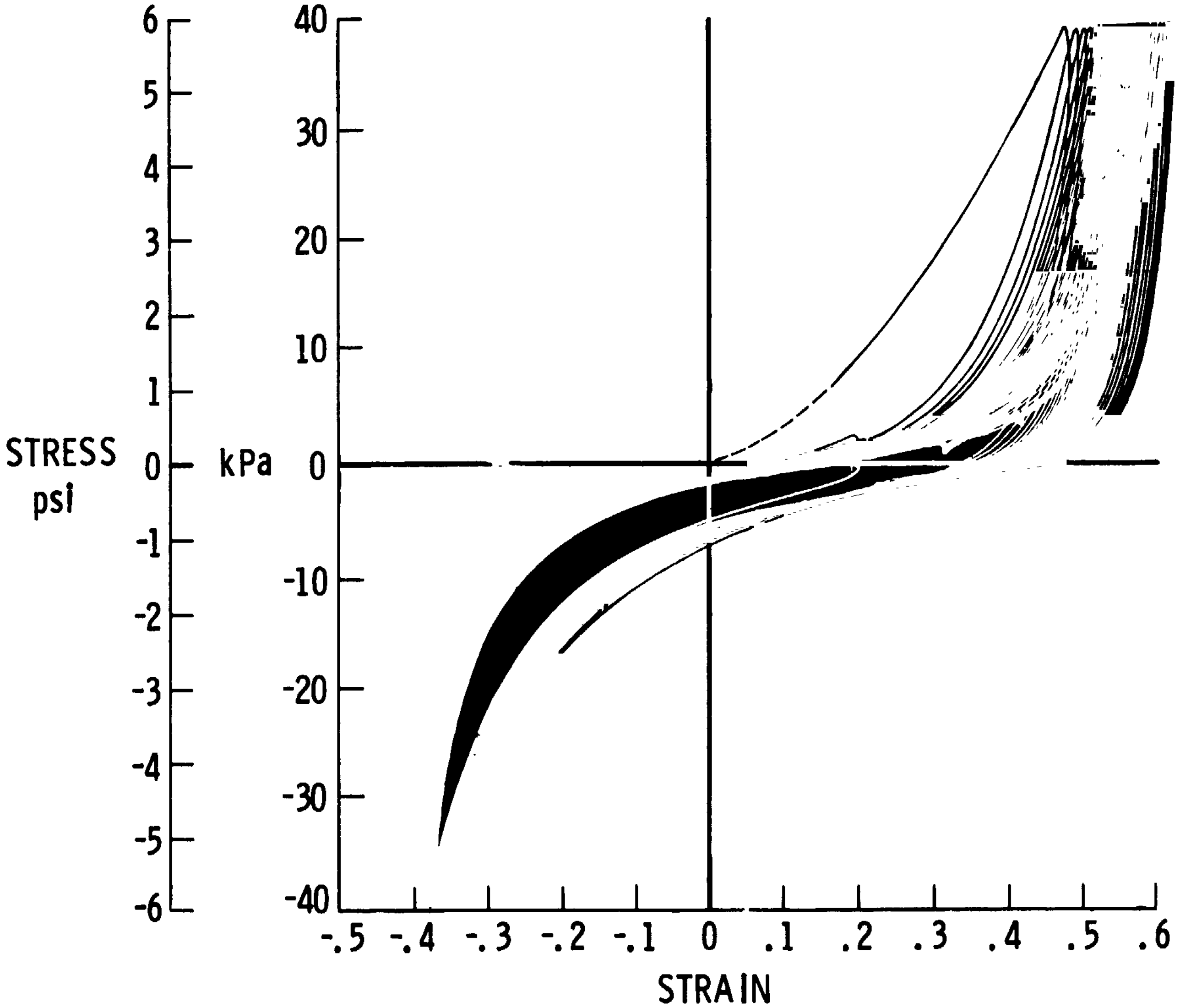
(b) Variation with strain

Figure 7 - Concluded.



(a) Proof test and cyclic load conditioning

Figure 8 - Effect of proof load and cyclic load conditioning on stress-strain behavior of .41 cm (.16 inch) thick SIP. Cyclic load rate = 10 sec/cycle.



(b) Cyclic load conditioning

Figure 8 - Concluded.

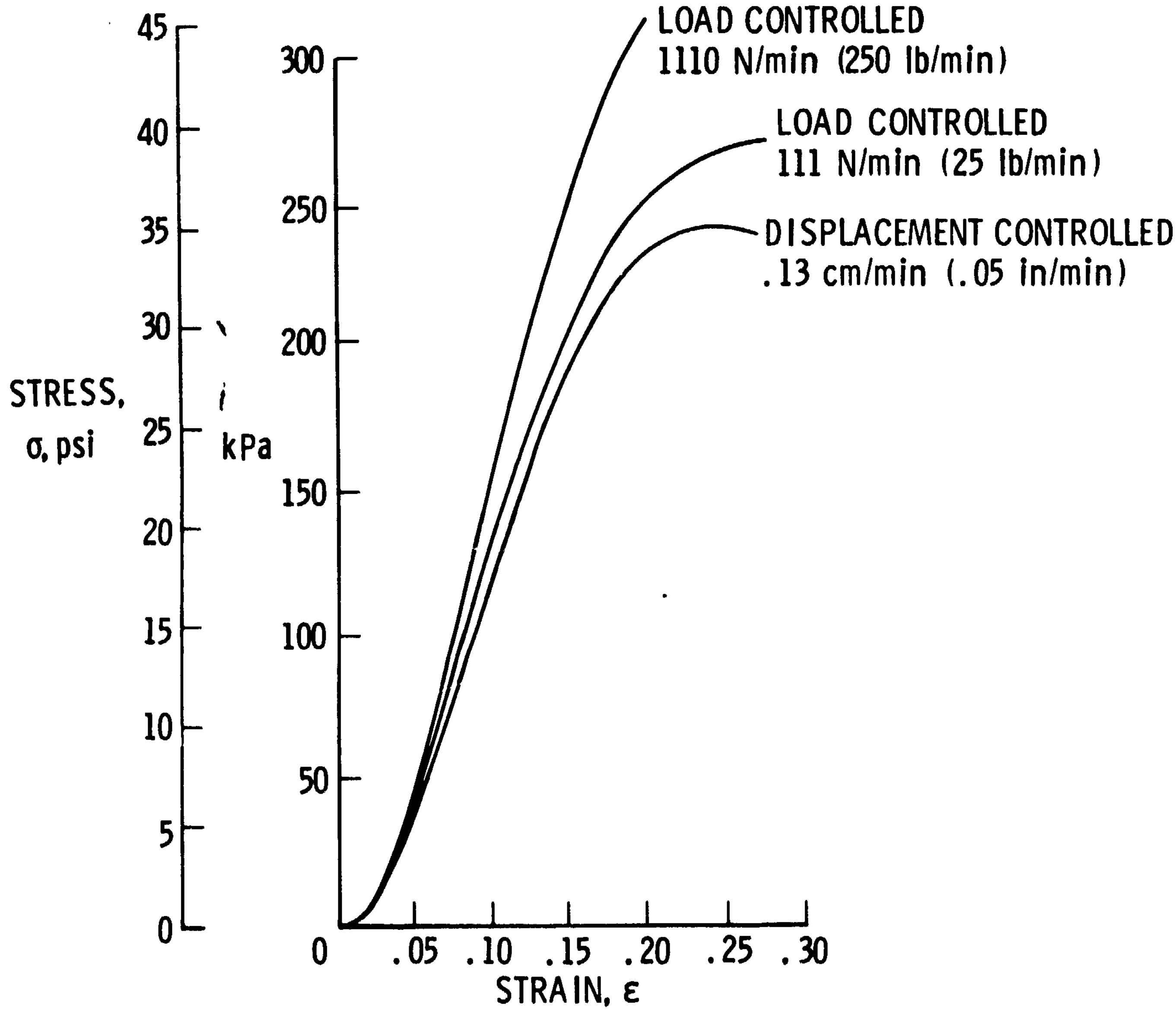
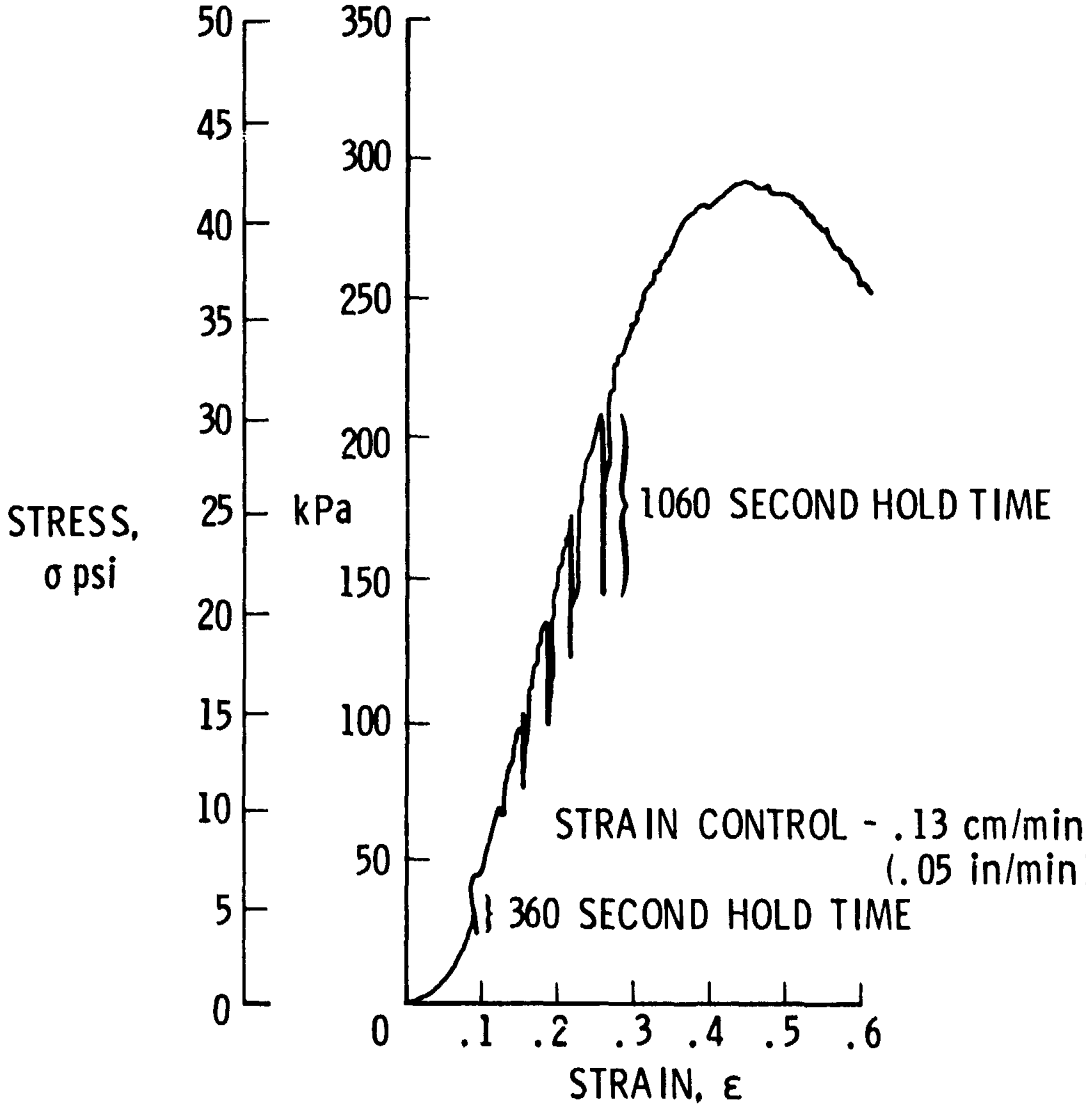
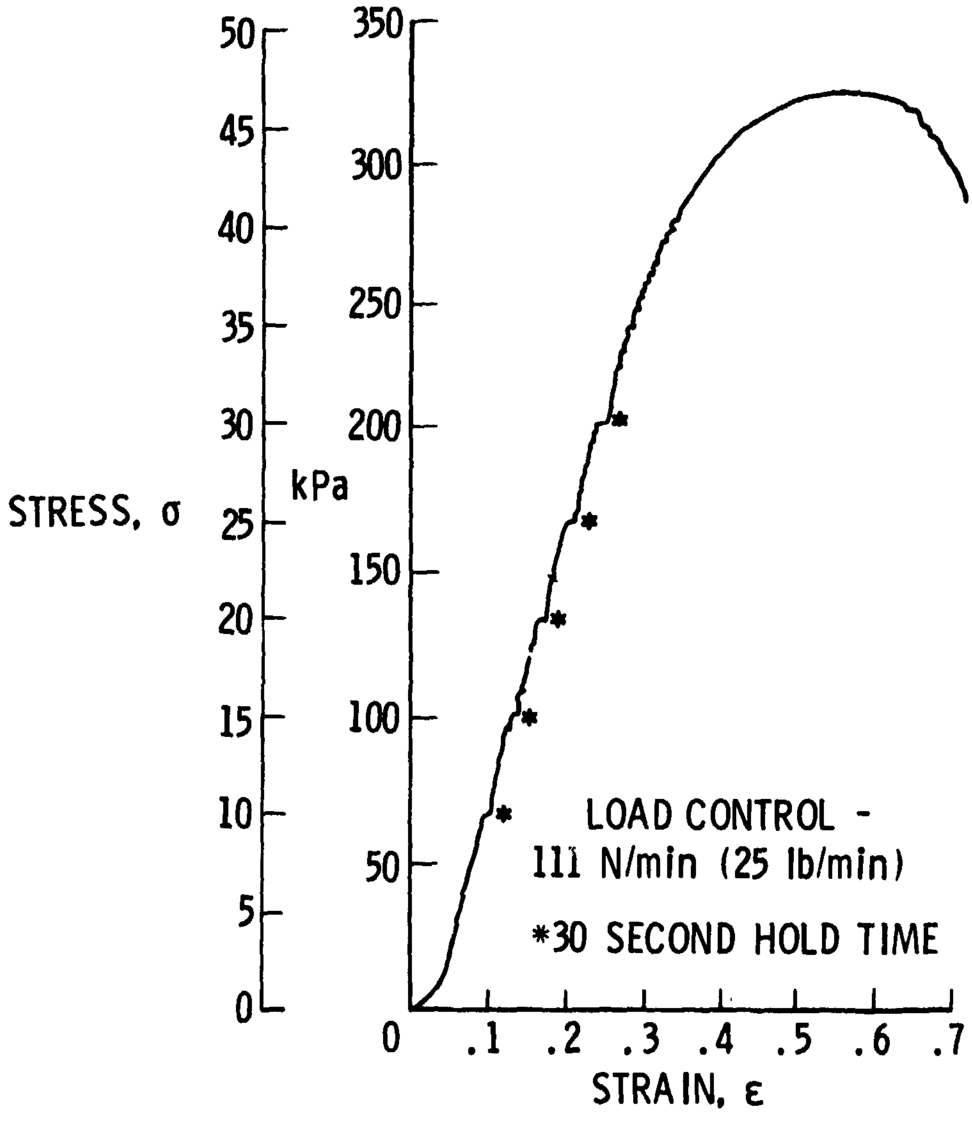


Figure 9 - Typical tension stress-strain behavior for different load and strain rates. Material is unproofed .41 cm (.16 inch) thick SIP.



(a) Relaxation response

Figure 10 - Short time relaxation and creep response for the .41 cm (.16 inch) thick SIP.



(b) Creep response

Figure 10 - Concluded.

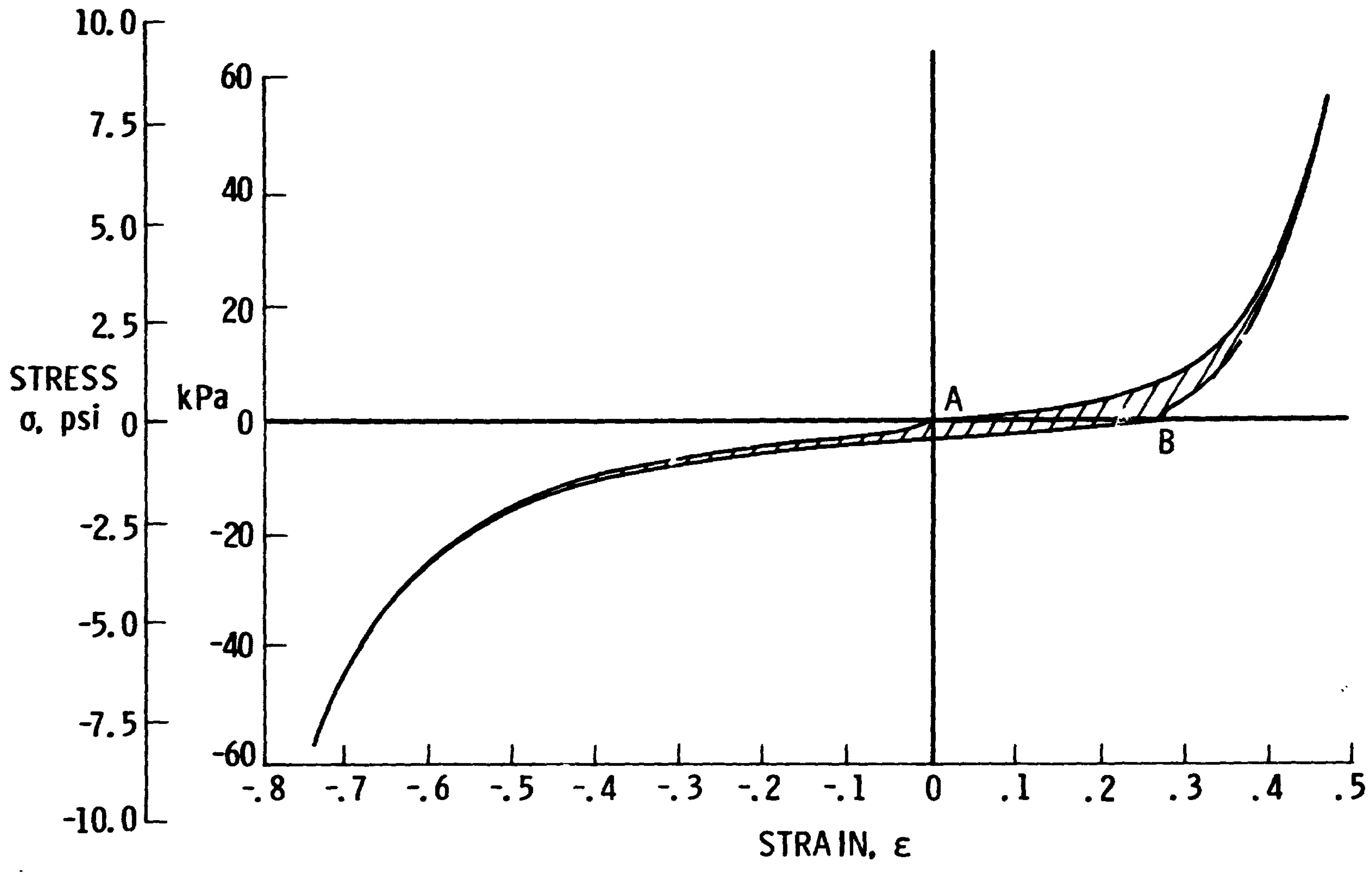
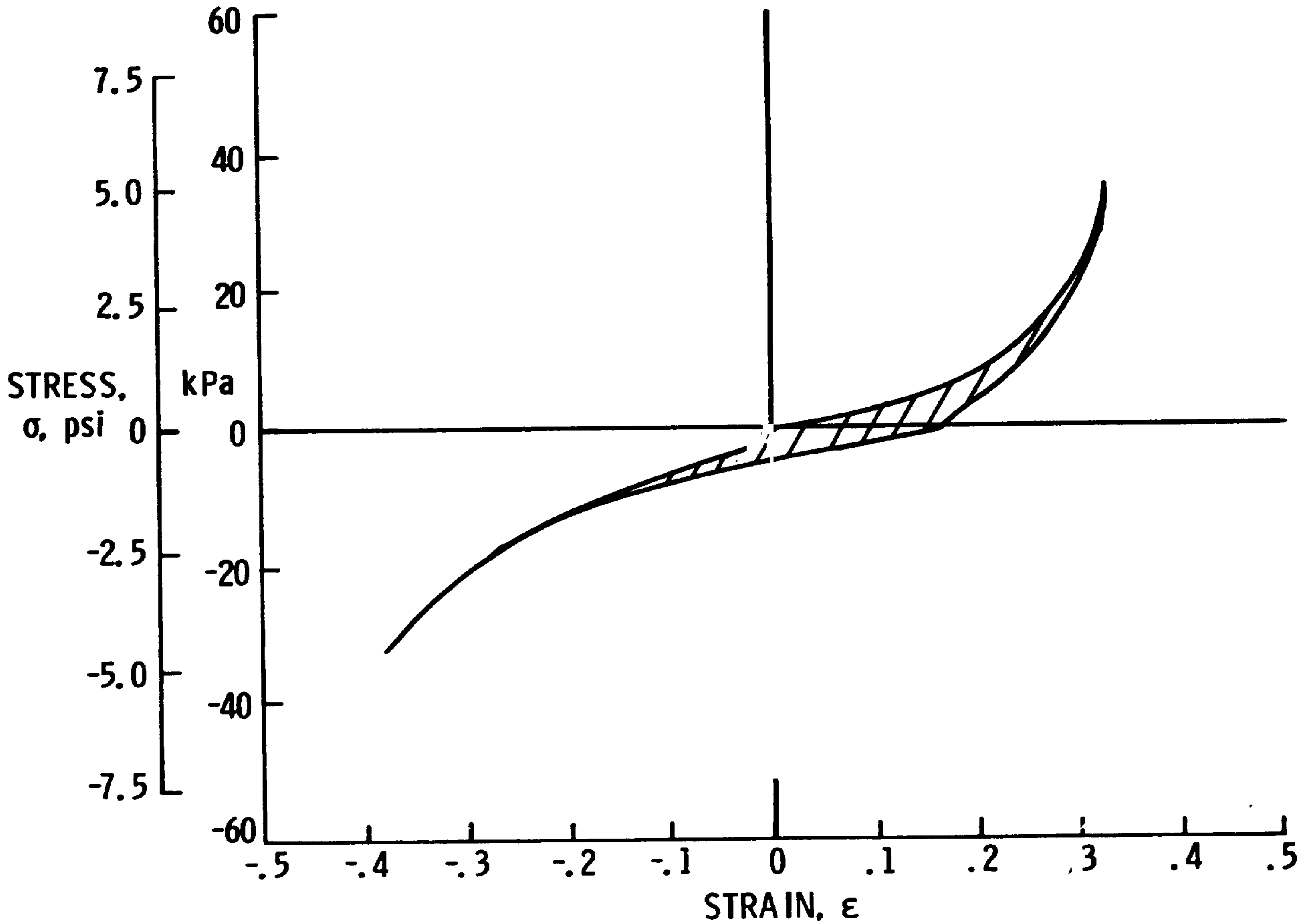
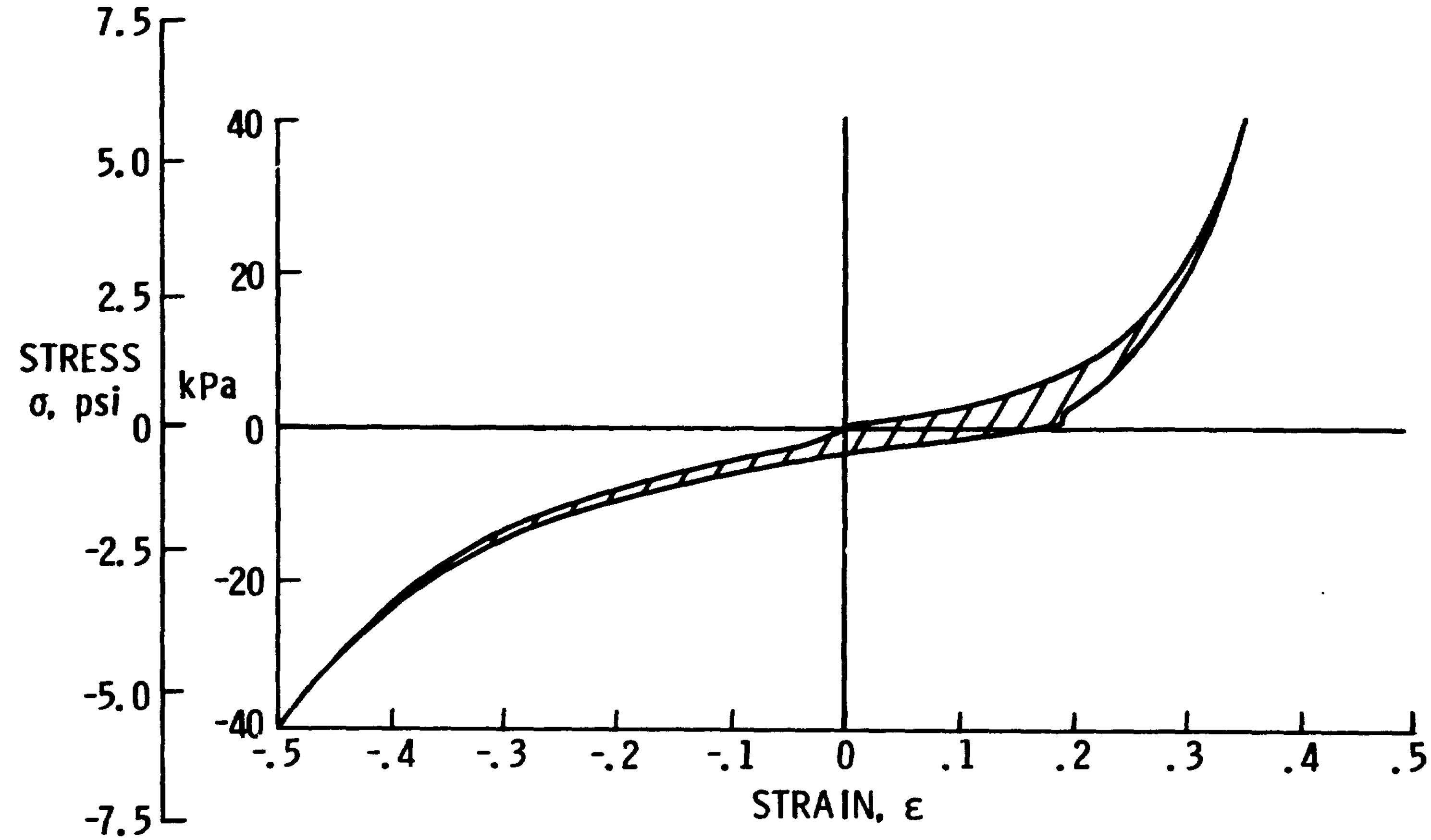


Figure 11 - Stress-strain boundaries for .41 cm (.16 inch) thick SIP after 69 kPa (10 psi) proof load and 100 load conditioning cycles at 80 percent of proof load.



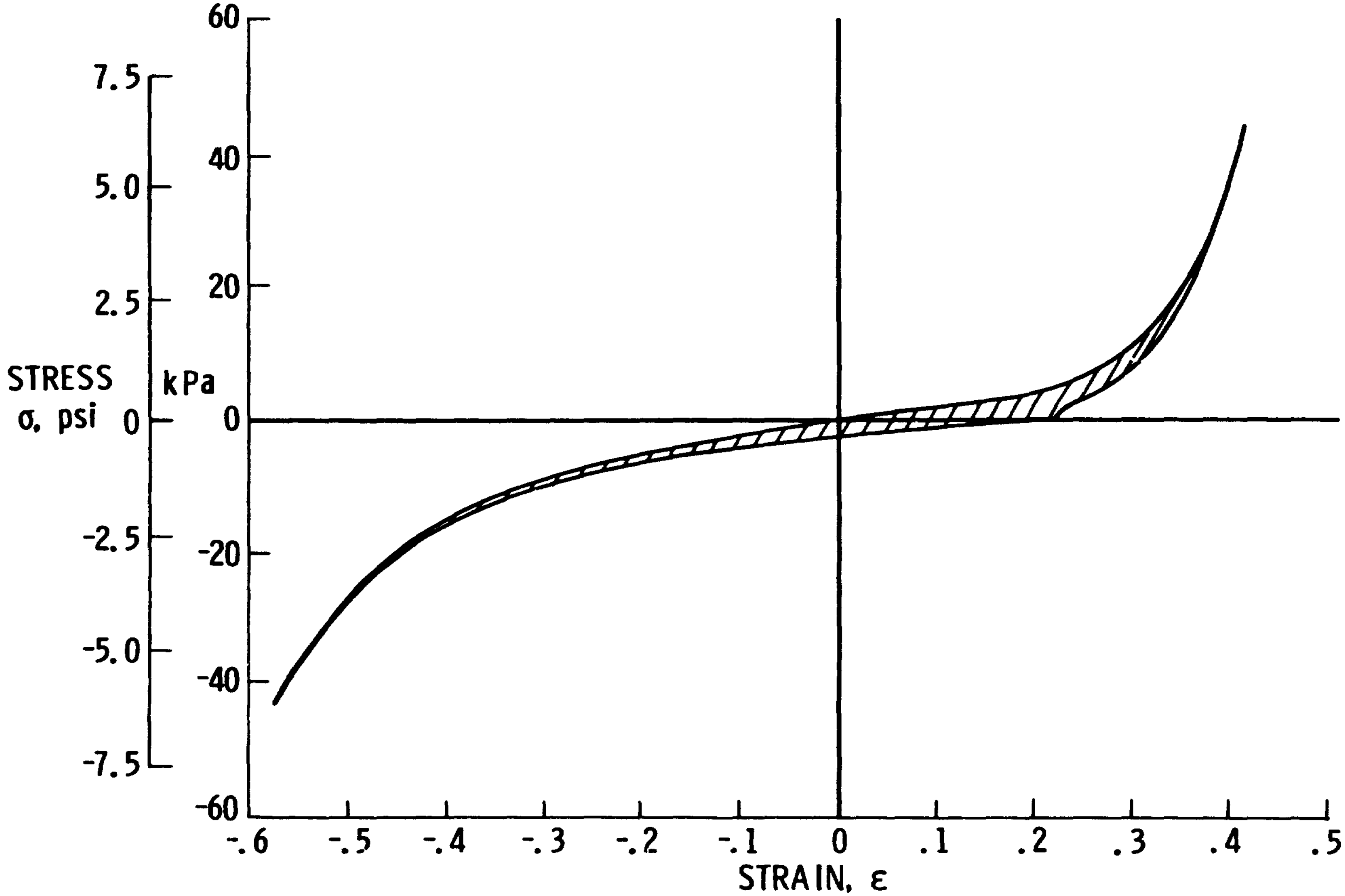
(a) 41 kPa (6 psi) proof load

Figure 12 - Stress-strain boundaries for .41 cm (.16 inch) thick SIP for various proof loads and 100 load conditioning cycles at 80 percent of proof load.



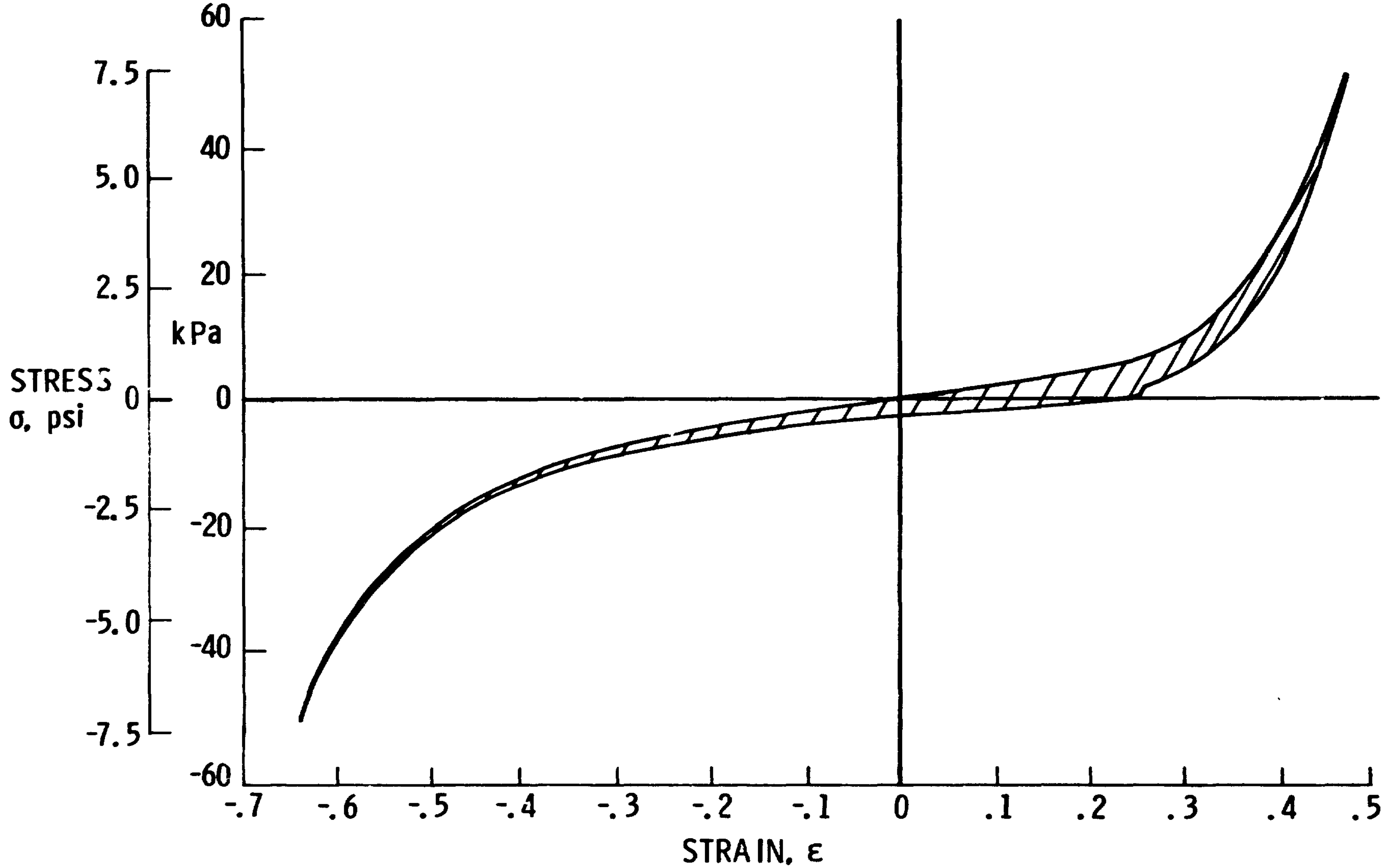
(b) 48 kPa (7 psi) proof load

Figure 12 - Continued.



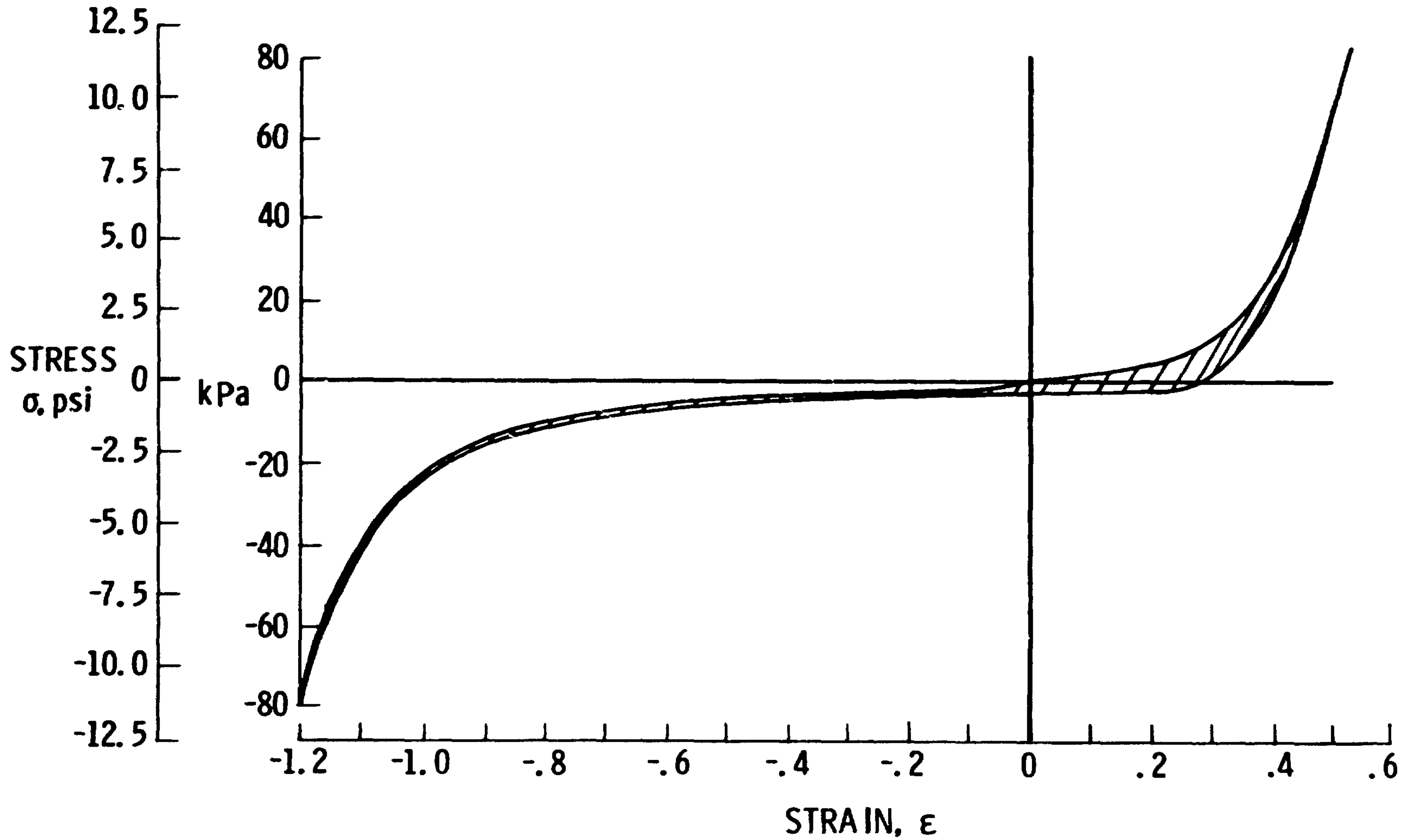
(c) 55 kPa (8 psi) proof load

Figure 12 - Continued.



(d) 62 kPa (9 psi) proof load

Figure 12 - Continued.



(e) 103 kPa (15 psi) proof load

Figure 12 - Concluded.

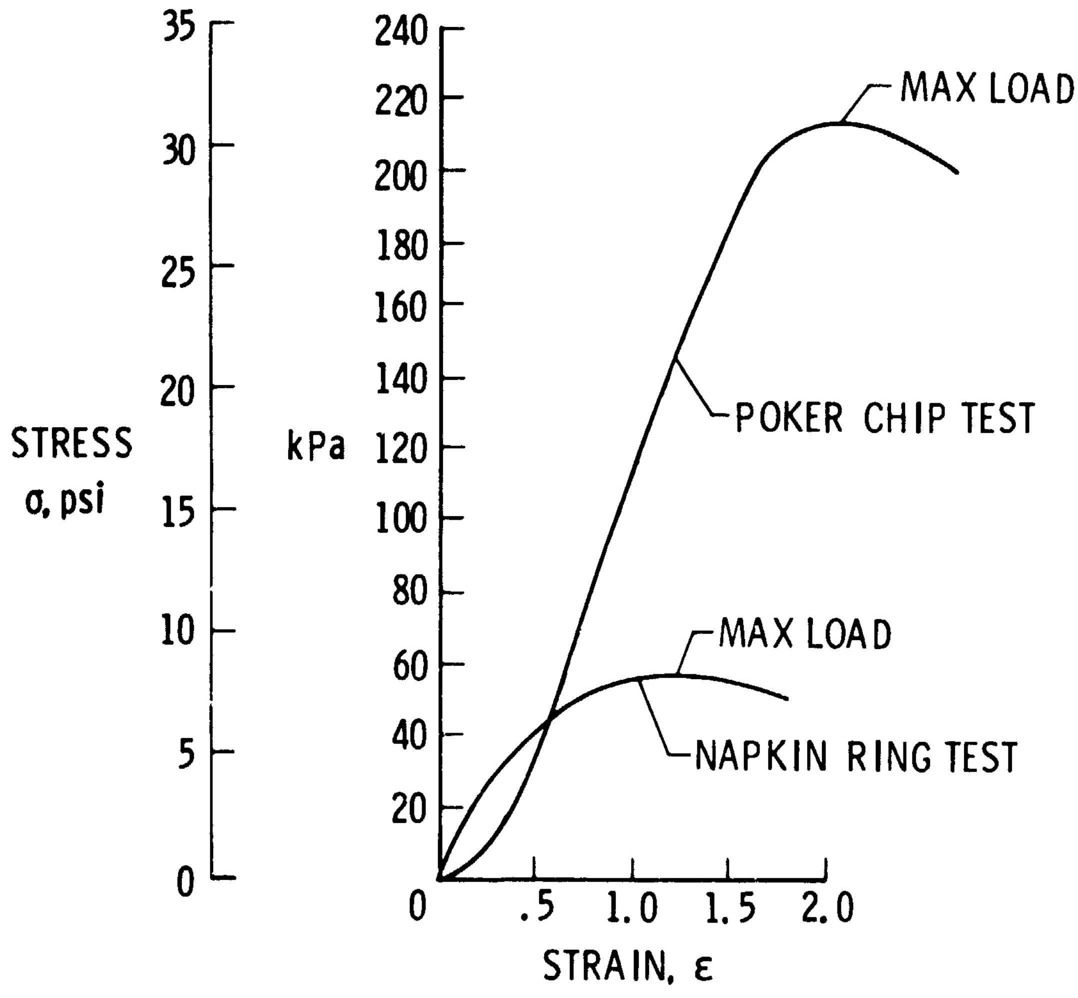


Figure 13 - Comparison of tension stress-strain results for poker-chip and napkin ring tests on .41 cm (.16 inch) thick SIP.