RELATIVE ENERGY ABSORPTION PROPERTIES OF FREE AND ENCLOSED CUSHIONS

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY

Karl Snow Willson

1958

RELATIVE ENERGY ABSORPTION PROPERTIES OF FREE AND ENCLOSED CUSHIONS

By

Karl Snow Willson

AN ABSTRACT

Submitted to the College of Agriculture of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Forest Products

1958

This study was initiated to evaluate some of the differences in the performance of package cushions under test conditions and in practice.

The standard tests which are used for determining cushion performance properties are performed with cushions compressed between two parallel platens. In use, however, cushions are restrained by containers which prevent lateral deformation under pressure and trap air within the cushions. These conditions were believed to have a measurable effect on energy absorption properties, and this difference was studied.

The materials used for the tests were Hairflex Grades II, III, IV, and 8, a commercial brand of latex-bonded animal hair.

Static compression tests were made on cushions between parallel platens, and on cushions in an enclosure. The energy absorbed by the cushions was determined from force-deflection curves and compared. Dynamic tests were conducted under similar conditions and the results compared as cushion factor-stress curves.

A definite increase in the stiffness of cushions was found to result from the lateral restraint in the static tests and from both lateral restraint and air trapped in the cushion by the dynamic test platen.

On the basis of these results, it is recommended that cushion design factor tests, both static and dynamic, be conducted on a more realistic basis. The use of cushion factor curves for design purposes must be reconsidered. Suggestions are made for modifications of package design to utilize the full capabilities of cushions, and several lines of investigation which should increase the understanding of cushion performance are recommended.

RELATIVE ENERGY ABSORPTION PROPERTIES
OF FREE AND ENCLOSED CUSHIONS

By

Karl Snow Willson

A THESIS

Submitted to the College of Agriculture of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Forest Products

1958

ACKNOWLEDGMENTS

The writer wishes to express his sincere appreciation to Mr. Robert E. Kimble and the Armour Cushioning Products Division for assistance and the furnishing of materials for this study.

Thanks are due Dr. James Goff and Dr. Harold Raphael of the Michigan State University School of Packaging, and Dr. John Turk and Mr. Richard Maxson of the Glass Container Manufacturers' Institute for suggestions and discussions regarding this project.

Finally, the writer is grateful to his wife for her assistance and encouragement.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
LIST OF FIGURES	v
INTRODUCTION	1
BACKGROUND	3
PLAN OF STUDY	6
STATIC TESTS	7
TABLES	12
GRAPHS	27
DYNAMIC TESTS	34
GRAPHS	43
TABLES	48
GENERAL CONCLUSIONS	58
RECOMMENDATIONS	59
SUGGESTIONS FOR FURTHER STUDIES	60
LIST OF REFERENCES	61
APPENDIX I: ENERGY CALCULATIONS FOR STATIC TESTS	62
APPENDIX II: USE OF STATIC ENERGY ABSORPTION DATA FOR CUSHION DESIGN	63
APPENDIX III: CUSHION DESIGN WITH CUSHION FACTOR CURVES	66
APPENDIX IV: CALIBRATION OF DYNAMIC SHOCK-MEASURING APPARATUS	67

APPENDIX V: PROPOSED IMPROVEMENTS IN DYNAMIC TEST INSTRUMENTATION 68

APPENDIX VI: ADDITIONAL SELECTED READINGS ON CUSHIONING AND SHOCK ABSORPTION 70

LIST OF FIGURES

FIGURE		PAGE
1.	OVERALL VIEW OF BALDWIN TESTING MACHINE USED FOR STATIC COMPRESSION TESTS	8
2.	CLOSE-UP OF BALDWIN TESTING MACHINE, SHOWING ENCLOSURE AND CUSHION IN PLACE	10
3.	DYNAMIC DROP TESTER	38
4.	DYNAMIC TESTER INSTRUMENTATION	39
5.	BLOCK DIAGRAM OF DYNAMIC TESTING CIRCUITS	40
6.	TYPICAL SHOCK WAVE PHOTOGRAPHS FOR FREE CUSHIONS .	41
7.	TYPICAL SHOCK WAVE PHOTOGRAPHS FOR ENCLOSED CUSHIONS	42
8.	BLOCK DIAGRAM OF PROPOSED MODIFICATIONS	69

INTRODUCTION

The several test methods which have evolved for the determination of cushion design characteristics all involve forces acting upon a cushion which is at rest and unrestrained.

In static tests for energy absorptions, the cushions are compressed between two platens and a load-deflection curve drawn. Dynamic tests, whether for determination of energy absorption or a Cushion Factor, also involve placing an unrestrained cushion against a platen while a movable platen in impacted upon it.

These test methods introduce a certain element of error into the design factor determinations. In packaging practice, cushions are customarily enclosed within a container which introduces additional factors into the situation.

Cushion friction against the sides of the container retards the load motion. This effect will vary with the nature and density of the cushioning material, and with the smoothness of the enclosing surface.

Confining of the cushion also prevents normal bulging of the stressed cushion, and increases its effective stiffness.

Entrapped air within the cushion is a major factor in changing cushion properties. Some air is compressed under the platen and trapped within the cushion during the brief duration of the shock even in dynamic tests with free cushions.

When the cushion is enclosed on five sides, with the movable platen making the sixth side, the closed system uses the trapped air as an additional cushion. The air also adds a damping effect to the system, reducing rebounds.

Trapped air introduces little, if any, changes in the static test results, since the loading rate is slow enough to permit escape of all of the air.

Materials, such as some plastic foams, having a closed cell structure, will not show major trapped air effects since the internal air is permanently enclosed. Restriction of lateral expansion may be more significant, as internal compression is limited by the internal pressure developed under stress.

This study is intended to establish some of the relationships between testing conditions and actual use conditions for cushioning materials, and to make recommendations for design data corrections and further investigations.

BACKGROUND

In packaging applications, certain properties of cushioning materials must be known to permit the design of cushioned packages by other than trial-and-error methods. The most common data are load-deflection curves, stress-energy curves, and cushion factor curves.

Static loading tests are a widely-used method of comparing cushioning materials. One method is to derive a curve of load vs. compression from a machine-made force-displacement curve. This load-compression curve can be used as a design curve, telling what deflection a cushion will undergo at a given load.

The load-compression curve can also be used to obtain a graph of stress vs. thickness of cushioning to use. The maximum stress which will be applied to a cushion is found by multiplying the static stress by the "g-factor", or the number of times the force of gravity the packaged object can withstand. (1) The total energy absorbed by the cushions in the above is represented by the area under the curves.

The "g-factor" which an object can withstand depends on the most fragile part of the object or product. It is defined as the ratio of the acceleration received by an object to the acceleration due to gravity. In packaging applications, the "g-factor" is a measure of the deceleration received by a package when it stops suddenly as it strikes a floor, wall, or other solid obstacle. The deceleration must be equal to the acceleration the package receives as it falls, or the weight multiplied by the acceleration due to gravity. The "g-factor" is also known as the fragility index, denoted by G.

Another method of applying force-displacement curves to design problems is to prepare stress-energy curves, or a pair of stress-strain and strain-energy curves. The energy absorbed by a cushion can then be found if the stress which it receives is known.

It is also necessary in some instances to know the deflection that will result under a static load, such as stacking in a warehouse. The elementary stress-displacement curve will reveal how much load can be applied to a package without crushing it enough to damage the contents.

Determination of dynamic energy absorption properties is accomplished by several methods, all using similar apparatus and calculations. One apparatus uses a drop hammer with a stylus attached, giving charts of both the dropping distance of the hammer and its penetration into the cushion. (1)

A more efficient method of finding the energy uses accelerometers and electronic apparatus to measure the shock imparted by a known force to a cushion. This method may yield either energy absorption curves or cushion factor curves, both of which are directly applicable to cushion design.

The cushion factor is a dimensionless quantity which is used as a computational device to simplify cushion designs.

The cushion factor varies with the force-energy ratio, and is plotted against stress. The cushion factor is equal to $C = (F/E)t = WG/Wh \times t = Gt/h$, where F is the force, E is the energy, W is the load weight, G is the "g-factor", h is the drop height, and t is the cushion thickness. The cushion factor is thus easily determined if the factor G can be measured. The stress is determined simultaneously with the cushion factor, and is equal to WG/A, where W is the weight of the impacting platen, A is the area of the platen, and G is the deceleration. A stress-cushion factor curve normally has a minimum point, at which stress the cushioning material is most efficient. The thickness of cushioning required for a given application is determined by rearranging the above cushion factor equation to $t = Ch/G$. Use of these cushion design properties is demonstrated in appendices II and III.

PLAN OF STUDY

In order to investigate some of the differential effects between cushion tests and performance under use conditions, tests were conducted on several cushions by both static and dynamic methods. Container conditions were simulated by a wooden enclosure for the cushions under test.

The static tests produced force-deflection curves, which were used to draw up stress-strain and strain-energy curves. The total energy absorbed in the tests was compared.

Dynamic tests were run to determine the fragility index G of the cushion for a known stress. The cushion factor was computed from G and comparative cushion factor-stress curves drawn.

The materials used for these tests were four grades of rubberized hair, known commercially as Hairflex Types II, III, IV, and 3. This material consists of curled animal hairs coated and bonded into molded shapes by latex rubber. The density of the material increases with increasing type numbers. The samples used for these tests were rectangular blacks, 12 inches square and a nominal two inches thick, except for the No. 8, which was in 10-inch squares.

It was not possible to condition the test specimens prior to use, but it is felt that the nature of the material minimized any variations due to changes in moisture content.

STATIC TESTS

Force-deflection curves were obtained by compressing the cushions between the platens of a Baldwin-Emory 50,000 pound, FG7-SR-4, Universal Testing Machine, using a 0-1000 pound range. This machine is equipped with a deflectometer and load recorder to produce direct force-deflection curves.

Cushions used in the initial test series were prestressed by compressing them to less than 50% of their nominal thickness for ten cycles, and then resting them for about 1/2 hour before testing. The loading rate was one inch per minute for both prestressing and for testing.

Tests of free cushions were made by compressing the specimens between two 12-inch-square platens to a thickness of about 0.4 inch. The tests were started with the spacing between the platens equal to the two-inch nominal thickness of the cushions. This introduced a small initial load to the specimens, but compensates for the non-uniform actual thickness of the specimens by giving a uniform initial thickness. Inasmuch as these are relative tests, such errors will not affect the usefulness of these data for comparative purposes.

To simulate the conditions present when a cushion is placed in a closed container, an enclosure was constructed of 3/4-inch plywood. This enclosure was just over twelve inches square, just clearing the sides of the platen, and two

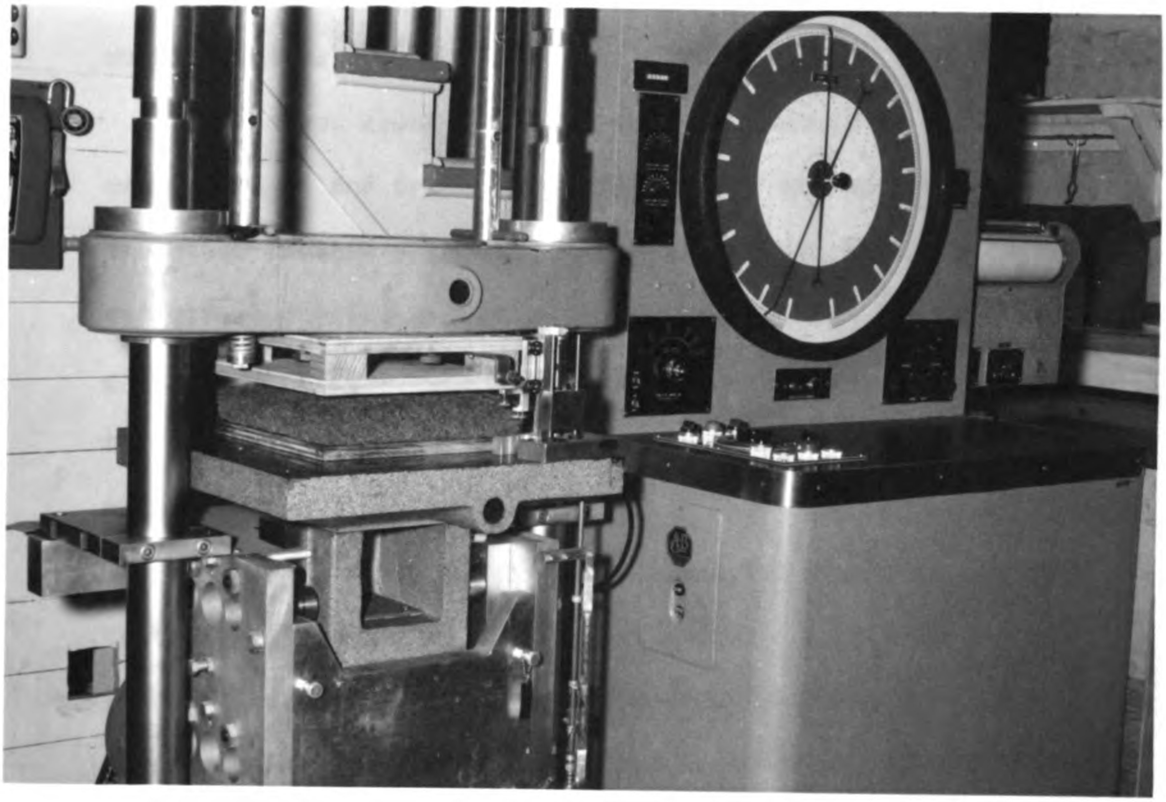


FIGURE 1

OVERALL VIEW OF BALDWIN TESTING MACHINE

USED FOR STATIC COMPRESSION TESTS

inches deep. Cushions were tested by placing them in the fixture, centering the platen, and compressing the cushions into the enclosure. The tests were started with the platens two inches apart, maintaining the conditions of the free cushion tests.

The forces recorded at 0.1-inch increments of deflection were averaged and entered into the energy computation sheets. The other factors were computed by the method of Appendix I, and stress-strain, strain-energy curves plotted for each set of test conditions. As a check of the effects of prestressing the test cushions, tests were also run using new cushions with no preworking prior to testing.

The comparative total energy absorptions for the static tests are given in Table I, and illustrated in Graphs 1-7 (pages 27 - 33). There is a definite increase in the energy absorption at a given stress, for each material, when enclosed, except for the decrease in absorption in the prestressed Type IV cushions. The reason for this difference in performance is unknown.

The increase in absorbed energy indicates that the cushion has a greater stiffness, and transmits more energy to the article it is intended to protect.

There is a greater increase in absorbed energy with the enclosure for cushions which have been prestressed. This is a result of a higher strain in the prestressed cushions, which is permitted by the loosening of internal bonds in the cushion

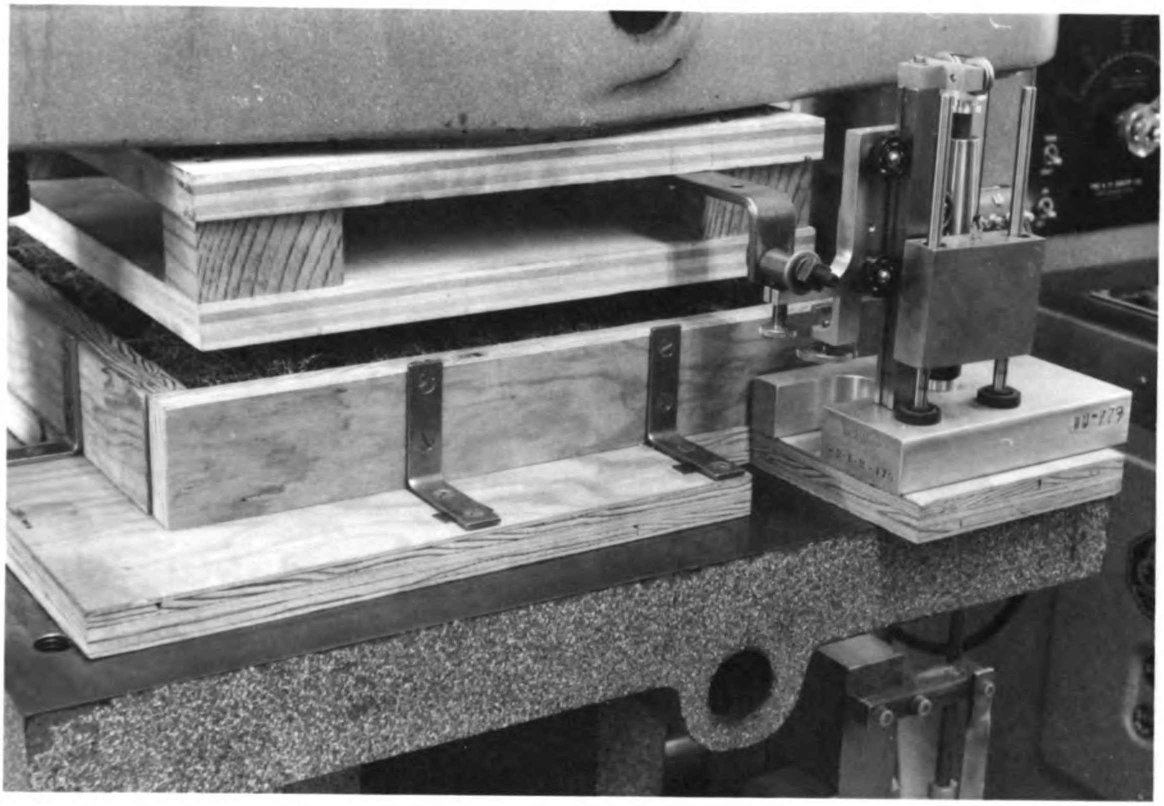


FIGURE 2

CLOSEUP OF BALDWIN TESTING MACHINE, SHOWING
ENCLOSURE AND CUSHION IN PLACE.
DEFLECTOMETER IS SHOWN IN RIGHT FOREGROUND

during prestressing.

The energy absorption at a given stress is not always increased by the enclosure, since the stress does not vary directly with the deflection. More force must be exerted on an enclosed cushion to produce a desired deflection, demonstrating that the enclosed cushion is definitely stiffer and offers more resistance to the compressing platen.

There is some effect in these tests due to friction between the edges of the cushion and the solid enclosure. This effect will be least with the lower-density materials, but the loose nature of the material should make this error negligible in proportion to the additional stiffness due to restraint of lateral motion in the compressed cushions.

The relatively slow loading rate and the clearance between the platen and enclosure render any additional energy due to entrapped air negligible.

TABLE 1

COMPARISON OF TOTAL ENERGY ABSORBED
IN STATIC COMPRESSION TESTS

CUSHION ENCLOSURE	STRESS AT 1.6" DEFLECTION	TOTAL ENERGY ABSORBED	CHANGE IN ENERGY ABSORBED BY ENCLOSED CUSHION
GRADE II PRESTRESSED			
Free Enclosed	1.98 p.s.i. 2.08	.36190 in-lbs/in^3 .39465	+ 9%
GRADE III PRESTRESSED			
Free Enclosed	3.20 3.53	.58580 .64965	+ 11%
GRADE III NOT PRESTRESSED			
Free Enclosed	3.01 3.42	.60250 .63700	+ 6%
GRADE IV PRESTRESSED			
Free Enclosed	4.81 5.77	1.1335 1.0775	- 5%
GRADE IV NOT PRESTRESSED			
Free Enclosed	5.37 6.03	1.0955 1.2975	+ 18%
CUSHION ENCLOSURE	**STRESS AT 1.3" DEFLECTION**	**TOTAL ENERGY ABSORBED**	**ENERGY CHANGE**
GRADE 8 PRESTRESSED			
Free Enclosed	13.28 psi 17.57	2.0040 in-lbs/in^3 2.9850	+ 49%
GRADE 8 NOT PRESTRESSED			
Free Enclosed	13.90 15.50	2.5760 3.0480	+ 18%

TABLE 2
STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE II, PRESTRESSED

DEFLECTION (inches)	MEAN LOAD (pounds)	STRAIN (inches/inch)	STRESS (psi)	STRAIN INCREMENT (inches/inch)	Mean STRESS (psi)	ENERGY (in-lbs/in^3)	TOTAL ENERGY (in-lbs/in^3)
0.1	0	.05	0	.05	0	0	0
0.2	4	.10	.03	.05	.015	.00075	.00075
0.3	8	.15	.06	.05	.045	.00225	.00300
0.4	13	.20	.09	.05	.048	.00240	.00540
0.5	19	.25	.13	.05	.110	.00550	.01090
0.6	25	.30	.17	.05	.150	.00750	.01840
0.7	31	.35	.22	.05	.195	.00975	.02815
0.8	40	.40	.28	.05	.250	.01250	.04065
0.9	50	.45	.35	.05	.315	.01575	.05640
1.0	64	.50	.44	.05	.395	.01975	.07615
1.1	80	.55	.56	.05	.500	.02500	.10115
1.2	97	.60	.67	.05	.615	.03075	.13190
1.3	120	.65	.83	.05	.750	.03750	.16940
1.4	151	.70	1.05	.05	.940	.04700	.21640
1.5	200	.75	1.39	.05	1.22	.0610	.27740
1.6	285	.80	1.98	.05	1.69	.0845	.36190

TABLE 3
STATIC ENERGY ABSORPTION
ENCLOSED CUSHIONS, GRADE II, PRESTRESSED

DEFLECTION (inches)	MEAN LOAD (pounds)	STRAIN inches/inch	STRESS (psi)	STRAIN INCREMENT inches/inch	MEAN STRESS (psi)	ENERGY (in-lbs/in^3)	TOTAL ENERGY (in-lbs/in^3)
0.1	4	.05	.03	.05	.015	.00075	.00075
0.2	9	.10	.06	.05	.045	.00225	.00300
0.3	14	.15	.10	.05	.079	.00395	.00695
0.4	19	.20	.13	.05	.114	.00570	.01265
0.5	25	.25	.17	.05	.150	.00750	.02015
0.6	30	.30	.21	.05	.190	.00950	.02965
0.7	38	.35	.26	.05	.235	.01175	.04140
0.8	45	.40	.31	.05	.285	.01425	.05565
0.9	54	.45	.38	.05	.345	.01725	.07290
1.0	67	.50	.47	.05	.425	.02125	.09415
1.1	79	.55	.55	.05	.510	.02550	.11965
1.2	104	.60	.72	.05	.635	.03175	.15140
1.3	127	.65	.88	.05	.800	.04000	.19140
1.4	160	.70	1.11	.05	.995	.04975	.24115
1.5	211	.75	1.47	.05	1.29	.0645	.30565
1.6	300	.80	2.08	.05	1.78	.0890	.39465

TABLE 4
STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE III, PRESTRESSED

DEFLECTION (inches)	MEAN LOAD (pounds)	STRAIN (inches/inch)	STRESS (psi)	STRAIN INCREMENT (inches/inch)	MEAN STRESS (psi)	ENERGY (in-lbs/in^3)	TOTAL ENERGY (in-lbs/in^3)
0.1	5	.05	.04	.05	.020	.00100	.00100
0.2	12	.10	.083	.05	.062	.00310	.00410
0.3	19	.15	.13	.05	.069	.00345	.00755
0.4	25	.20	.17	.05	.150	.00750	.01505
0.5	32	.25	.22	.05	.195	.00975	.02480
0.6	39	.30	.27	.05	.245	.01225	.03705
0.7	49	.35	.34	.05	.305	.01525	.05230
0.8	61	.40	.42	.05	.380	.01900	.07130
0.9	77	.45	.53	.05	.475	.02375	.09505
1.0	102	.50	.71	.05	.620	.03100	.12605
1.1	129	.55	.90	.05	.805	.04025	.16630
1.2	155	.60	1.08	.05	.990	.04950	.21580
1.3	191	.65	1.33	.05	1.21	.06050	.27630
1.4	243	.70	1.69	.05	1.51	.07550	.35180
1.5	321	.75	2.23	.05	2.72	.13600	.58580 ↕
1.6	461	.80	3.20	.05	2.72	.13600	.44980

TABLE 5
STATIC ENERGY ABSORPTION
ENCLOSED CUSHIONS, GRADE III, PRESTRESSED

DEFLECTION	MEAN LOAD	STRAIN	STRESS	STRAIN INCREMENT	MEAN STRESS	ENERGY	TOTAL ENERGY
0.1	6	.05	.04	.05	.021	.00100	.00100
0.2	14	.10	.097	.05	.069	.00345	.00445
0.3	21	.15	.15	.05	.124	.00620	.01065
0.4	28	.20	.19	.05	.170	.00850	.01915
0.5	35	.25	.24	.05	.215	.01075	.02990
0.6	44	.30	.31	.05	.275	.01375	.04365
0.7	55	.35	.38	.05	.345	.01725	.06090
0.8	68	.40	.47	.05	.425	.02125	.08215
0.9	85	.45	.59	.05	.530	.02650	.10865
1.0	109	.50	.76	.05	.675	.03375	.14240
1.1	137	.55	.95	.05	.855	.04275	.18515
1.2	174	.60	1.21	.05	1.08	.05400	.23915
1.3	212	.65	1.47	.05	1.34	.06700	.30615
1.4	270	.70	1.88	.05	1.68	.08400	.39015
1.5	357	.75	2.48	.05	2.18	.10900	.49915
1.6	509	.80	3.53	.05	3.01	.15050	.64965

TABLE 6

STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE III, NOT PRESTRESSED

DEFLECTION	MEAN LOAD	STRAIN	STRESS	STRAIN INCREMENT	MEAN STRESS	ENERGY	TOTAL ENERGY
0.1	10	.05	.07	.05	.04	.00200	.00200
0.2	20	.10	.14	.05	.11	.00550	.00750
0.3	29	.15	.20	.05	.17	.00850	.01600
0.4	38	.20	.26	.05	.23	.01150	.02750
0.5	46	.25	.32	.05	.29	.01450	.04200
0.6	54	.30	.38	.05	.35	.01750	.05950
0.7	64	.35	.44	.05	.41	.02050	.08000
0.8	74	.40	.51	.05	.48	.02400	.10400
0.9	86	.45	.60	.05	.56	.02800	.13200
1.0	102	.50	.71	.05	.66	.03300	.16500
1.1	121	.55	.84	.05	.78	.03900	.20400
1.2	145	.60	1.01	.05	.93	.04650	.25050
1.3	179	.65	1.24	.05	1.13	.05650	.30700
1.4	231	.70	1.60	.05	1.42	.07100	.37800
1.5	314	.75	2.18	.05	1.89	.09450	.47250
1.6	434	.80	3.01	.05	2.60	.13000	.60250

TABLE 7

STATIC ENERGY ABSORPTION

ENCLOSED CUSHIONS, GRADE III, NOT PRESTRESSED

DEFLECTION (inches)	MEAN LOAD (pounds)	STRAIN (inches/inch)	STRESS (psi)	STRAIN INCREMENT (inches/inch)	MEAN STRESS (psi)	ENERGY (in-lbs/in^3)	TOTAL ENERGY (in-lbs/in^3)
0.1	9	.05	.06	.05	.03	.00150	.00150
0.2	19	.10	.13	.05	.10	.00800	.01450
0.3	28	.15	.19	.05	.16	.00500	.00650
0.4	37	.20	.26	.05	.23	.01150	.02600
0.5	45	.25	.31	.05	.29	.01450	.04050
0.6	53	.30	.37	.05	.34	.01700	.05750
0.7	63	.35	.44	.05	.41	.02050	.07800
0.8	74	.40	.51	.05	.48	.02400	.10200
0.9	87	.45	.60	.05	.56	.02800	.13000
1.0	104	.50	.72	.05	.66	.03300	.16300
1.1	126	.55	.88	.05	.80	.04000	.20300
1.2	157	.60	1.09	.05	.99	.04950	.25250
1.3	194	.65	1.35	.05	1.22	.06100	.31350
1.4	250	.70	1.74	.05	1.55	.07750	.39100
1.5	338	.75	2.34	.05	2.04	.10200	.49300
1.6	493	.80	3.42	.05	2.88	.14400	.63700

TABLE 8
STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE IV, PRESTRESSED

DEFLECTION	MEAN LOAD	STRAIN	STRESS	STRAIN INCREMENT	MEAN STRESS	ENERGY	TOTAL ENERGY
0.1	12	.05	.08	.05	.04	.0020	.0020
0.2	29	.10	.20	.05	.14	.0070	.0090
0.3	45	.15	.31	.05	.26	.0130	.0220
0.4	61	.20	.42	.05	.37	.0185	.0405
0.5	76	.25	.53	.05	.48	.0240	.0645
0.6	92	.30	.64	.05	.59	.0295	.0940
0.7	110	.35	.76	.05	.70	.0350	.1290
0.8	132	.40	.92	.05	.84	.0420	.1710
0.9	162	.45	1.13	.05	1.03	.0515	.2225
1.0	210	.50	1.46	.05	1.30	.0650	.2875
1.1	263	.55	1.83	.05	1.65	.0825	.3700
1.2	308	.60	2.14	.05	1.99	.0995	.4695
1.3	367	.65	2.55	.05	2.35	.1175	.5870
1.4	454	.70	3.15	.05	2.85	.1425	.7295
1.5	591	.75	4.10	.05	3.63	.1815	.9110
1.6	693	.80	4.81	.05	4.45	.2225	1.1335

TABLE (9)
STATIC ENERGY ABSORPTION
ENCLOSED CUSHIONS, GRADE IV, PRESTRESSED

Deflection	Mean Load	Strain	Stress	Strain Increment	Mean Stress	Energy	Total Energy
0.1	9	.05	.06	.05	.03	.0015	.0015
0.2	23	.10	.16	.05	.11	.0055	.0070
0.3	37	.15	.26	.05	.21	.0105	.0175
0.4	51	.20	.35	.05	.31	.0155	.0330
0.5	64	.25	.44	.05	.40	.0200	.0530
0.6	77	.30	.53	.05	.49	.0245	.0775
0.7	95	.35	.66	.05	.60	.0300	.1075
0.8	116	.40	.81	.05	.74	.0370	.1445
0.9	142	.45	.99	.05	.90	.0450	.1895
1.0	184	.50	1.28	.05	1.14	.0570	.2465
1.1	229	.55	1.59	.05	1.44	.0720	.3185
1.2	283	.60	1.97	.05	1.78	.0890	.4075
1.3	343	.65	2.38	.05	2.18	.1090	.5165
1.4	438	.70	3.04	.05	2.71	.1335	.6520
1.5	590	.75	4.10	.05	3.57	.1785	.8305
1.6	831	.80	5.77	.05	4.94	.2470	1.0775

TABLE 10
STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE IV, NOT PRESTRESSED

Deflection (inches)	Mean Load (pounds)	Strain (inches/inch)	Stress (psi)	Strain Increment (inches/inch)	Mean Stress (psi)	Energy (in-lbs/in^3)	Total Energy (in-lbs/in^3)
0.1	24	.05	.17	.05	.09	.0045	.0045
0.2	44	.10	.31	.05	.24	.0120	.0165
0.3	62	.15	.43	.05	.37	.0185	.0350
0.4	77	.20	.53	.05	.48	.0240	.0590
0.5	92	.25	.64	.05	.59	.0295	.0885
0.6	107	.30	.74	.05	.69	.0345	.1230
0.7	123	.35	.85	.05	.80	.0400	.1630
0.8	140	.40	.97	.05	.91	.0455	.2085
0.9	161	.45	1.12	.05	1.05	.0525	.2610
1.0	187	.50	1.30	.05	1.21	.0605	.3215
1.1	218	.55	1.51	.05	1.41	.0705	.3920
1.2	258	.60	1.79	.05	1.65	.0825	.4745
1.3	317	.65	2.20	.05	2.00	.1000	.5745
1.4	406	.70	2.82	.05	2.51	.1255	.7000
1.5	548	.75	3.81	.05	3.32	.1660	.8660
1.6	773	.80	5.37	.05	4.59	.2295	1.0955

TABLE 11

STATIC ENERGY ABSORPTION

ENCLOSED CUSHIONS, GRADE IV, NOT PRESTRESSED

Deflection	Mean Load	Strain	Stress	Strain Increment	Mean Stress	Energy	Total Energy
0.1	32	.05	.22	.05	.11	.0055	.0055
0.2	56	.10	.39	.05	.31	.0155	.0210
0.3	79	.15	.55	.05	.47	.0235	.0445
0.4	97	.20	.67	.05	.61	.0305	.0750
0.5	113	.25	.78	.05	.73	.0365	.1115
0.6	130	.30	.90	.05	.84	.0420	.1535
0.7	147	.35	1.02	.05	.96	.0480	.2015
0.8	167	.40	1.16	.05	1.09	.0545	.2560
0.9	189	.45	1.31	.05	1.24	.0620	.3180
1.0	219	.50	1.52	.05	1.42	.0710	.3890
1.1	256	.55	1.78	.05	1.65	.0825	.4715
1.2	310	.60	2.15	.05	1.97	.0985	.5700
1.3	379	.65	2.63	.05	2.39	.1195	.6895
1.4	483	.70	3.35	.05	2.98	.1490	.8385
1.5	646	.75	4.49	.05	3.92	.1960	1.0345
1.6	868	.80	6.03	.05	5.26	.2630	1.2975

TABLE 12

STATIC ENERGY ABSORPTION

FREE CUSHIONS, GRADE 8, PRESTRESSED

Deflection (inches)	Mean Load (pounds)	Strain (inches/inch)	Stress (psi)	Strain Increment (inches/inch)	Mean Stress (psi)	Energy (in-lbs/in3)	Total Energy (in-lbs/in3)
0.1	16	.05	.16	.05	.08	.0040	.0040
0.2	41	.10	.41	.05	.29	.0145	.0185
0.3	65	.15	.65	.05	.53	.0265	.0450
0.4	94	.20	.94	.05	.80	.0400	.0850
0.5	122	.25	1.22	.05	1.08	.0540	.1390
0.6	154	.30	1.54	.05	1.38	.0690	.2080
0.7	198	.35	1.98	.05	1.76	.0880	.2960
0.8	250	.40	2.50	.05	2.24	.1120	.4080
0.9	332	.45	3.32	.05	2.91	.1455	.5535
1.0	471	.50	4.71	.05	4.02	.2010	.7545
1.1	671	.55	6.71	.05	5.71	.2855	1.0400
1.2	928	.60	9.28	.05	8.00	.4000	1.4400
1.3	1328	.65	13.28	.05	11.28	.5640	2.0040
1.4	1888	.70	18.88	.05	16.08	.8040	2.8080

TABLE 13
STATIC ENERGY ABSORPTION
ENCLOSED CUSHIONS, GRADE 8, PRESTRESSED

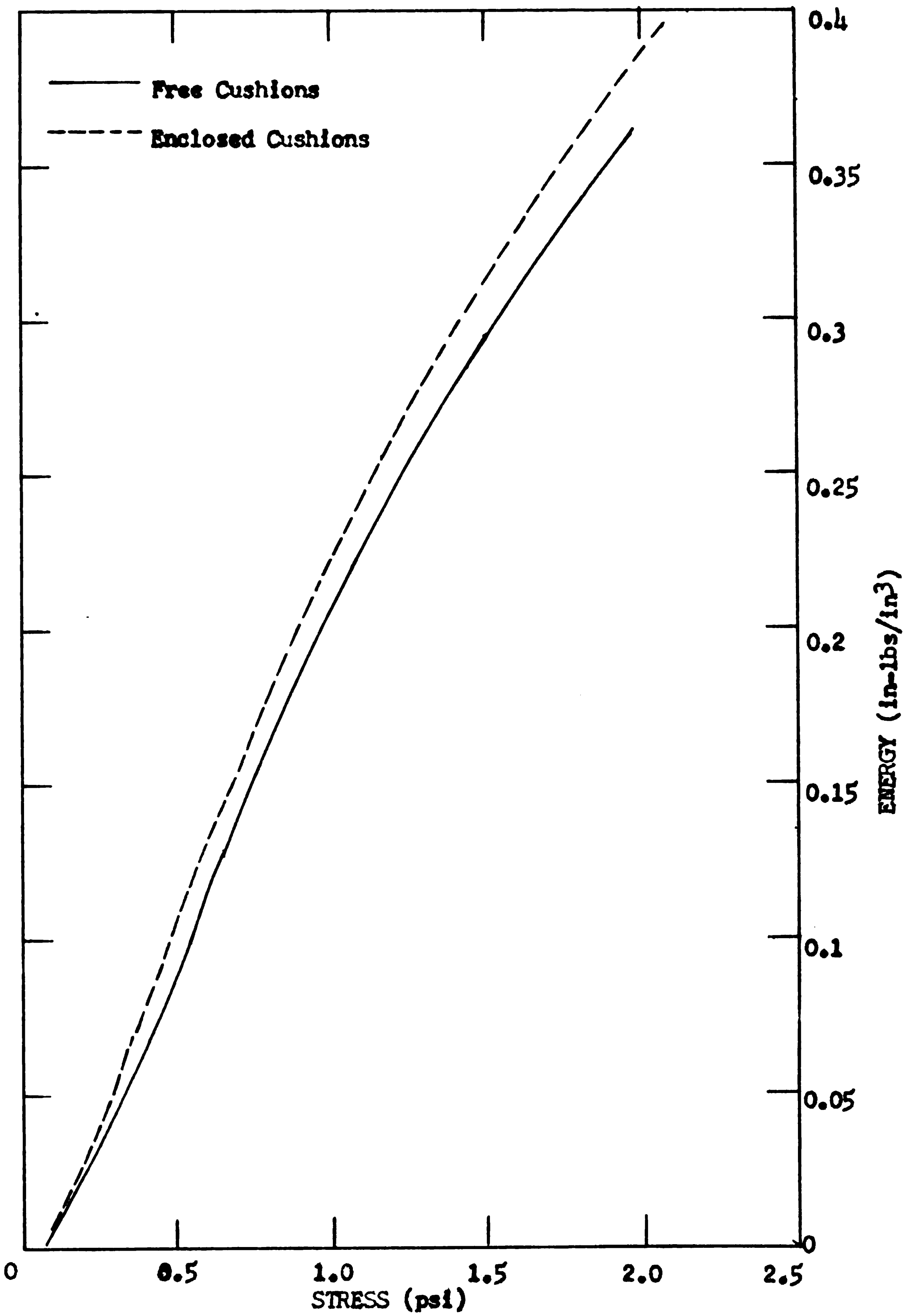
Deflection	Mean Load	Strain	Stress	Strain Increment	Mean Stress	Energy	Total Energy
0.1	28	.05	.28	.05	.14	.0070	.0070
0.2	69	.10	.69	.05	.49	.0245	.0315
0.3	111	.15	1.11	.05	.90	.0450	.0765
0.4	152	.20	1.52	.05	1.32	.0660	.1452
0.5	194	.25	1.94	.05	1.73	.0865	.2290
0.6	245	.30	2.45	.05	2.20	.1100	.3390
0.7	307	.35	3.07	.05	2.76	.1380	.4770
08	392	.40	3.92	.05	3.50	.1750	.6520
0.9	506	.45	5.06	.05	4.49	.2245	.8765
1.0	693	.50	6.93	.05	6. 00	.3000	1.1765
1.1	1012	.55	10.12	.05	8.53	.4265	1.6030
1.2	1379	.60	13.79	.05	11.96	.5980	2.2010
1.3	1757	.65	17.57	.05	15.68	.7840	2.9850

TABLE 14
STATIC ENERGY ABSORPTION
FREE CUSHIONS, GRADE 8, NOT PRESTRESSED

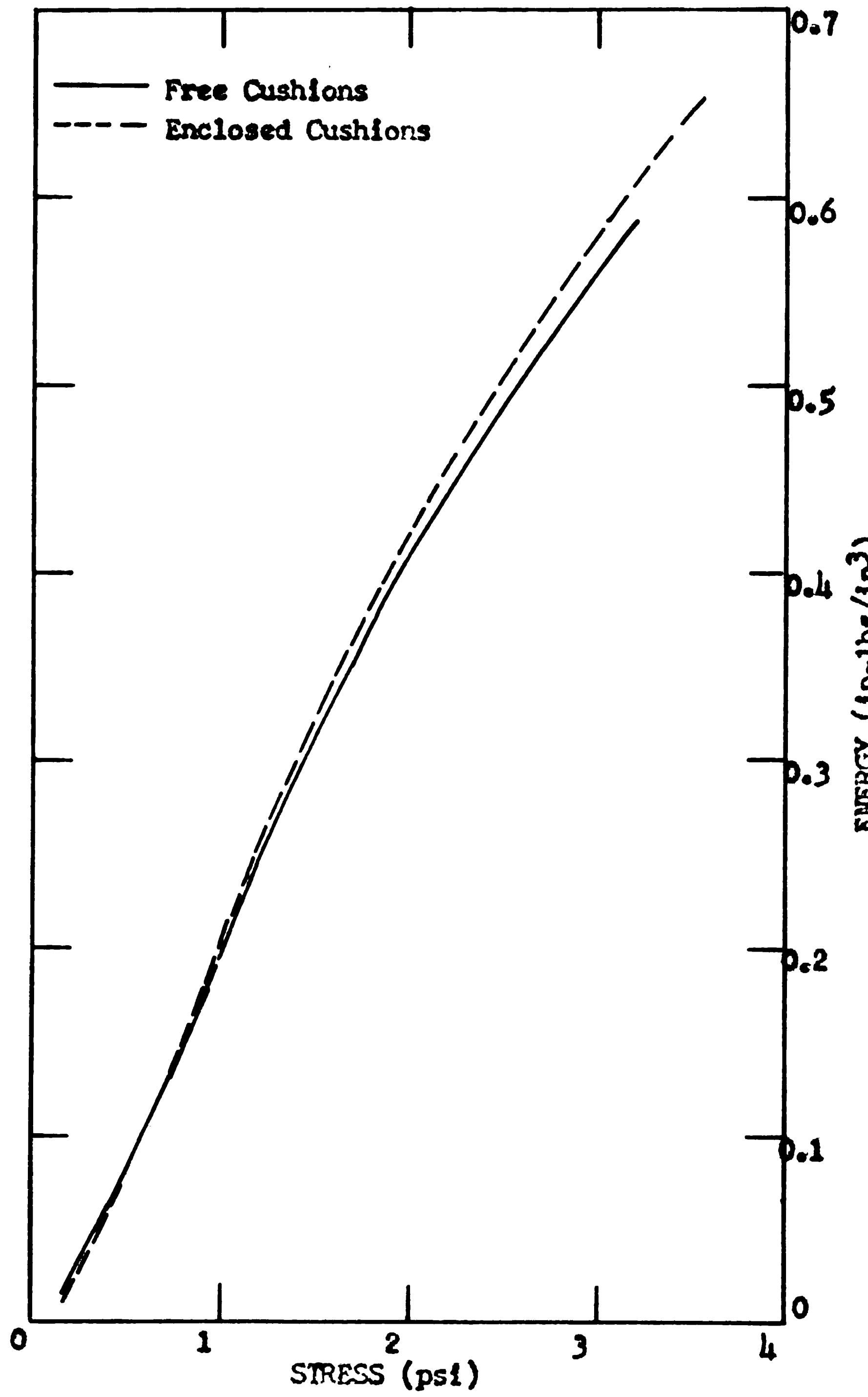
Deflection	Mean Load	Strain	Stress	Strain Increment	Mean Stress	Energy	Total Energy
0.1	60	.05	.60	.05	.30	.0150	.0150
0.2	107	.10	1.07	.05	.84	.0420	.0570
0.3	152	.15	1.52	.05	1.30	.0650	.1220
0.4	191	.20	1.91	.05	1.72	.0860	.2080
0.5	228	.25	2.28	.05	2.10	.1050	.3130
0.6	268	.30	2.68	.05	2.48	.1240	.4370
0.7	318	.35	3.18	.05	2.93	.1465	.5835
0.8	370	.40	3.70	.05	3.44	.1720	.7555
0.9	455	.45	4.55	.05	4.13	.2065	.9620
1.0	575	.50	5.75	.05	5.15	.2575	1.2195
1.1	740	.55	7.40	.05	6.58	.3290	1.5485
1.2	989	.60	9.89	.05	8.65	.4325	1.9810
1.3	1390	.65	13.90	.05	11.90	.5950	2.5760
1.4	1939	.70	19.39	.05	16.65	.8325	3.4085

TABLE 15
STATIC ENERGY ABSORPTION
ENCLOSED CUSHIONS, GRADE 8, NOT PRESTRESSED

Deflection (inches)	Mean Load (pounds)	Strain (inches/inch)	Stress (psi)	Strain Increment (inches/inch)	Mean Stress (psi)	Energy (in-lbs/in^3)	Total Energy (in-lbs/in^3)
0.1	77	.05	.77	.05	.39	.0195	.0195
0.2	129	.10	1.29	.05	1.03	.0515	.0710
0.3	178	.15	1.78	.05	1.54	.0770	.1480
0.4	224	.20	2.24	.05	2.01	.1005	.2485
0.5	267	.25	2.67	.05	2.46	.1230	.3715
0.6	315	.30	3.15	.05	2.91	.1455	.5170
0.7	375	.35	3.75	.05	3.45	.1725	.6895
0.8	450	.40	4.50	.05	4.13	.2065	.8960
0.9	548	.45	5.48	.05	4.99	.2495	1.1455
1.0	690	.50	6.90	.05	6.19	.3095	1.4550
1.1	890	.55	8.90	.05	7.90	.3950	1.8500
1.2	1175	.60	11.75	.05	10.33	.5165	2.3665
1.3	1550	.65	15.50	.05	13.63	.6815	3.0480
1.4	1974	.70	19.74	.05	17.62	.8810	3.9290

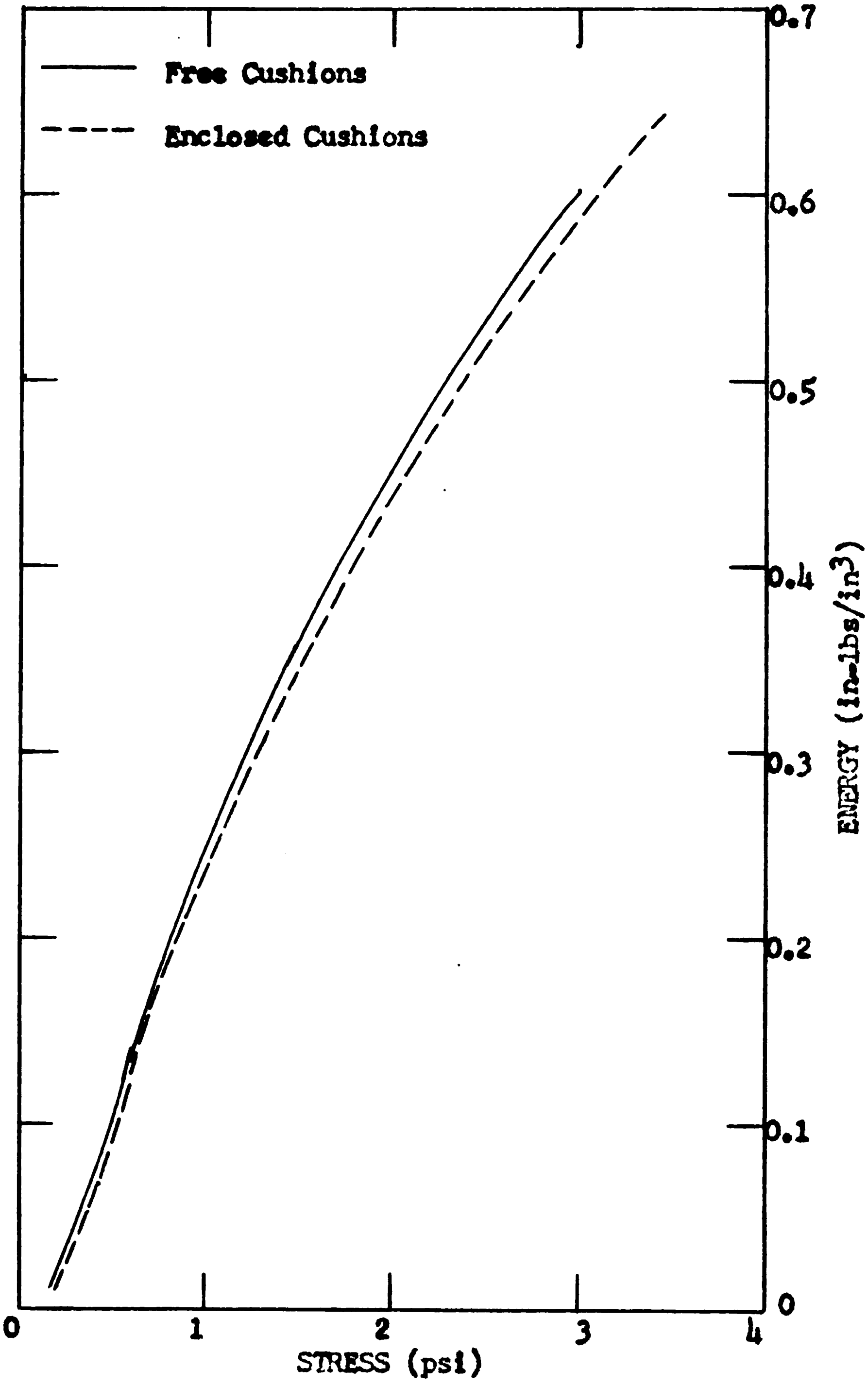


GRAPH 1
COMPARATIVE STRESS-ENERGY CURVES
GRADE II CUSHIONS, PRESTRESSED



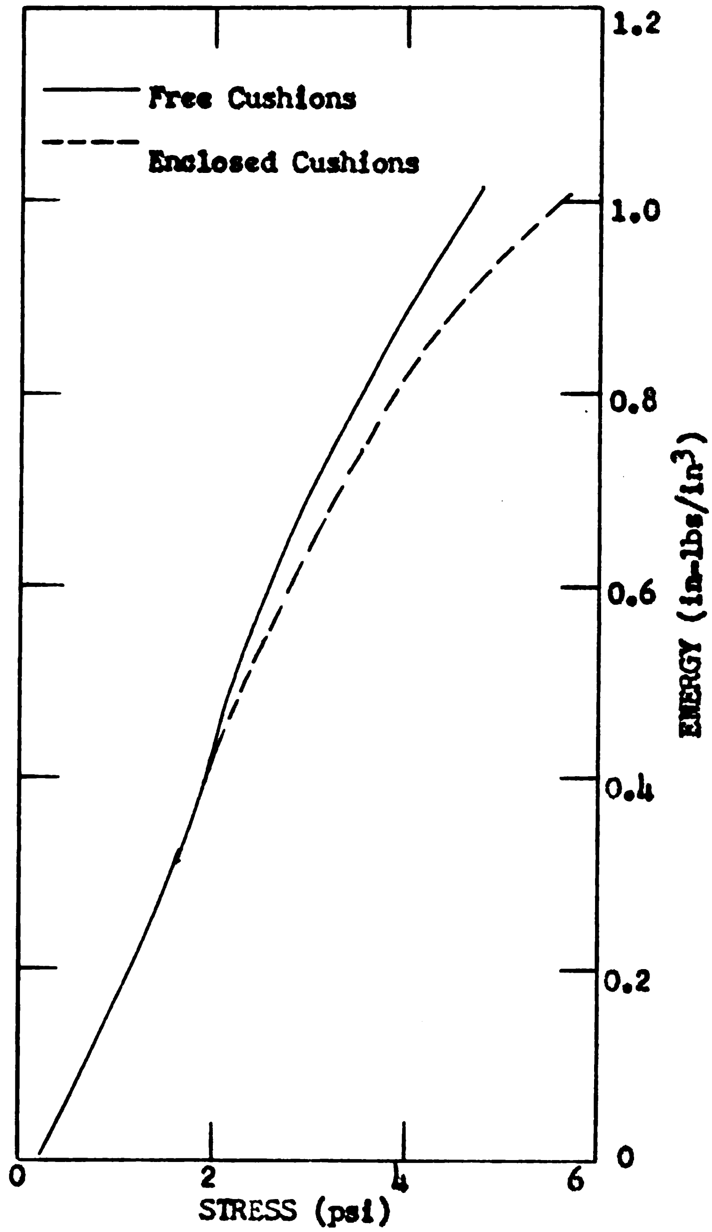
GRAPH 2

COMPARATIVE STRESS-ENERGY CURVES
GRADE III CUSHIONS, PRESTRESSED



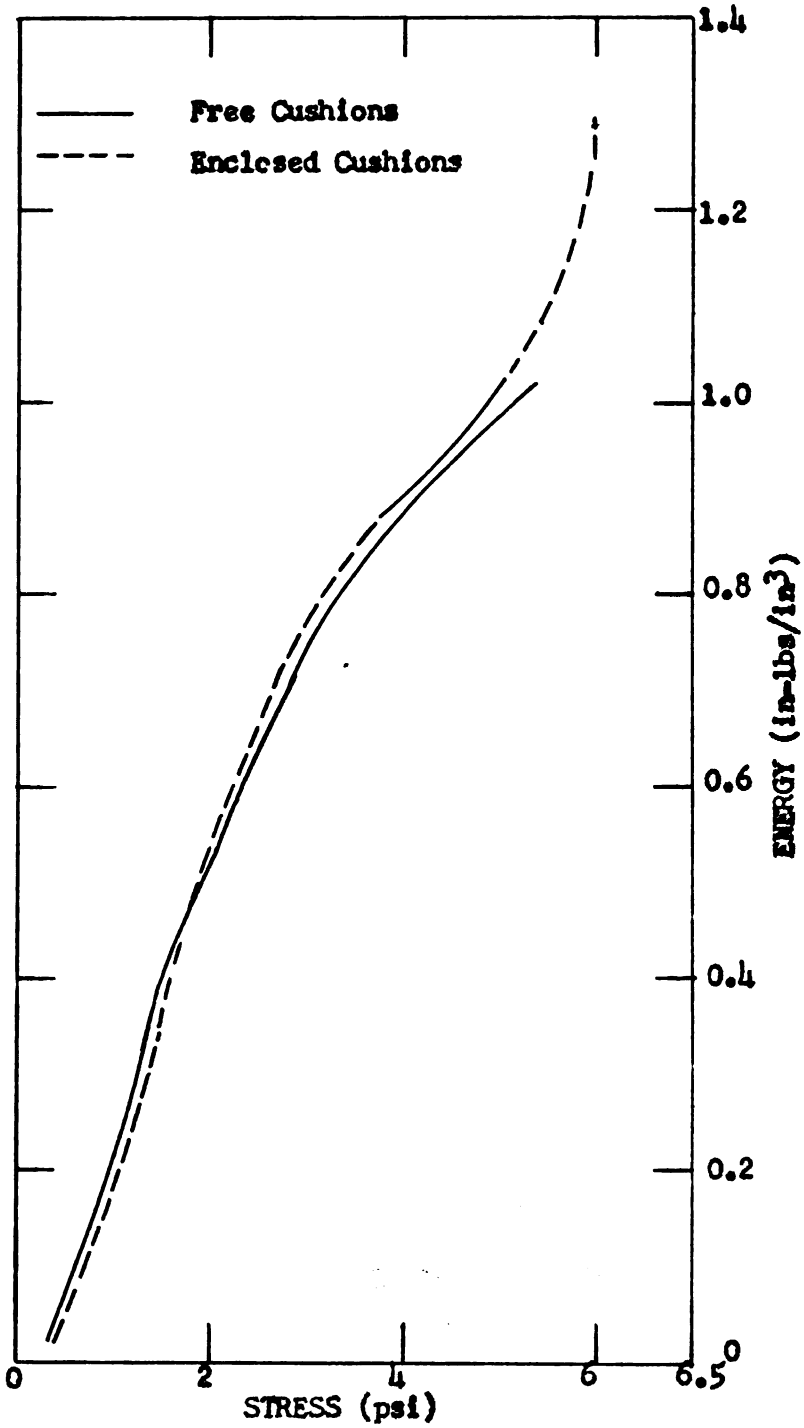
GRAPH 3

COMPARATIVE STRESS-ENERGY CURVES
GRADE III CUSHIONS, NOT PRESTRESSED



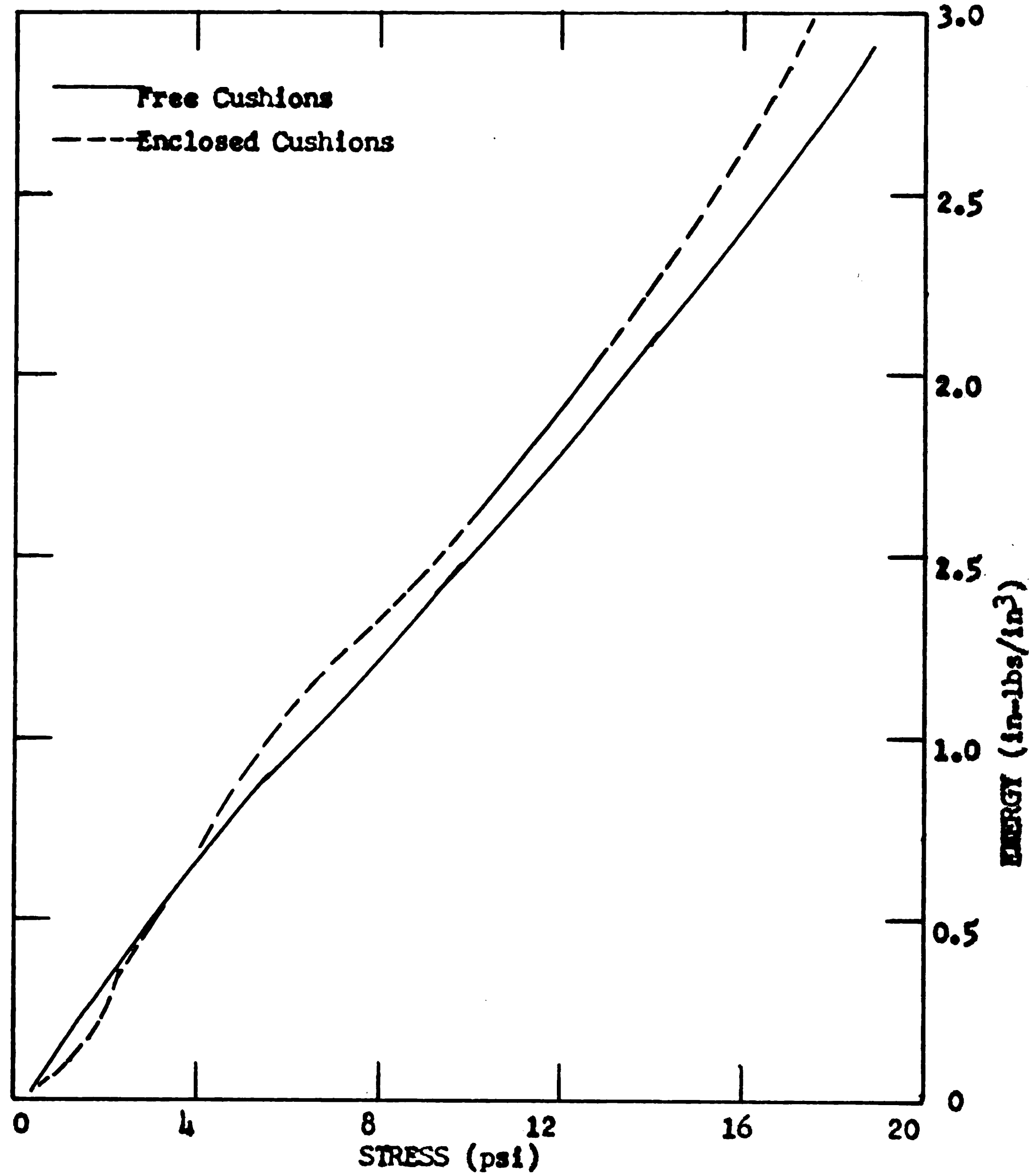
GRAPH 4

COMPARATIVE STRESS-ENERGY CURVES
GRADE IV CUSHIONS, PRESTRESSED



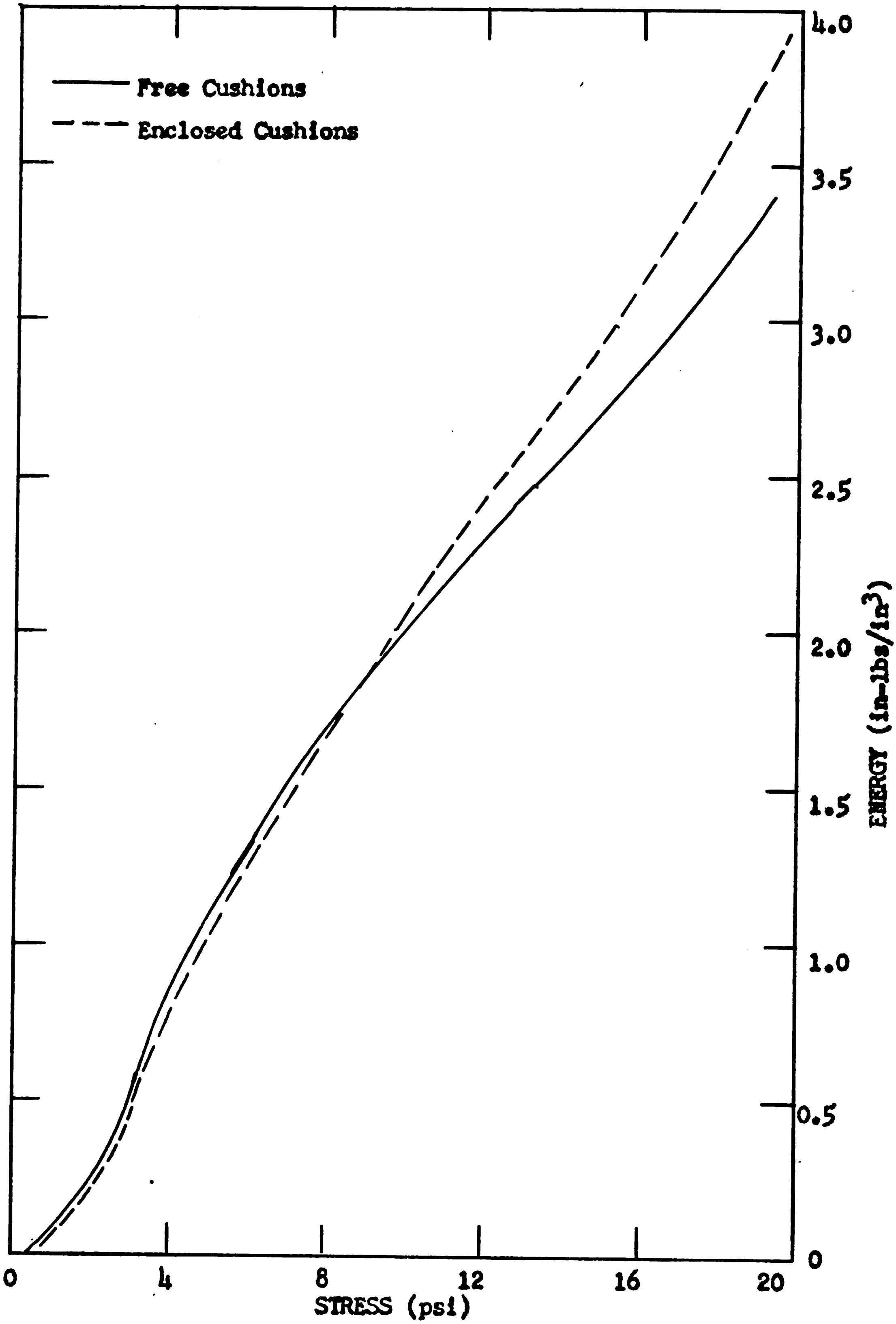
Graph 5

COMPARATIVE STRESS-ENERGY CURVES
GRADE IV CUSHIONS, NOT PRESTRESSED



Graph 6

COMPARATIVE STRESS-ENERGY CURVES
GRADE 8 CUSHIONS, PRESTRESSED



GRAPH 7
COMPARATIVE STRESS-ENERGY CURVES
GRADE 8 CUSHIONS, NOT PRESTRESSED

DYNAMIC TESTS

Dynamic shock tests to determine the force in G's absorbed by a cushion were run on the drop test apparatus in the Michigan State University Packaging Laboratory.

The drop unit consists of a foot-square platen operating vertically on two precision-ground supports. The platen is guided by super-precision frictionless sleeve bearing of the recirculating ball type. The system has negligible friction losses when a heavy platen is used. The maximum possible vertical travel is about 50 inches for the moving arm, and about 46 inches with the platen attached. The platen used had a depth of about three inches to permit entry into the solid enclosure.

The shock received by the platen on striking a cushion generates a current in a barium titanate crystal accelorometer. This current is amplified in a cathode follower amplifier, into an oscilloscope. The noise filter is necessary to remove signal static due to the movement of the bearings on the vertical shafts.

In use, the voltage calibrator is used to feed a signal equivalent to a known number of G's into the oscilloscope for calibration purposes. (see Appendix III). This signal can then be compared with the shock impulse to determine the shock strength.

An audio oscillator and a pulse former were used to superimpose a 500-cycle blanking signal on the accelerometer signal, permitting a determination of the duration of the shock. An electronic decade counter was used to measure the frequency of the blanking signal so that its accuracy could be maintained.

The oscilloscope trace was recorded photographically on a Polaroid oscillograph camera. To get a clear signal, a photoelectric cell was used to trigger a single sweep of the signal at the time of impact.

With the oscilloscope screen scale calibrated for a known number of G's per division, the shock signal strength is easily read from the photographs.

For the dynamic tests, a set of statically prestressed cushions were tested one by one under the platen falling from a measured height above the cushion. The platen was then reset to a new height and the series of drops repeated. Some comparative tests were made with cushions that had no prior working. The maximum shock readings resulting from these tests were averaged and recorded on the data sheets along with the platen weight, drop height, cushion thickness, and cushion area

The stress experienced by the cushion at maximum shock is computed from the relation $F = WG/A$, where F is the stress in pounds per square inch, W is the drop head weight in pounds, A is the platen area in square inches, and G is the maximum shock recorded on the oscilloscope.

The cushion factor is computed from the defining equation $C = TG/H$, where C is the cushion factor, which is dimensionless, T is the cushion thickness, G is the shock, and H the height of the drop onto the cushion. This relation is derived from the force-energy ratio of the impact to the thickness, i.e., $C = F/E \times T = WG/WH \times T = G/H \times T$.

Comparative graphs were made up plotting stress <u>vs.</u> cushion factor for each test condition. The minimum value of the cushion factor occurs at the stress where the cushion is most efficient. This can be seen by solving the cushion factor equation for T, where $T = HC/G$. The minimum thickness of cushion required in a given situation is thus proportional to the cushion factor. In practice, the stress can often be adjusted to the lowest cushion factor by changing the weight or surface area of the packaged article.

The curves do not reach a minimum value for the cushion factor within the stress range covered, when the cushions are enclosed. For the grade II and III cushions, the free cushions had a lower cushion factors throughout the stress range studied. This means that the use of free-cushion cushion factors for design purposes gives insufficient protection in this stress range.

The use of cushion factors derived from tests in enclosures requires thicker cushions to protect the article. The explanation for this is that the cushion is rendered considerably stiffer when air is trapped and the lateral deflection restricted, and the cushion therefore transmits a larger portion of the shock to the packaged article.

This is in agreement with the static tests, where the enclosed cushions absorbed more energy because it could not be dissipated in lateral Poisson-type deformation.

The tests with enclosed cushions also impart noticeably less rebound to the platen. This is a further indication that the cushion is absorbing a greater portion of the energy on the initial impact. This damping effect can be attributed to the fact that the cushion cannot deflect normally because of the trapped air.

There is more latitude for equipment and procedural errors in the dynamic tests than in the static tests. Calibration of the electronic circuits is a particularly exacting task. Care must be taken to assure that the platen strikes wholly inside the enclosure. On low-level drops, striking the walls of the enclosure would give an erroneous reading which might not be apparent.

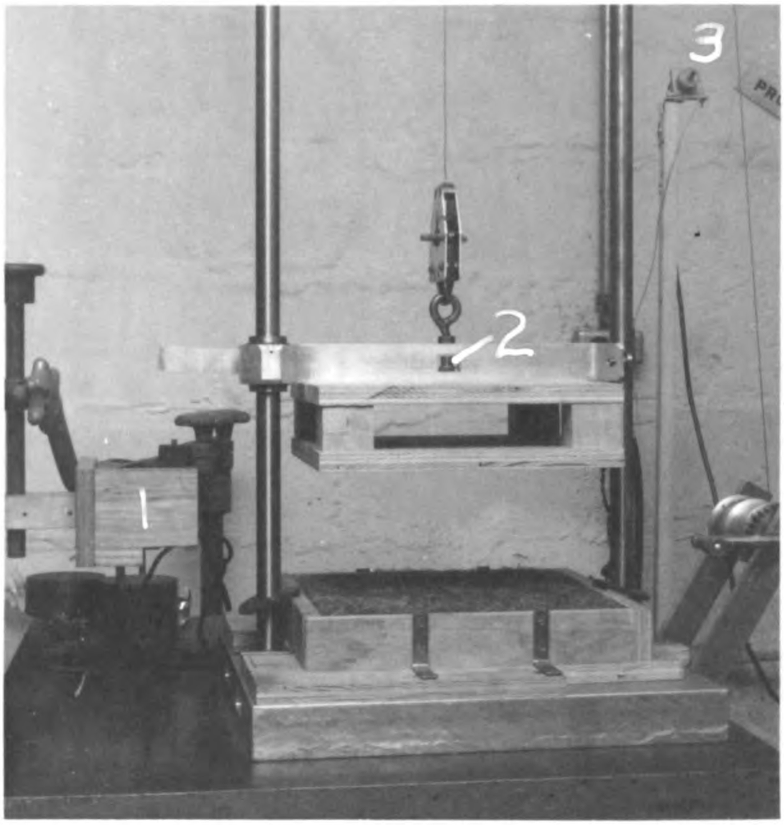


FIGURE 3

DYNAMIC DROP TESTER, SHOWING PHOTOCELL (1), ACCELEROMETER (2), AND CATHODE FOLLOWER AMPLIFIER (3). ENCLOSURE AND CUSHION ARE IN PLACE. DROP HEAD IS RAISED AND READY FOR RELEASE.


4
5
6

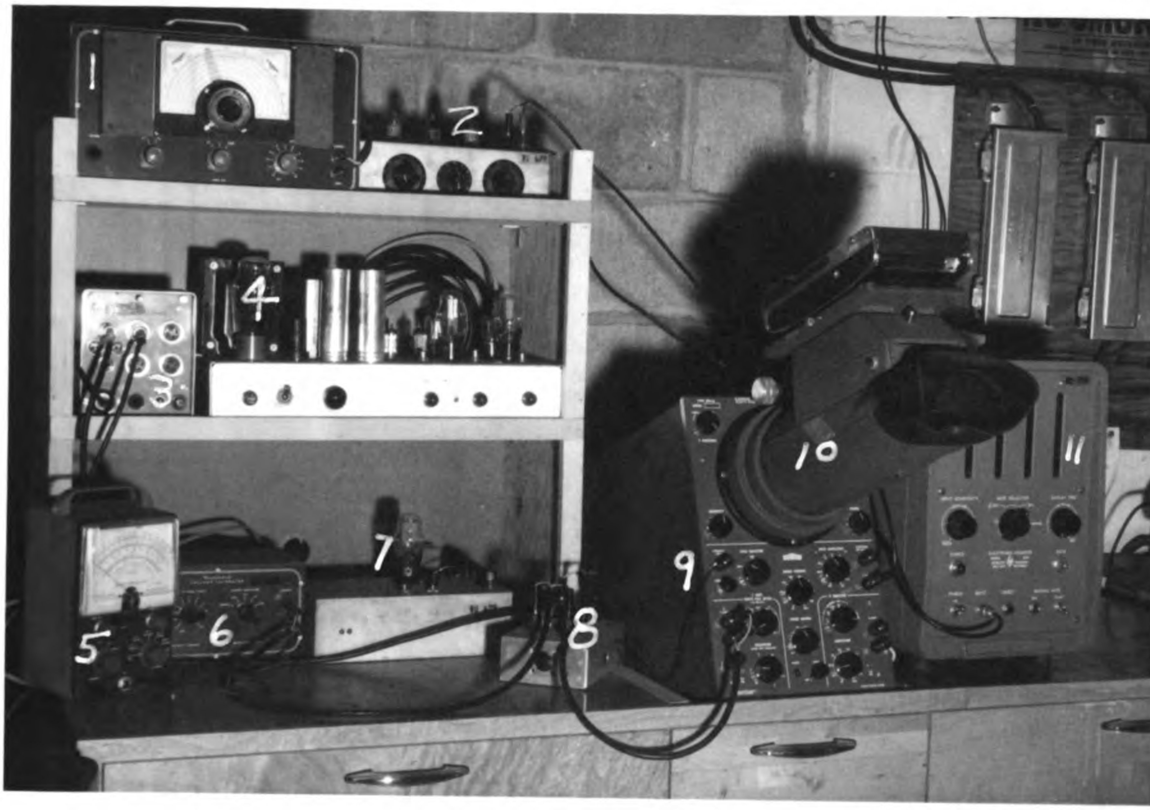


FIGURE 4

DYNAMIC TESTER INSTRUMENTATION, SHOWING OSCILLATOR (1), PULSE FORMER (2), CATHODE FOLLOWER POWER SUPPLY (3), ELECTRONIC SWITCH (NOT IN USE) (4), VACUUM TUBE VOLTMETER (5) VOLTAGE CALIBRATOR (6), SINGLE SWEEP TRIP (7), NOISE FILTER (8), OSCILLOSCOPE (9), POLAROID CAMERA ATTACHMENT (10), AND PULSE COUNTER (11). HOOKUP IS SHOWN IN FIGURE 5.

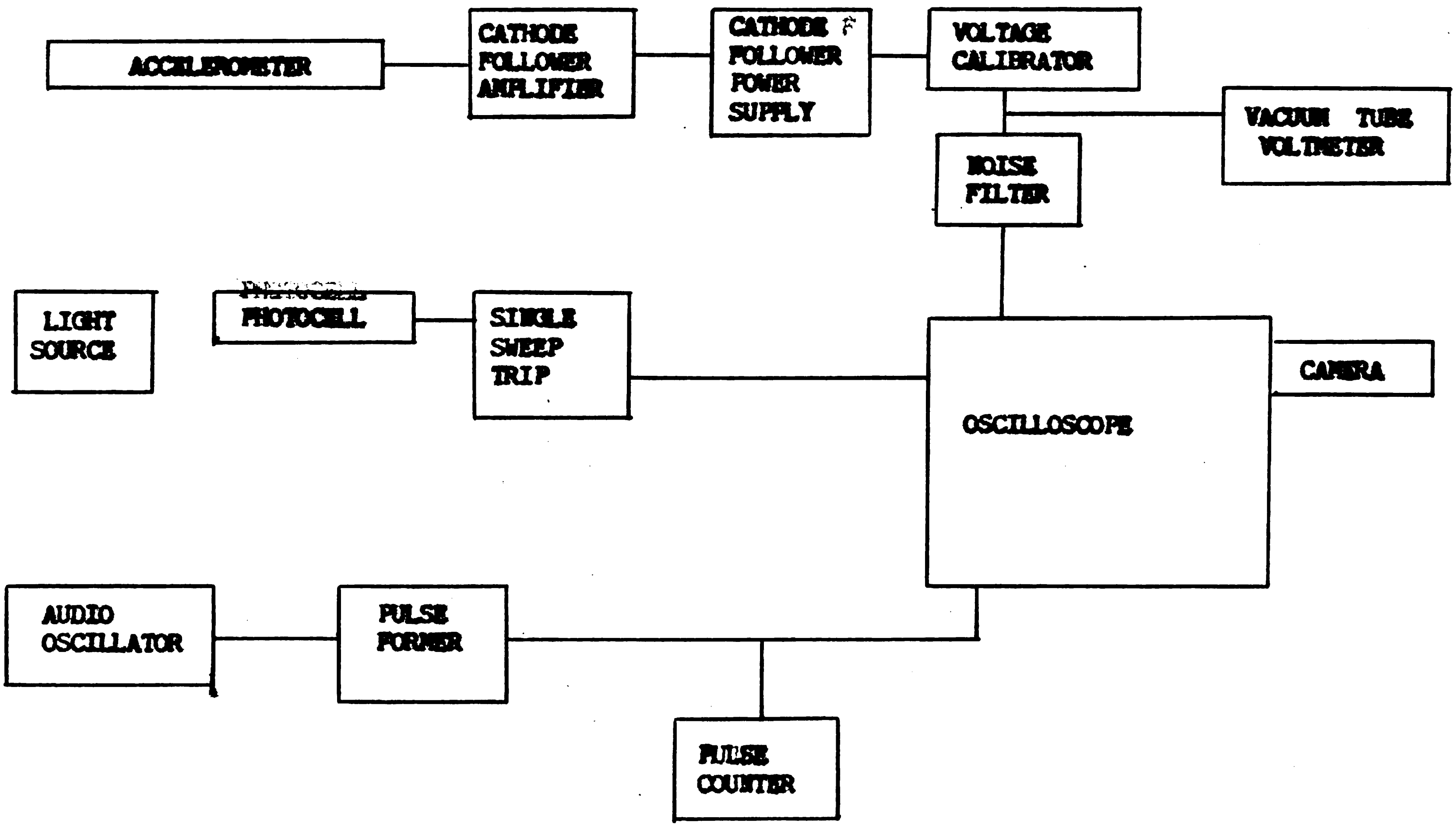


FIGURE 5

BLOCK DIAGRAM OF DYNAMIC TESTING CIRCUITS

18 G's

.026 sec.

19 G's

.024 sec.

FIGURE 6

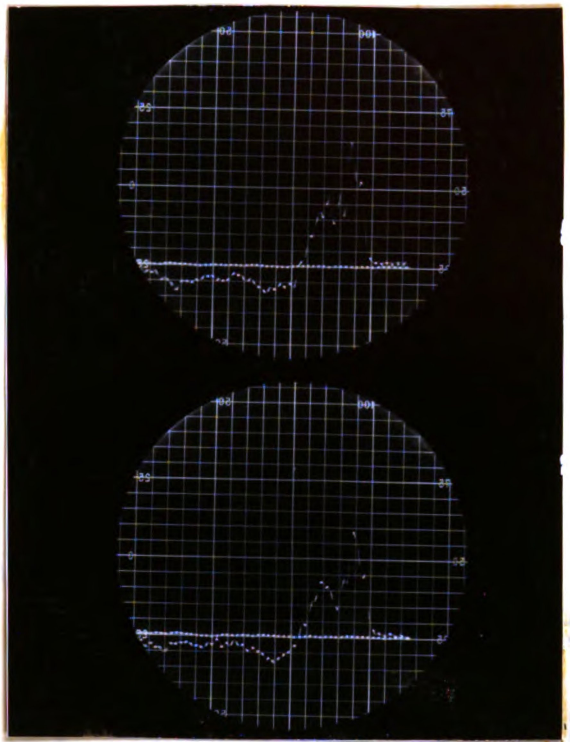
DYNAMIC TESTS

TYPICAL SHOCK WAVE PHOTOGRAPHS

HAIRFLEX GRADE IV

12" DROP

FREE CUSHION



16 G's

.028 sec.

14 G's

.028 sec.

FIGURE 7

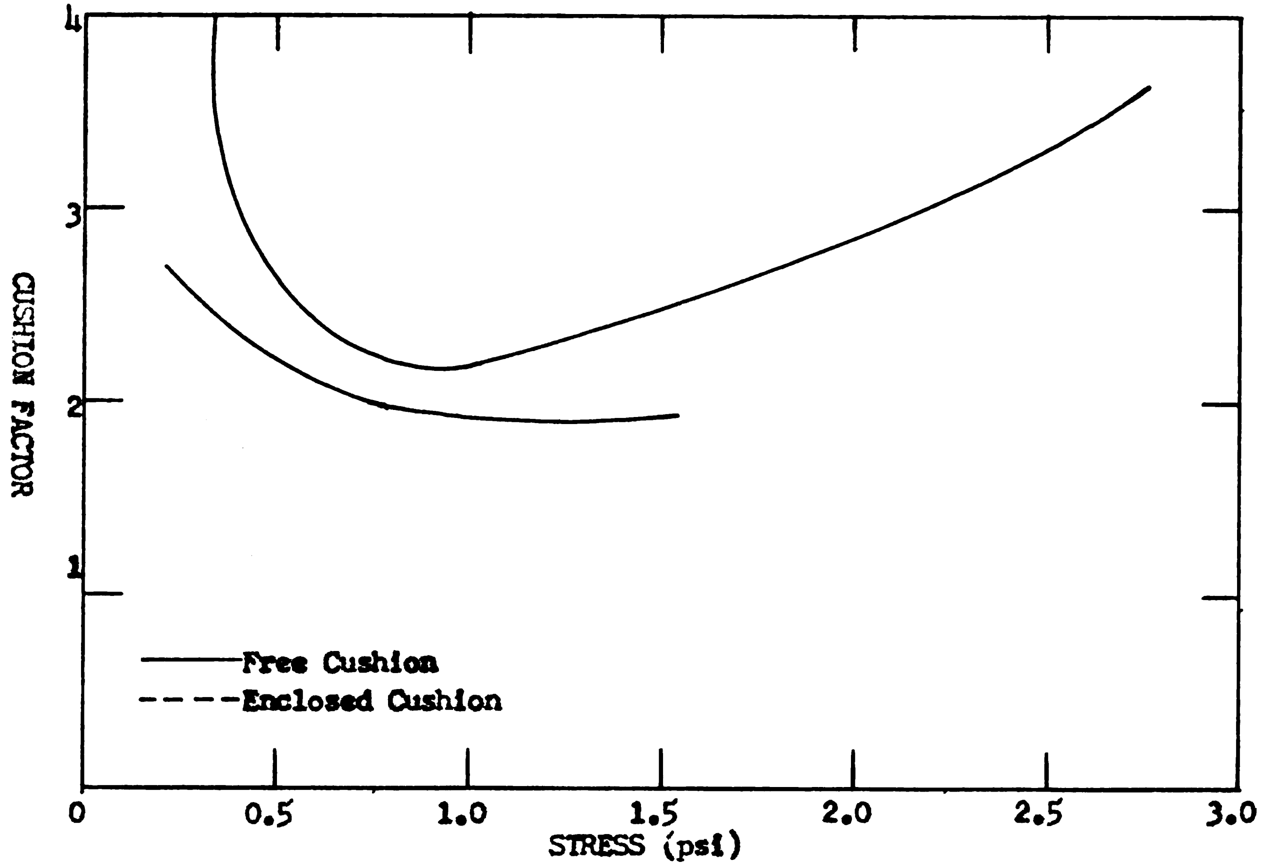
DYNAMIC TESTS

TYPICAL SHOCK WAVE PHOTOGRAPHS

HAIRFLEX GRADE IV

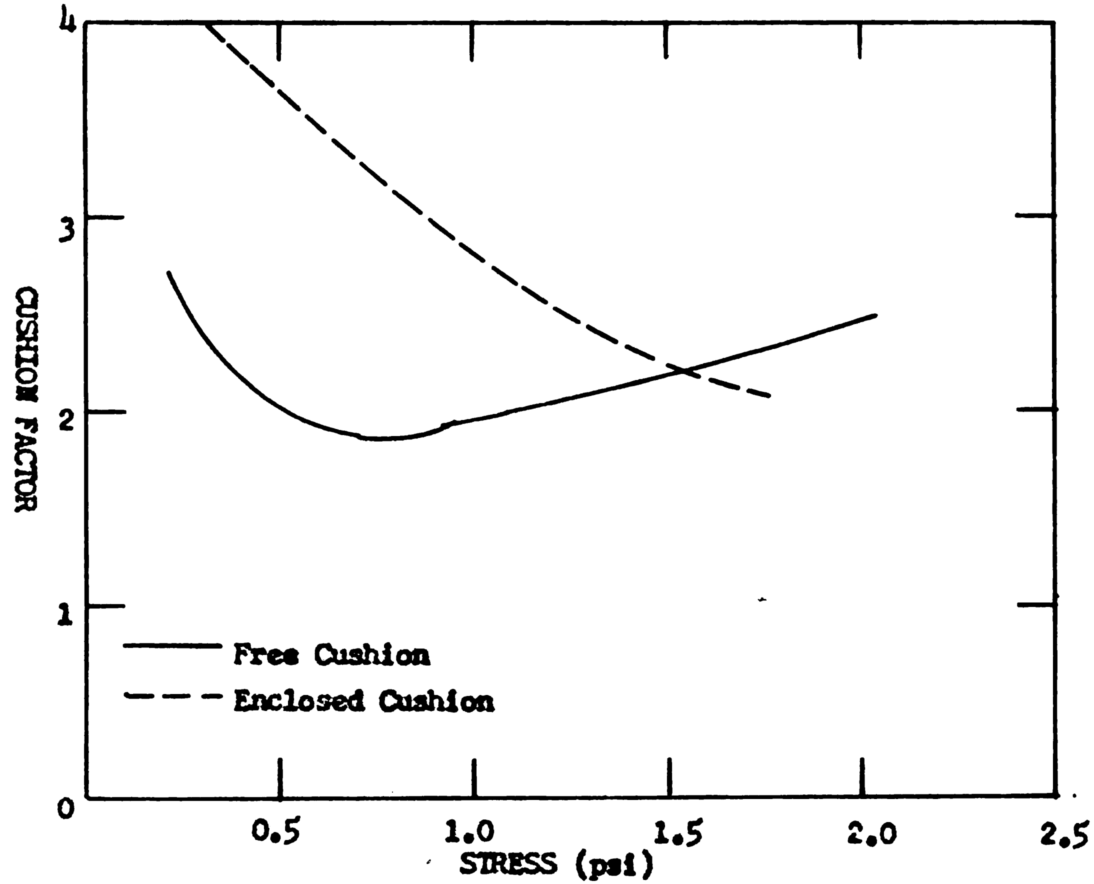
12" DROP

ENCLOSED CUSHION



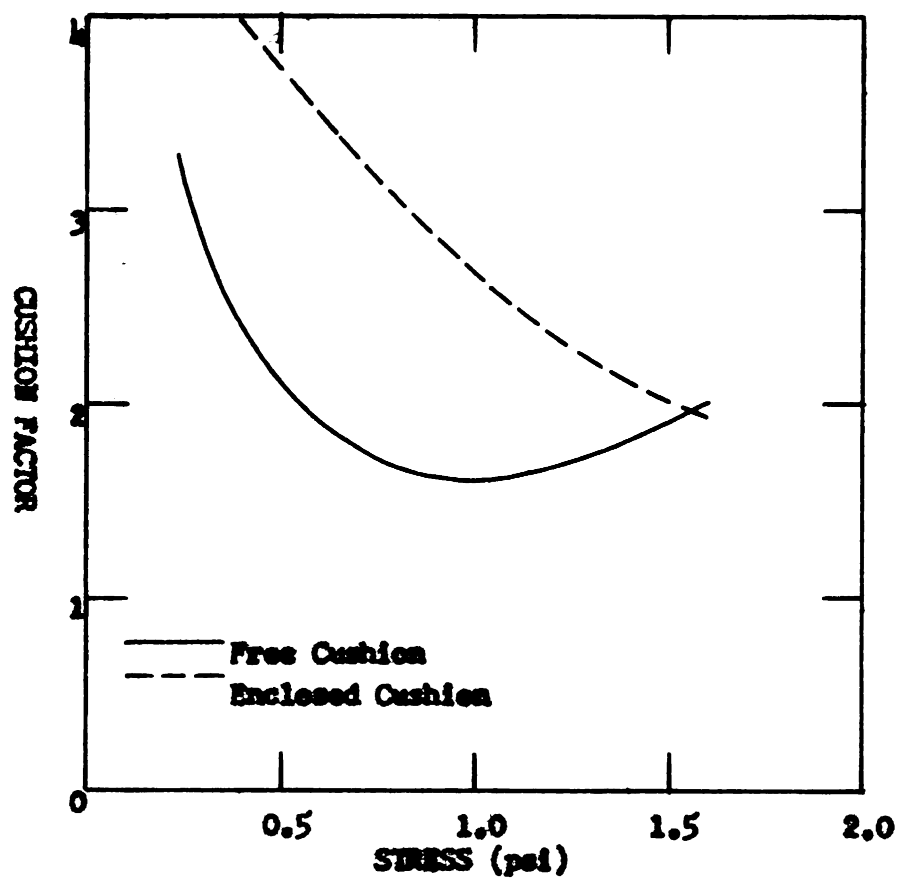
GRAPH 8

CUSHION FACTOR-STRESS CURVES
GRADE II CUSHIONS, PRESTRESSED



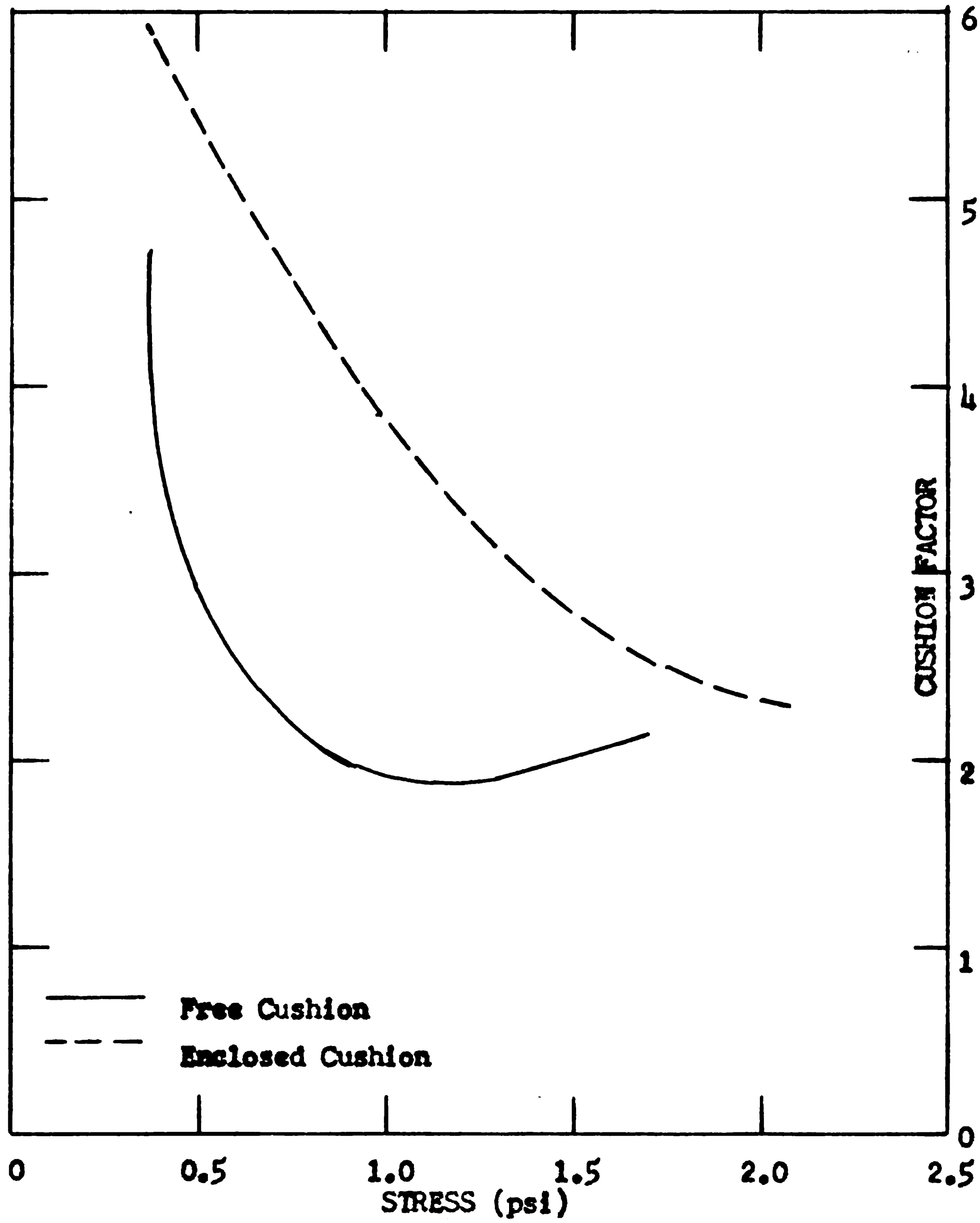
GRAPH 9

CUSHION FACTOR-STRESS CURVES
GRADE III CUSHIONS, PRESTRESSED

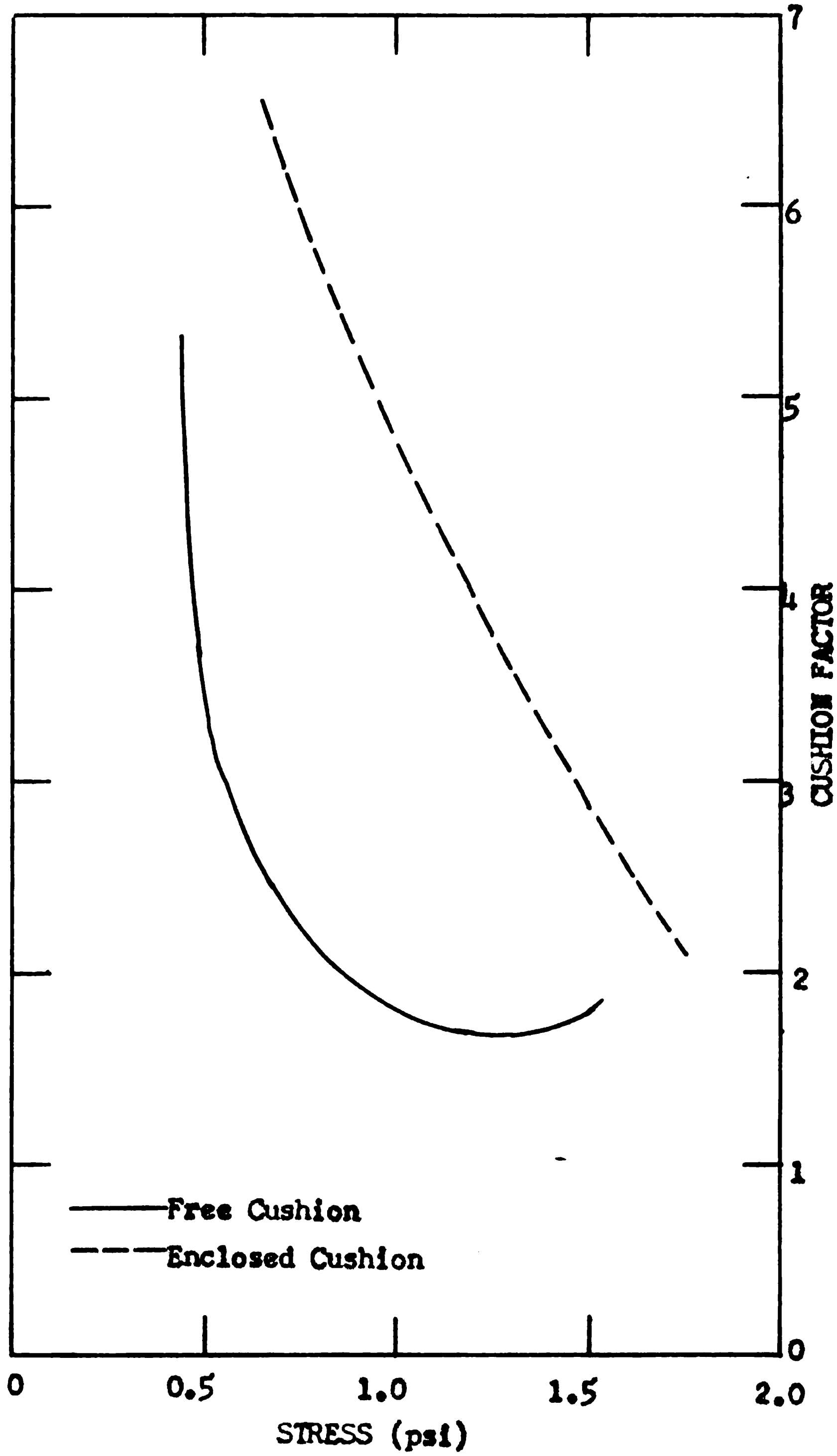


GRAPH 10

CUSHION FACTOR-STRESS CURVES
GRADE III CUSHIONS, NOT PRESTRESSED



GRAPH 11
CUSHION FACTOR-STRESS CURVES
GRADE IV CUSHIONS, PRESTRESSED



GRAPH 12
CUSHION FACTOR-STRESS CURVES
GRADE IV CUSHIONS, NOT PRESTRESSED

TABLE 16

STRESS—CUSHION FACTOR DATA

HAIRFLEX GRADE II

FREE CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	6	.33	4.0
6	7	.38	2.3
9	10	.55	2.2
12	14	.77	2.3
15	18	.93	2.4
18	21	1.15	2.3
21	27	1.48	2.6
24	33	1.80	2.8
27	40	2.19	3.0
30	51	2.79	3.4

TABLE 17

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE II

ENCLOSED CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	4	.22	2.7
6	7	.38	2.3
9	11	.60	2.4
12	12	.66	2.0
15	15	.82	2.0
18	18	.93	2.0
21	20	1.09	1.9
24	23	1.26	1.9
27	25	1.37	1.9
30	28	1.53	1.9

TABLE 18

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE III

FREE CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	4	.22	2.7
6	7	.38	2.3
9	9	.49	2.0
12	11	.60	1.8
15	15	.82	2.0
18	17	.93	1.9
21	21	1.15	2.0
24	26	1.42	2.2
27	31	1.70	2.3
30	37	2.02	2.5

TABLE 19

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE III

ENCLOSED CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	6	.33	4.0
6	11	.60	3.7
9	13	.71	2.9
12	19	1.04	3.2
15	20	1.09	2.7
18	23	1.26	2.6
21	25	1.37	2.4
24	27	1.48	2.3
27	30	1.64	2.2
30	32	1.75	2.1

TABLE 20

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE III

FREE CUSHION, NOT PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	5	.27	3.3
6	7	.38	2.3
9	9	.49	2.0
12	10	.55	1.7
15	13	.71	1.7
18	15	.82	1.7
21	18	.93	1.7
24	20	1.09	1.7
27	26	1.42	1.9
30	29	1.59	1.9

TABLE 21

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE III

ENCLOSED CUSHION, NOT PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	6	.33	4.0
6	10	.55	3.3
9	14	.77	3.2
12	18	.98	3.0
15	21	1.15	2.8
18	22	1.20	2.4
21	25	1.37	2.4
24	27	1.48	2.3
27	29	1.59	2.1
30	29	1.59	1.9

TABLE 22

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE IV

FREE CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	7	.38	4.7
6	8	.44	2.7
9	10	.55	2.2
12	13	.71	2.2
15	16	.88	2.1
18	19	1.04	2.1
21	22	1.20	2.1
24	24	1.31	2.0
27	28	1.53	2.1
30	31	1.70	2.1

TABLE 23

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE IV

ENCLOSED CUSHION, PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	9	.49	6.0
6	13	.71	4.3
9	17	.93	3.8
12	20	1.09	3.3
15	24	1.31	3.2
18	26	1.42	2.9
21	30	1.64	2.9
24	33	1.80	2.8
27	33	1.80	2.4
30	38	2.08	2.5

TABLE 24

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE IV

FREE CUSHIONS, NOT PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	8	.44	5.3
6	11	.60	3.6
9	14	.77	3.1
12	14	.77	2.3
15	16	.88	2.1
18	19	1.04	2.1
21	1[illegible]	.93	1.7
24	1[illegible]	1.20	1.8
27	2[illegible]	1.15	1.6
30	[illegible]	1.42	1.7

TABLE 25

STRESS-CUSHION FACTOR DATA

HAIRFLEX GRADE IV

ENCLOSED CUSHION, NOT PRESTRESSED

Cushion Thickness 2"

Drop Head Weight 7 lbs. 14 oz.

DROP HEIGHT	AVERAGE MAXIMUM	STRESS (lbs/in^2)	CUSHION FACTOR
3	10	.55	6.7
6	15	.82	5.0
9	22	1.20	4.9
12	20	1.09	3.3
15	26	1.42	3.5
18	28	1.53	3.1
21	29	1.59	2.8
24	31	1.70	2.6
27	30	1.64	2.2
30	32	1.75	2.1

GENERAL CONCLUSIONS

Both static and dynamic tests have established that there is a significant increase in the effective stiffness of a cushion when it is enclosed. This increase must be considered when designing protective packages.

The energy absorbed by a cushion increases when the lateral expansion of the cushion is restrained. Under static loading conditions, such as warehouse stacking, a cushion would be able to support a greater load than normal design figures would indicate, but would also transmit a greater load to the cushioned article, possibly causing damage.

Use of conventional cushion-factor curves for cushion design may give insufficient protection. This will be particularly true when a cushion is tightly fitted into the container. This probably goes unnoticed in many cases because a "safety factor" is added to the design thickness. This is a trial-and-error technique, and is certainly not to be recommended as a general practice.

The flexibility of the walls of the container and the freedom of the cushion within the container may govern the degree of protection in some instances.

RECOMMENDATIONS

On the basis of the information gathered in this study, several recommendations can be made for cushion design factor determination tests.

Both static and dynamic design-factor tests for packaging use should be made with enclosed cushions in order to obtain results which more closely approximate actual conditions.

Packages for cushioned articles should be designed loosely to permit some expansion of the cushion under stresses.

If the nature of the product is not prohibitive, cushioned packages should be vented to reduce the amount of air trapped in the cushion when a stress is applied. If packages cannot be vented, then the impact area of the cushioned article should be less than the cushion area, to permit air transfer within the package. This last will require a compromise design between maximizing the article area to reduce stress and allowint air-movement space.

The use of cushion factors as design elements should be reconsidered. The factors as currently determined are remote from what they should be and re-determination with enclosures will not produce a curve having a minimum, except possibly at relatively high stresses.

SUGGESTIONS FOR FURTHER STUDIES

To gain a more thorough understanding of the energy absorption properties of enclosed cushions, the following suggestions are offered. These ideas have not been investigated sufficiently to establish their merit, and are offered without any recommendations as to sequence or validity.

The effects of friction between the cushion and container walls might be studied by methods similar to those of this study, using enclosure materials of varying smoothness and cushions of several surface densities.

Measurement of horizontal forces due to cushion compression would help in determining the required strength of the outer continer.

The proportion of absorption increase due to lateral deflection might be studied by use of an open-sided enclosure that permits air to escape while restraining the cushion. Some efforts in this direction were made during the current project, but the vented enclosure constructed was unsuccessful.

Studies should be made to determine the relationship between normal cushion factors and cushion behavior under actual conditions, with the intention of finding a new factor to replace the cushion factor. Such a factor should be determinate under various test conditions and applicable to a wide range of applications.

LIST OF REFERENCES

(1) Keith W. Kellicutt, Application of the Properties of Cushioning Materials in the Design of Cushions, Report No. 1627, Forest Products Laboratory, Madison, Wisconsin, reissued 1955.

(2) R. E. Jones and W. L. James, Simplified Method of Selecting and Designing Package Cushioning Materials, Report No. 2031, Forest Products Laboratory, Madison, Wisconsin, 1955.

(3) R. R. Jansson, Selecting Package Cushioning Materials to Provide Minimum Container Cubage, North American Aviation Corporation, Los Angeles, California, October, 1952.

(4) H. M. Hatae, "A Dynamic Cushion Tester--Its application to Cushion Design", Joint Industry Conference on Cushioning in Packing, Wayne University, December 1953.

(5) R. E. Jones and W. L. James, "Calculating Cushion Requisites", Modern Packaging, February, 1956.

APPENDIX I

ENERGY CALCULATIONS FOR STATIC TESTS

The absorbed energy for statically-loaded cushions was computed as follows:

Column 1 The deflection in increments of 0.1 inch.

Column 2 The mean load at each deflection point, from the recorder chart.

Column 3 Strain is computed by dividing the deflection by the original thickness.

Column 4 Stress is the mean load divided by the cushion area.

Column 5 The strain increment $\Delta\epsilon$ is the strain change over each increment, taken from the strain data in column 3.

Column 6 The mean stress per increment is calculated by adding the stresses at the beginning and end of each increment and dividing the sum by two.

Column 7 The energy increment is represented by the area under the increment, and is the product of the strain increment and the mean stress in the increment.

Column 8 The summation of the energies is the sum of the energies in the increments to the point under consideration. The last figure in this column is the total energy absorbed in the compression test.

APPENDIX II

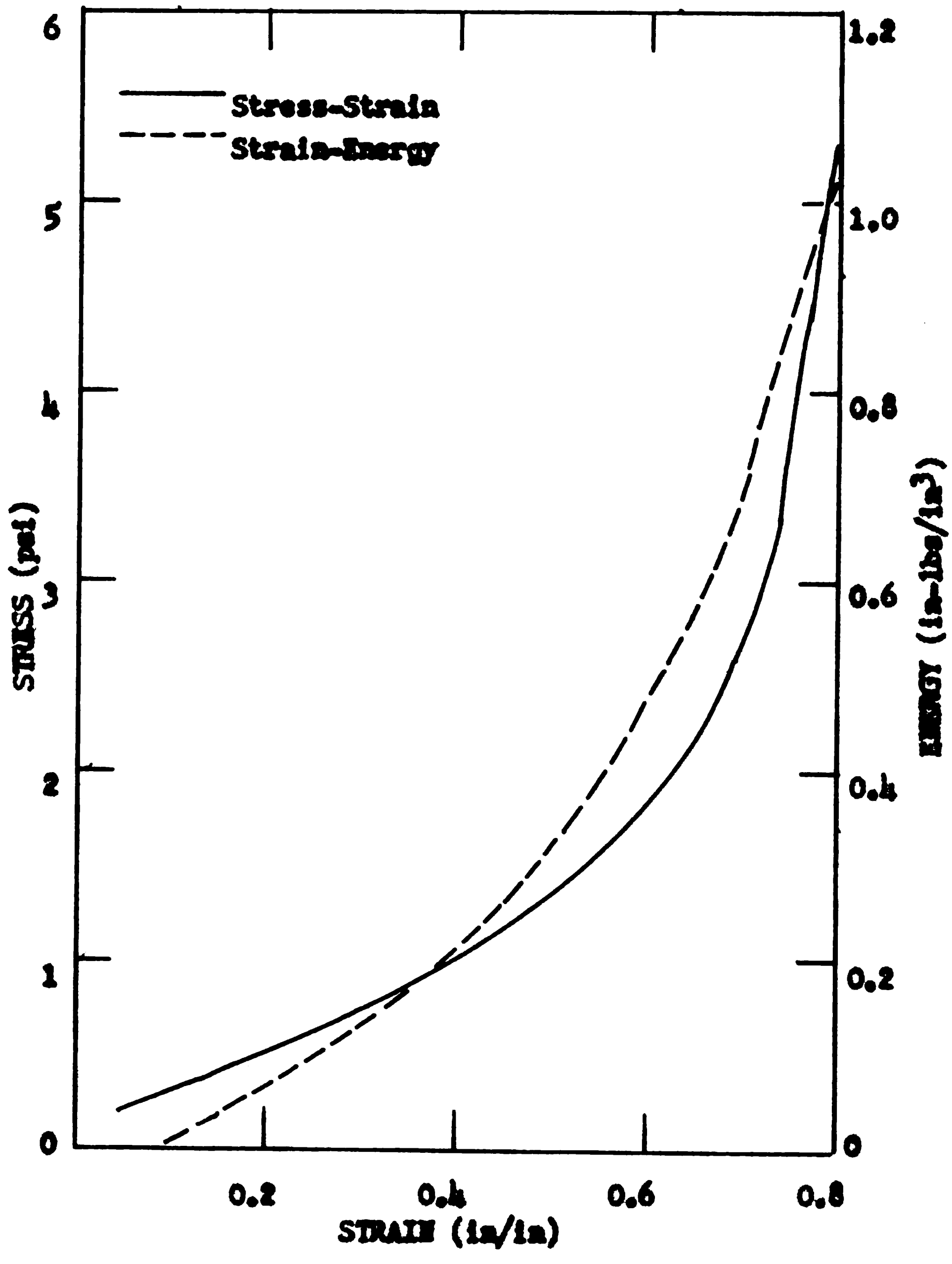
USE OF STATIC ENERGY ABSORPTION DATA FOR CUSHION DESIGN

Stress-energy or stress-strain and strain-energy can readily be used to determine the energy which will be absorbed by a cushion for a given stress.

As an example, consider the case of an object with a flat surface area of 120 square inches and a weight of 5.0 pounds. It is desired to protect the object against shocks up to 60 G's. From the formula $F = WG/A$, the stress is found to be 2.5 pounds per square inch.

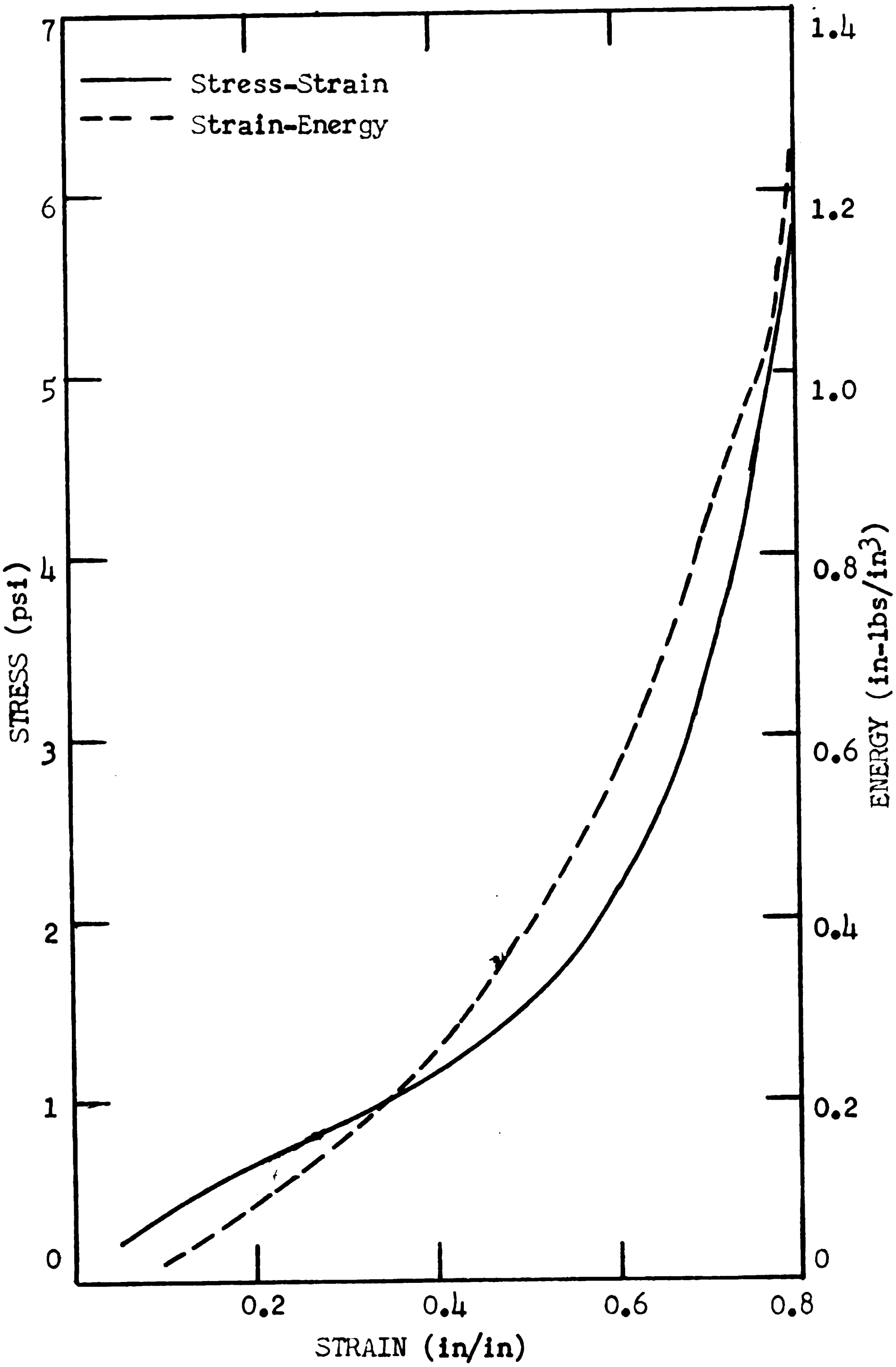
Using graph 13, for free grade IV cushions, the strain corresponding to a stress of 2.5 p.s.i. is 0.68 in/in. The energy absorbed at this strain is 0.64 inch-pounds per cubic inch. This is the energy the cushion will absorb in protecting the packaged object at the maximum shock of 60 G's.

For an identical cushion enclosed in the package, the strain corresponding to a stress of 2.5 p.s.i. is 0.64 in/in (graph 14), and the energy which is absorbed is 0.66 inch-pounds per cubic inch. This indicates that the enclosed cushion absorbs 3% more energy or that it transmits that much more energy to the article it is expected to protect.



GRAPH 13

STRESS-STRAIN AND STRAIN-ENERGY CURVES
GRADE IV FREE CUSHIONS, NOT PRESTRESSED



STRESS-STRAIN AND STRAIN-ENERGY CURVES
GRADE IV ENCLOSED CUSHIONS, NOT PRESTRESSED

GRAPH 14

APPENDIX III

CUSHION DESIGN WITH CUSHION FACTOR CURVES

The use of cushion factors for design of cushions is a valuable technique, since cushion factor-stress curves may be made up for the various materials and filed for handy reference. To illustrate the use of cushion factors, consider the following hypothetical situation:

An object weighing 9.0 pounds and having an impact area of 300 square inches is to be protected from shocks over 20 G's at drop heights up to 40 inches. Determination of the thickness of Type III cushions, using the usual free cushion design curve, is accomplished easily. The stress is WG/A = 9 x 20/225 = 0.80 p.s.i. The cushion factor corresponding to this stress is 1.87 (Graph 9). The necessary cushion thickness T is then T = CH/G = 1.87 x 40/20 = 3.74 inches.

However, for an enclosed cushion, Graph 9 also gives a cushion factor of 3.13 as the cushion factor for a stress of 0.80 p.s.i. This requires a thickness of T = CH/G = 3.13 x 40/20 = 6.26 inches. This indicates that about 67% more cushioning is needed than might be indicated by the usual method.

APPENDIX IV

CALIBRATION OF DYNAMIC SHOCK-MEASURING APPARATUS

EQUIPMENT SPECIFICATIONS:

Accelerometer output -- 8.6 mv/G r.m.s.

Accelerometer output -- 8.6 x 1.414 = 12.16 mv/G peak-to-peak

Cathode follower amplification factor -- 0.94

Noise filter amplification factor -- 0.70

Input to oscilloscope -- 12.16 x 0.9 x 0.70 = 8.00 mv/G peak-to-peak

Input to oscilloscope: 5.67 mv/G r.m.s.

CALIBRATION:

Calibration was accomplished by feeding a signal equivalent to 10 G's (56.6 mv r.m.s.) into the oscilloscope. The y-axis scale was adjusted to make the 10 G signal fit five scale divisions (1"), so that the calibration was 1/5" = 2G's. This calibration was used for a majority of the drop tests, but some tests had to be made using scales of 1/5" = 4 or 5G's to get the full signal on the screen.

APPENDIX V

PROPOSED IMPROVEMENTS IN DYNAMIC TEST INSTRUMENTATION

The dynamic tester used in this study is destined for the addition of a circuit to determine the velocity of the platen near the point of impact.

The addition consists of an electronic switch which controls the counting time of the decade counter. The photocell box will be modified to use two cells. When the platen falls, an arm will actuate the two photocells in sequence. The decade counter will receive a sine wave signal, and the number of cycles elapsing during the time when the platen arm trips the first and second photocells will determine the elapsed time. This time and the distance between the two photocell slits can be used to determine the platen velocity.

The switch must also actuate the sweep trigger of the oscilloscope, and a contact is provided for this purpose.

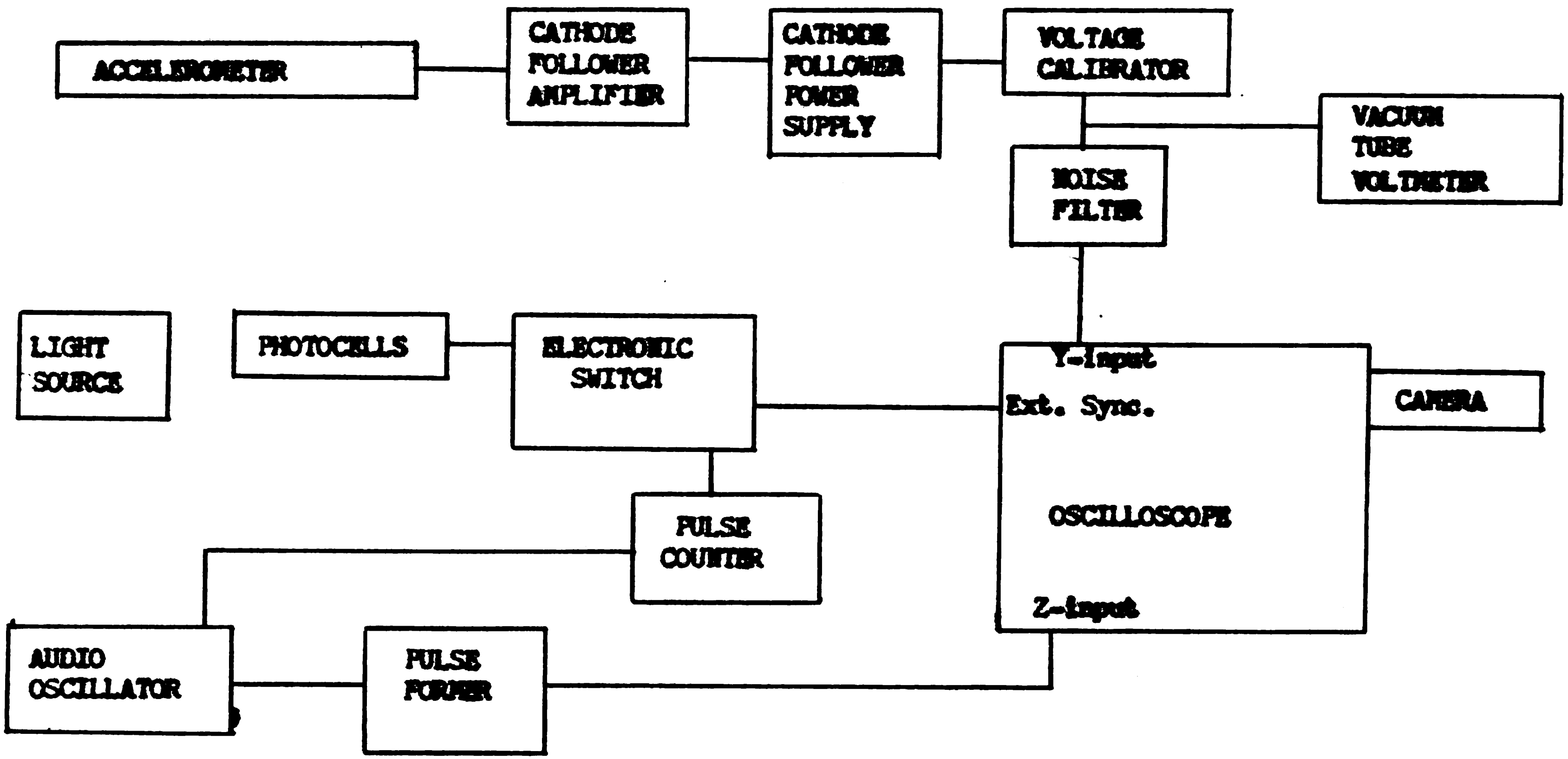


FIGURE 8

BLOCK DIAGRAM OF PROPOSED MODIFICATIONS

APPENDIX VI

ADDITIONAL SELECTED READINGS ON CUSHIONING AND SHOCK ABSORPTION

1. C. E. Crede Vibration and Shock Isolation, John Wiley and Sons, New York, 1951.

2. J. L. Gretz "Engineering a Cushioned Package", Modern Packaging, May 1953.

3. R. E. Jones, "Demonstration of Basic Principles of Package Cushioning", Joint Industry Conference on Cushioning in Packing, Wayne University, December, 1955.

4. M. Mosel, "A Mathematical Approach to Cushioning", Modern Packaging, May 1953.

5. R. D. Mindlin, "Dynamics of Package Cushioning, Bell System Technical Journal, Monograph B 1369, October, 1945.

6. A. M. Underhill, "What Makes Cushioning Work", Modern Materials Handling, November, 1955.