EFFECT OF ATMOSPHERIC MOISTURE CONTENT UPON SHOCK CUSHIONING PROPERTIES OF CORRUGATED FIBERBOARD PADS

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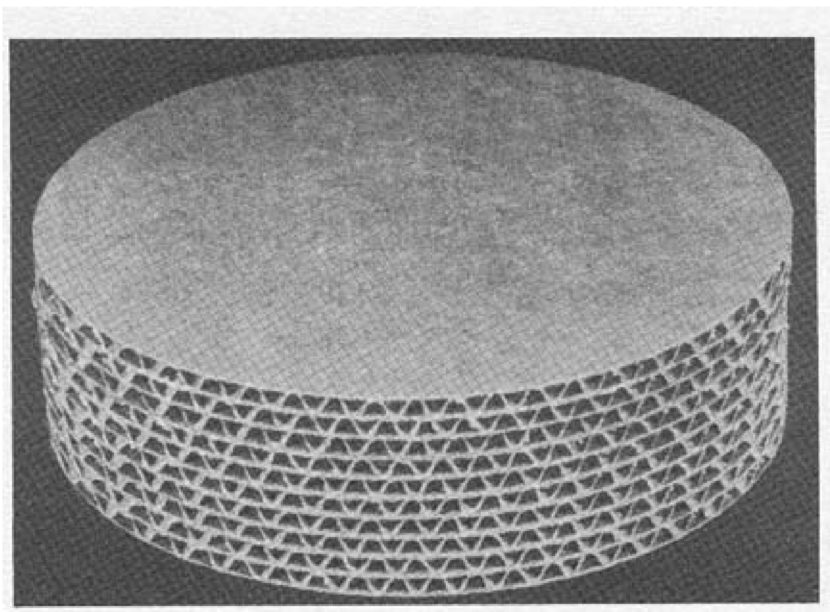

U.S. DEPARTMENT OF AGRICULTURE * FOREST SERVICE
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ABSTRACT

The shock absorption capability of untreated corrugated fiberboard pads changes very little with atmospheric moisture content increases up to those encountered at 80° F. and 65 percent relative humidity; pads tested at 80° F. and 90 percent relative humidity showed appreciable softening. In this study to determine the relationship between moisture content and shock absorption performance, pad moisture content was controlled by exposure to various temperatures and relative humidities. Impact test data were computed and analyzed as peak acceleration-static stress (G_m -W/A) shock isolation curves. The results also show the magnitude and nature of variation of individual specimens.

EFFECT OF ATMOSPHERIC MOISTURE CONTENT UPON SHOCK CUSHIONING PROPERTIES OF CORRUGATED FIBERBOARD PADS

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INTRODUCTION

Being hygroscopic, untreated fiberboard quickly changes moisture content, with the change dependent on temperature and relative humidity of the surrounding atmosphere. Treatment of the fiberboard or its components with waxes, resins, or plastic laminates retards, but does not stop, water vapor exchange with the atmosphere. In selecting the proper corrugated fiberboard pads to protect fragile items from shock and vibration during shipment, the package designer must insure that the pads will perform satisfactorily over the expected range of conditions. Because most packages are not vaporproof, he must consider a wide range of atmospheric conditions, such as those included in this study.

The shock absorption behavior was determined on materials that represent the range of corrugated fiberboard pad thicknesses commonly used by American industry as determined from an estimate by the Technical Committee of the Fibre Box Association.

This report is the fourth in a series dealing with the shock cushioning characteristics of corrugated fiberboard pads. The first report (6)[3] defined (a) the cushioning capability of one- to five-layer, A-flute pads under a single loading cycle and (b) a new data computation and analysis method that reduced the amount of experimental data required; the second (11) described the shock isolation features of similar B- and C-flute pads under single loading; and the third (12) described the response under repeated loading of one- to five-layer, A- and B-flute pads.

In the packaging field, shock isolation curves for the peak acceleration-static stress relationship (G_m-W/A curves) are a common form of shock reduction design curves currently being used (3,15). Accordingly, the shock reduction qualities of corrugated fiberboard pads as affected by moisture content are reported here as G_m-W/A design curves.

Shocks received by fragile items in packages are composite forms including the performance of the cushions and "container effects." The latter are caused by deformation of the outer container, the amount of void air space within the container and other factors described in (5) and (15). Container effects sometimes change the basic pad cushioning values significantly. Therefore, overall shock and vibration performance of packages must eventually be considered in the design of the total package. However, the shock absorption properties of the pads alone, as reported here, serve as a good begin-

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[1] The author gratefully acknowledges the technical contributions of W. D. Godshall, Engineer, and J. W. Koning, Forest Products Technologist.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3] Underlined numbers in parentheses refer to Literature Cited at the end of this report.

ning in designing the cushioning systems for packages by involving fewer and more tangible variables. Additionally. this approach provides data usable for material specifications and procurement on a performance basis, such as required by military specifications (16).

MATERIAL

Pad material was double-faced, single-wall, A-flute corrugated fiberboard. The fiberboard components were bonded with starch adhesive.

Linerboard.--Linerhoards were manufactured from 100 percent kraft pulp, consisting of approximately 90 percent southern pine and 10 percent mixed sweetgum and oak. Linerboard basis weights were 40.7 and 40.9 pounds per 1,000 square feet and average thicknesses were 0.115 and 0.117 inch.

Corrugating medium. - - Corrugating medium was manufactured from approximately 90 percent semichemical pulp (aspen and birch) and 10 percent kraft pulp (95 percent southern pine and 5 percent Douglas-fir). Basis weight was 26.5 pounds per 1,000 square feet and average thickness was 0.009 inch.

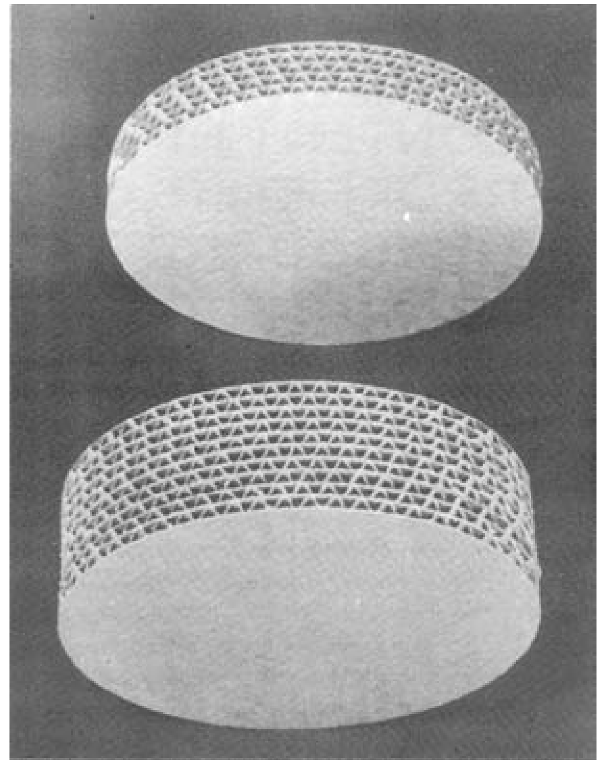

Figure 1.--Cushions included in this study: five- and ten-layer, A-flute, freely ventilated pads. (M 136 310)

TEST SPECIMENS

As in earlier related studies (6,11,12), individual sheets of fiberboard were selected at intervals throughout the lot of material. Next, the sheets were cut into blanks and numbered consecutively. These in turn were randomly selected, cut into 6.75-inch diameter disks, and glued into five- and ten-layer pads. During assembly, the flutes in the various layers were alined parallel to each other, but not superimposed except by chance. Sodium silicate (water glass) was used to glue the blanks together, and a pressure of 1.0 pound per square inch (p.s.i.) was applied continuously during drying. Typical five- and ten-layer pads are shown in figure 1. All pads had open, freely ventilated ends.

Because a random sample of pads, drawn from the same lot of material, was evaluated in this work and that reported in (6, 11, 12), progressive bias was eliminated and pad performance could be compared directly between studies. Pad performance variation. though probably larger by this technique, was offset by the use of a large sample size.

CONDITIONING

Specimens were preconditioned for 1 week in an atmosphere drier than that used for final conditioning. This was followed by exposure for 5 weeks to the desired conditioning atmosphere. The schedules are given in table 1.

The preconditioning in drier atmospheres was done so that all of the pads would approach equilibrium moisture content from the drier condition. This reduced variation resulting from hysteresis in moisture equilization (4, 9, 10, 13, 14).

Specimen Transfer

The specimens being equilibrated with 73° F., 50 percent relative humidity were conditioned in the same room as the dynamic compression testing system, and therefore underwent no change in moisture content because of transfer before testing. However, because the testing system could not be moved, the other test specimens were conditioned in separate chambers and then transferred to the 73° F., 50 percent relative

Table 1.--Conditioning schedules used to prepare specimens for testing

Preconditioning--1 week			Conditioning--5 weeks		
Temperature	Relative humidity	EMC[1]	Temperature	Relative humidity	EMC[1]
°F.	Pct.	Pct.	°F.	Pct.	Pct.
90	20	4.1	80	30	5.0
80	30	5.0	73	50	7.5
80	30	5.0	80	65	10.5
80	30	5.0	80	90	20.0

[1] The equilibrium moisture content of double-faced, single-wall fiberboard bonded with starch adhesive at the corresponding condition.

humidity room for dynamic compression testing. To measure the quantitative change in shock absorption ability of the pads with absorbed moisture content it was necessary to minimize the time outside the conditioning chamber. Therefore, two pads at a time were placed inside a 2-mil polyethylene bag inside an insulated corrugated fiberboard box (fig. 2,A). The top of the bag was wound and clamped as shown in figure 2,B. The box was then closed and transferred to the 73° F., 50 percent relative humidity room. The transfer was made in 5 minutes or less. Immediately after their removal from the transfer container in the 73° F., 50 percent relative humidity room the specimens were tested. A maximum time of 1.3 minutes was required to remove the pads from the transfer package and test them. Pad moisture content changes due to transfer ranged from a loss of 0.30 percent moisture content for specimens equilibrated with 80° F., 90 percent relative humidity to no change in moisture content for those conditioned in the 80° F., 30 percent relative humidity room

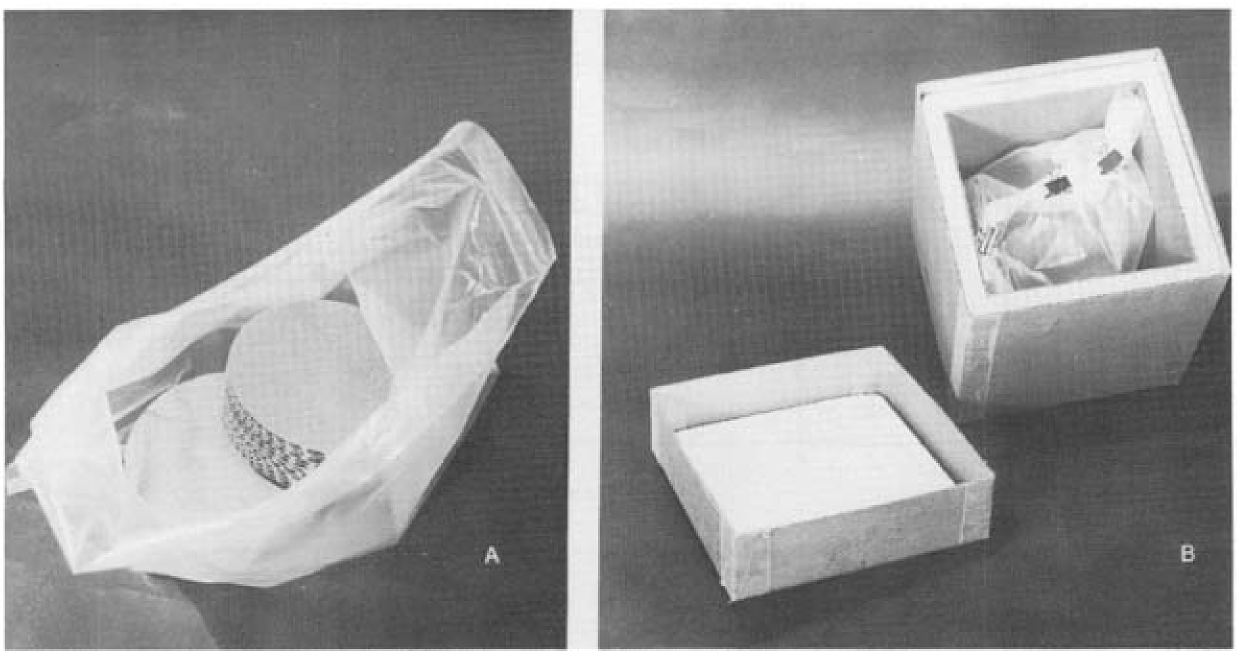

Figure 2.--Packaging technique for transfer of pads. A, Pads in open polyethylene bag; B, closed bag inside insulated container. (M 136 335)

Moisture Content at Impact

Conditioning produced specimens at equilibrium with the various atmospheres, as shown in figure 3. Initially, moisture content of the pads rose sharply. The change then gradually became asymptotic with certain equilibrium moisture content (EMC) values. It is noteworthy that these sodium silicate-bonded pads at high atmospheric humidity reached EMC at considerably higher moisture content than is ordinarily expected of the fiberboard components alone (table 1).

DYNAMIC COMPRESSION TESTS

Each pad was impact tested, using the FPL pendulum-impact cushion test apparatus. Basically, a single test consisted of releasing the loading head from a predetermined height and allowing it to swing flatwise against a corrugated fiberboard specimen. The test simulated the fundamental loading action of a fragile item in a package when impacted flatwise against a corrugated fiberboard pad. To aid analysis and simulation in the laboratory testing, the loading head and anvil were constructed so that their lowest resonance was distinguishable from transient acceleration components encountered in the tests of corrugated fiberboard pads.

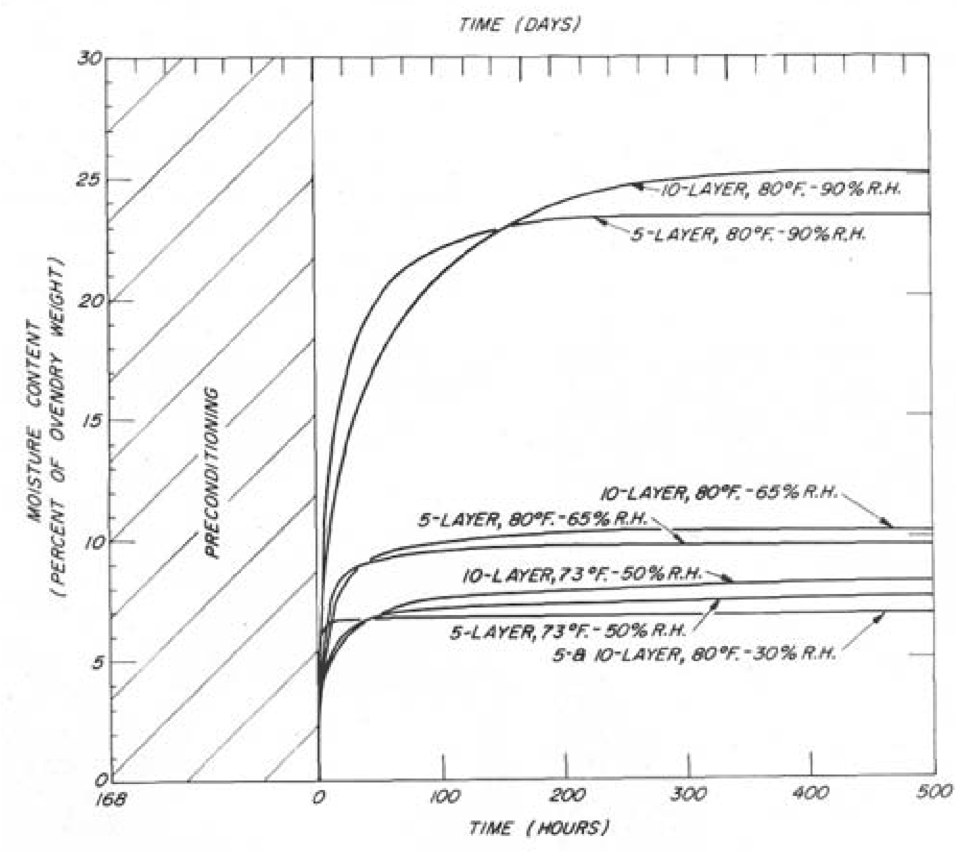

Figure 3.--The time-related change in pad moisture content with ambient atmospheric conditions. (M 136 633)

Testing System

Pendulum loading head.--The materials and construction of the loading head are indicated in figure 4, while figure 5 shows the loading head with attached accelerometer and light beam interrupter vane. A detailed description of the loading head and its ringing characteristics is given in (2).

Anvil, --The impacts were made against a 2-ton block of concrete and steel (fig. 6). The block was anchored by heavy steel brackets and lugs to a large section of concrete. Various checks conducted before the test series confirmed that the impact plate of the abutment was solidly supported by the anvil and its supporting slab.

Sensing and Recording Systems

The basic recording system used in this work is represented by the test setup shown in figure 6 and the block diagram in figure 7. Unlike the repeated loading tests of corrugated fiberboard pads, this work concerned single-loading characteristics. Therefore, it was advantageous to use the indicated apparatus rather than the abbreviated recording system used in (12). The initial step, involving recording of the acceleration analog, was followed by introduction through a bridge balance, amplification by a direct current preamplifier, and recording by an FM magnetic tape recorder. The tape recorder speed during the initial receipt of the acceleration data was 15 inches per second (i.p.s.). Later, the resulting acceleration-time data were played back at 1-7/8 i.p.s. through the galvanometer amplifier into an oscillograph having a suitable chart speed (40 or 80 i.p.s.) for manual digitization. The use of the variable speed tape recorder extended the limiting 0 to 600 Hertz (cycles per second) flat frequency response of the preamplifier by a factor of 8.0.

An oscilloscope camera combination was used for direct: readout of the acceleration-time (a-t) pulses resulting from the tests. Similarly, an oscilloscope was used occasionally to monitor the output of the tape recorder during the playback.

Velocity measurement.--Loading head velocity was computed from a time measurement made by the loading head 1.0 inch away from the impact surface of the pad. Little error was introduced in the impact velocity computation, because the wires of the pendulum were 10 feet long at the lateral. axis of symmetry through the loading head and velocity was essentially constant at the bottom of the swing, In operation, the interrupter vane (fig, 5) of the loading head obscured two narrow beams of parallel light incident on a pair of phototubes behind two slits. The slits were spaced 1,008 inches apart. The two pulses generated were amplified to reduce triggering time error of a coupled digital electronic counter. Thus, the digital record of the time required for the head to traverse a known distance between the slits provided information to compute head impact velocity. This was measured at each impact to hold impact velocity error to within ±1.0 percent,

Accelerometer.--A single oil-damped, resistance type, strain gage accelerometer, having a range of ±500 g., was used for all tests. As indicated by Levy and Kroll (7). the response of a damped spring-mass accelerometer varies with the type of pulse and degree of damping. Portions of pulses encountered in this work represent three types: square, triangular, and half-sine. Nevertheless, they concluded that to have an accuracy of better than 5 percent an accelerometer of this type must have a natural period of about $\frac{\tau}{3}$, where τ is the acceleration pulse duration, and a value for the damping constant of 0.4 to 0.7 critical.[4] Expressed in terms of the natural frequency f_n of the accelerometer, $f_n \geq \frac{3}{\tau}$. By this rule the accelerometer used, having a natural frequency of 1,550 Hertz. was suitable for measuring peak acceleration pulses having a duration higher than 1.9 milliseconds with an accuracy of better than 5 percent.

The accelerometer calibration sensitivity specified by the manufacturer was checked by the FPL linear deadweight calibrator. Details of this system are given in (1).

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[4] "Critical damping" is defined as the minimum coefficient of damping C_c that will just prevent a damped transient oscillation of a damped seismic system in response to displacement. numerically, $C_c = 2\sqrt{km}$, where k is the spring constant and m is the mass.

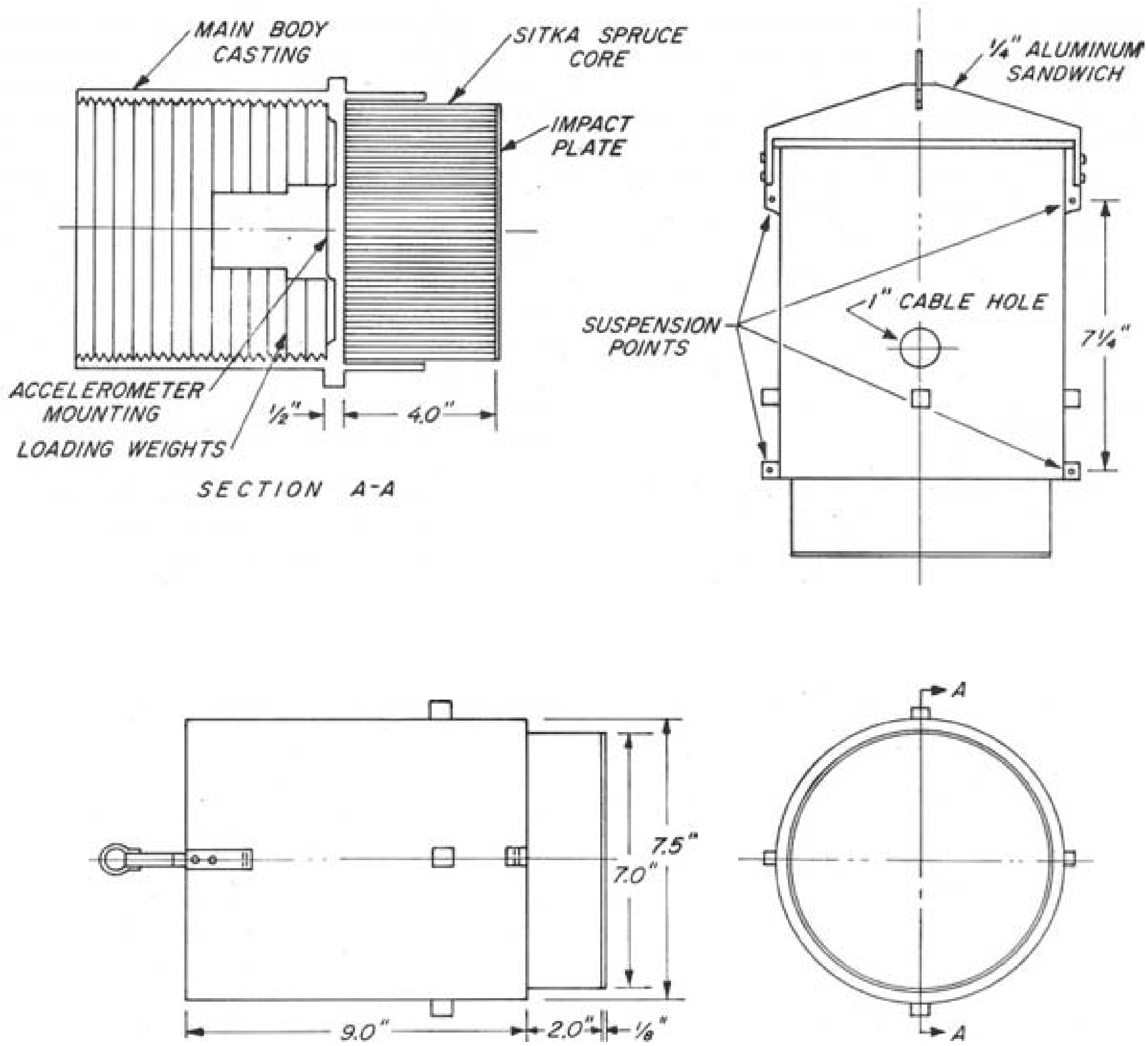

Figure 4.--Construction details of cylindrical aluminum loading head.
(M 133 035)

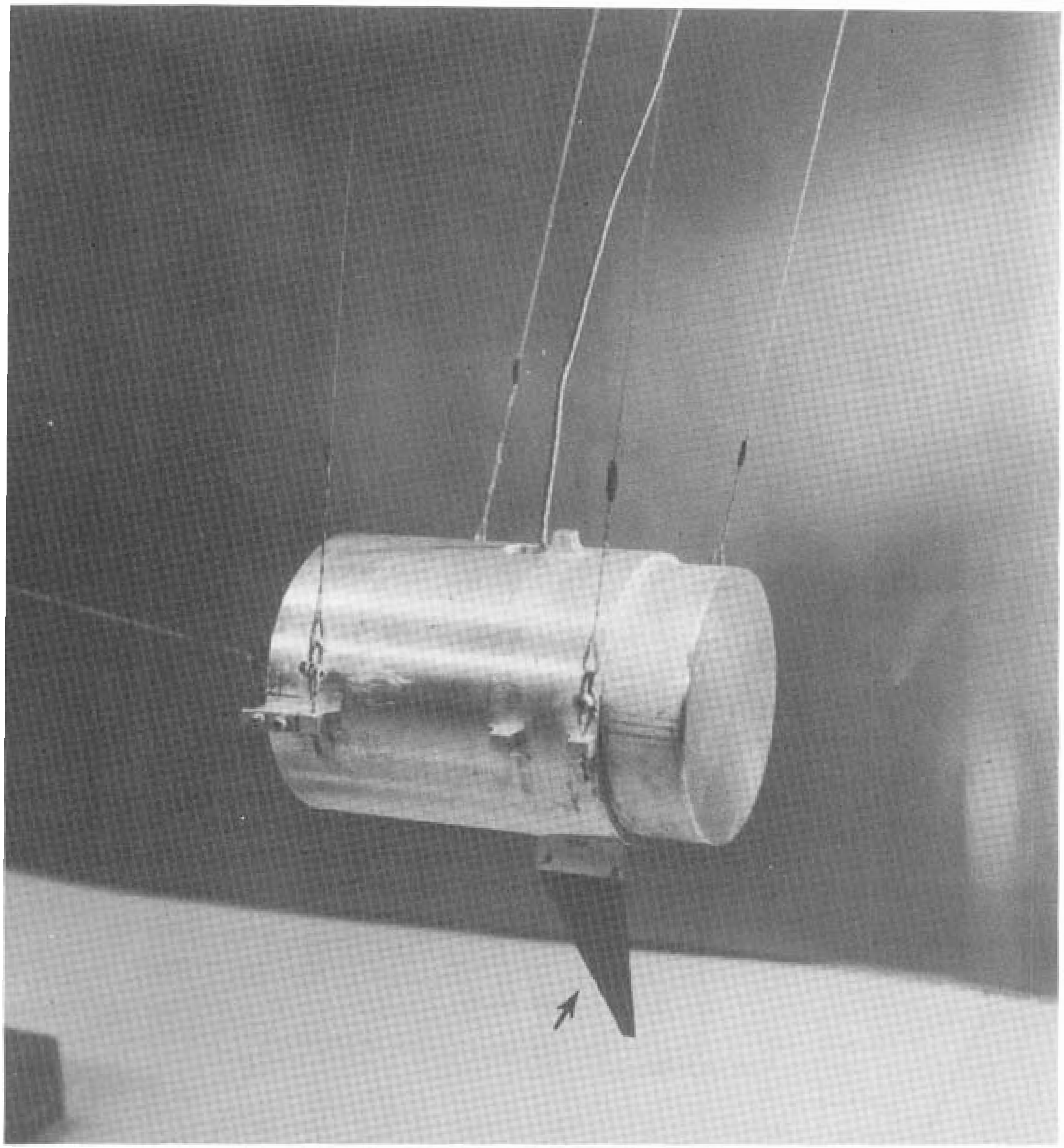

Figure 5.--Instrumented loading head. Arrow indicates light beam interrupter vane.

(M 126 919)

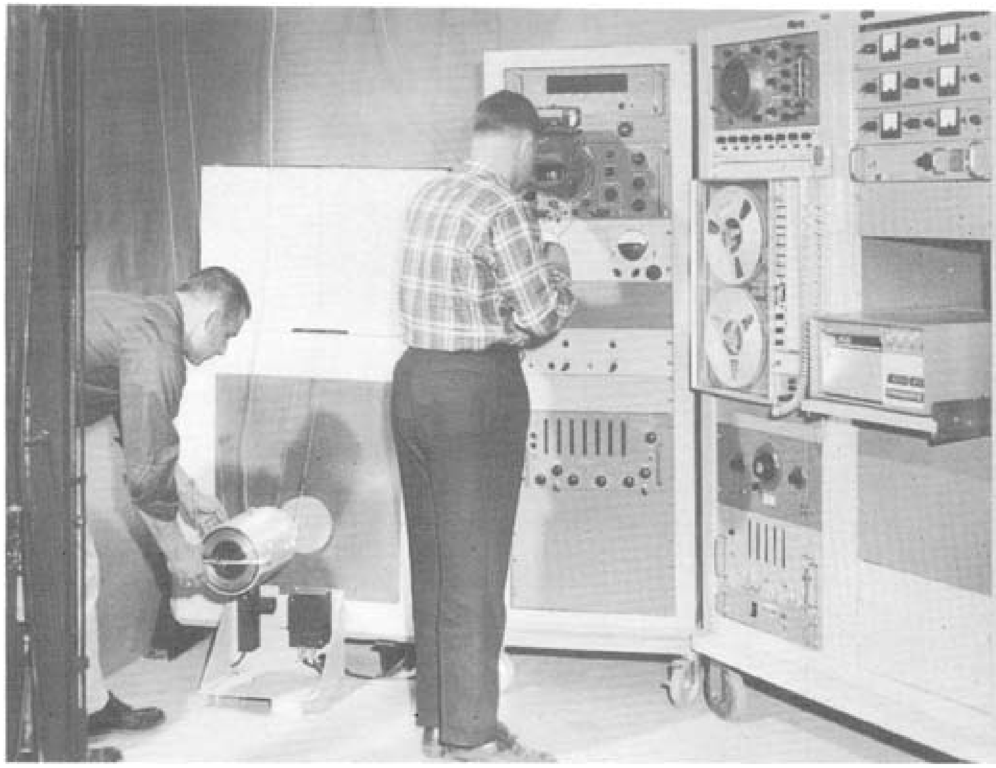

Figure 6.--Dynamic compression test in progress. (M 128 365)

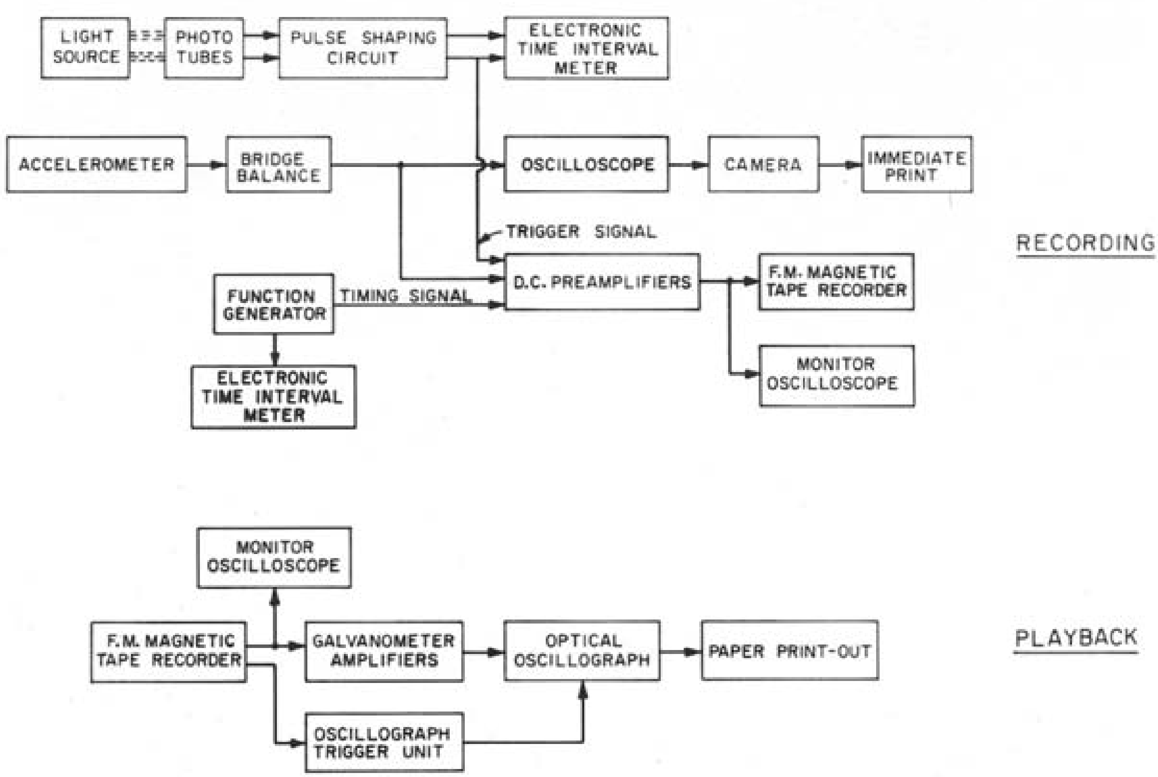

Figure 7.--Block diagram of system for recording and playback of dynamic compression test data. (M 132 852)

Test Procedure

A single test consisted of swinging the impact head from a resting position at the desired impact velocity against a corrugated fiberboard pad. The head was adjusted so that it did not rotate in flight and would strike the test pad squarely. Before the start of the swing, the loading head was held in a horizontal position by an adjustable solenoid–activated release mechanism. The pad was attached vertically to the abutment with pressure–sensitive tape with the adhesive on both sides. Just before impact with the pad, the instantaneous velocity of the head was measured. Adjustments were made in the position of the release to achieve the desired velocity. Each specimen was given a single impact with just sufficient input energy to cause bottoming. The input energy E_k was computed by

$$E_k = \frac{W}{2g} \left(\frac{s}{t}\right)^2 \qquad (1)$$

where W is the weight of the loading head, s is the distance between the slits of the velocity measuring system t is the time required to traverse the slits, and g is gravitational free–fall acceleration at sea level.

Fifteen specimens or more were tested for each combination of variables, because data from previous studies of this material indicated that this large a sample was necessary to achieve statistical meaning. A total of 127 test specimens was included in this work, and a schedule of all tests is reported in table 2.

Table 2.––Tests conducted in this work

Number of specimens	Effective drop height	Loading head weight	Conditioning atmospheres: Temperature	Conditioning atmospheres: Relative humidity
	Inches	Pounds	°F.	Percent
FIVE–LAYER, A–FLUTE PADS				
15	24	12.30	80	90
15	24	28.89	80	65
15	24	26.31	73	50
21	24	26.31	80	30
TEN–LAYER, A–FLUTE PADS				
16	24	38.63	80	90
	24	28.89		
15	24	54.60	80	65
15	24	49.27	73	50
15	24	49.27	80	30

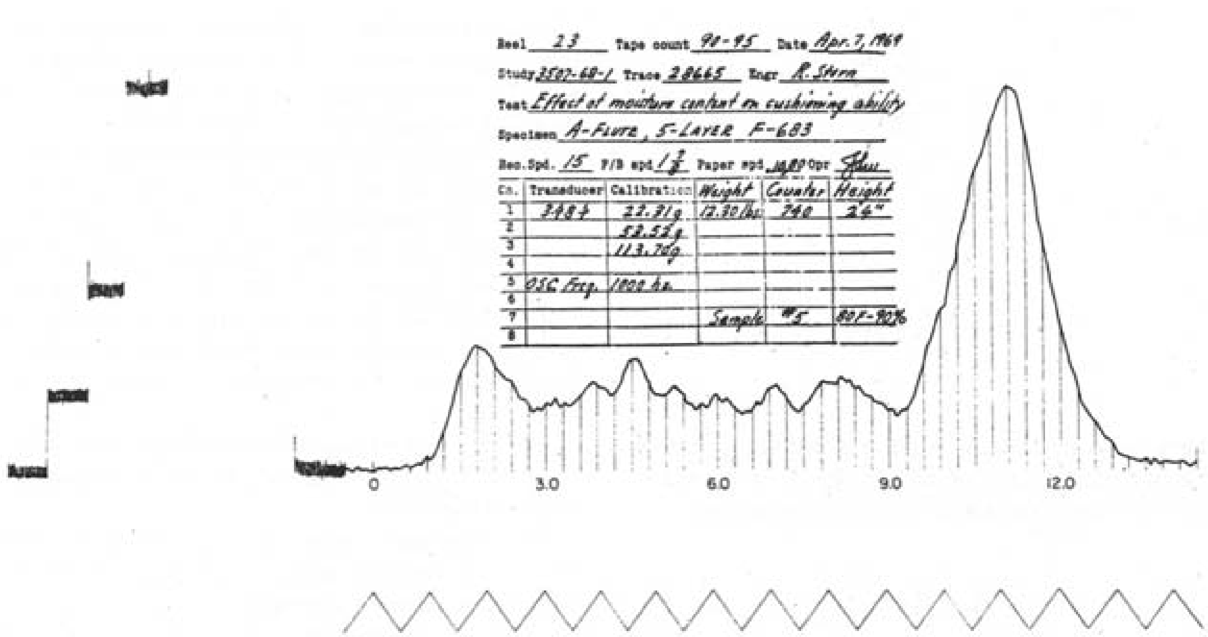

Figure 8.––A typical acceleration-time pulse digitized for computation. (M 136 668)

Computation

The experimental work produced a series of acceleration-time (a-t) pulses, such as that shown in figure 8. These were digitized manually and calculated by digital computer, according to the following steps:

1. Entry of the digitized a-t data.
2. Integration of the a-t until instantaneous velocity (v) = 0.
3. Integration of the v-t relationship until displacement (s) = 0.
4. Computation of the dynamic force-displacement (F_d-s) relationship. (Because F_d and s are related to the same time values, they are related to each other on the same basis).
5. Integration of the F_d-s relationship to obtain the energy-displacement relationship.
6. Computation of corresponding G_m-W/A data for theoretically frictionless drops from heights of 12, 18, 24, and 30 inches.

The input potential energy (E_p) can be expressed in terms of W and the free-fall drop height (h) as

$$E_p = Wh \quad \text{or} \quad W = \frac{E_p}{h} \tag{2}$$

Therefore, when specimen area is A, the static stress (W/A) is given by

$$\frac{W}{A} = \frac{E_p}{Ah} \tag{3}$$

Also,

$$F = ma = \frac{W}{g} = WG \tag{4}$$

where m is mass, a is acceleration. and G is the dimensionless ratio of acceleration to the constant acceleration due to gravity. Therefore,

$$G = \frac{F}{W} \tag{5}$$

RESULTS

The shock isolation characteristics of the pads were plotted as the G_m-W/A design graphs shown in figures 9 and 10. The log-log coordinates produced linear graphs having a slope (m) = -1.0. Mathematically,

$$G_m = m\frac{W}{A} + b \tag{6}$$

where b is the y-axis intercept.

The graphs representing the three lower relative humidity conditioning atmospheres differ little. However, the G_m-W/A graph for pads equilibrated with the 80° F., 90 percent relative humidity atmosphere differed markedly from the others. An increase in moisture content from about 6.7 to 10.2 percent of pad ovendry weight produced little change in pad shock absorption performance. However, an increase in pad moisture content from 10.2 to 23 percent resulted in a transposition of the graph to correspond with lower stress values. The minima for all graphs and the corresponding drop heights (impact velocities) evaluated did not differ greatly.

This relationship was evident from the variance analysis of the intercepts for the two pad thicknesses (8). Specifically, the x-axis intercepts were analyzed for the five-layer pads at 0.6 pound per square inch and at 1.0 pound per square inch for the ten-layer pads. No statistical difference existed at the 95 percent confidence level between the arithmetic means for the following:

(a) Five-layer pads equilibrated with 73° F., 50 percent relative humidity or 80° F., 30 percent relative humidity.

(b) Ten-layer pads equilibrated with either 80° F., 65 percent relative humidity or 73° F., 50 percent relative humidity.

The maximum variation of the intercepts about the mean was 46 percent, and the range of differences for the combinations of variables is given in talble 3. The analysis confirmed that only slight statistically sigificant difference (or none) existed between the data for the specimens equilibrated with 80° F., 65 percent relative humidity; 73° F., 50 percent relative humidity; and 80° F., 30 percent relative humidity. Collectively, the intercepts (and, therefore, the positions of the G_m–W/A graphs) for these specimens differed considerably from those for the specimens equilibrated with 80° F., 90 percent relative humidity.

Another point illustrated by figures 9 and 10 is that, while the position of the G_m–W/A graphs varied, their "bottoming" points with respect to G_m did not vary greatly. This difference would be inconsequential if the designer expected a pad to absorb several severe impacts during shipment. In such instances the designer would use an upper portion of the G_m–W/A for shock design purposes. A more complete discussion of this principle is given in (12).

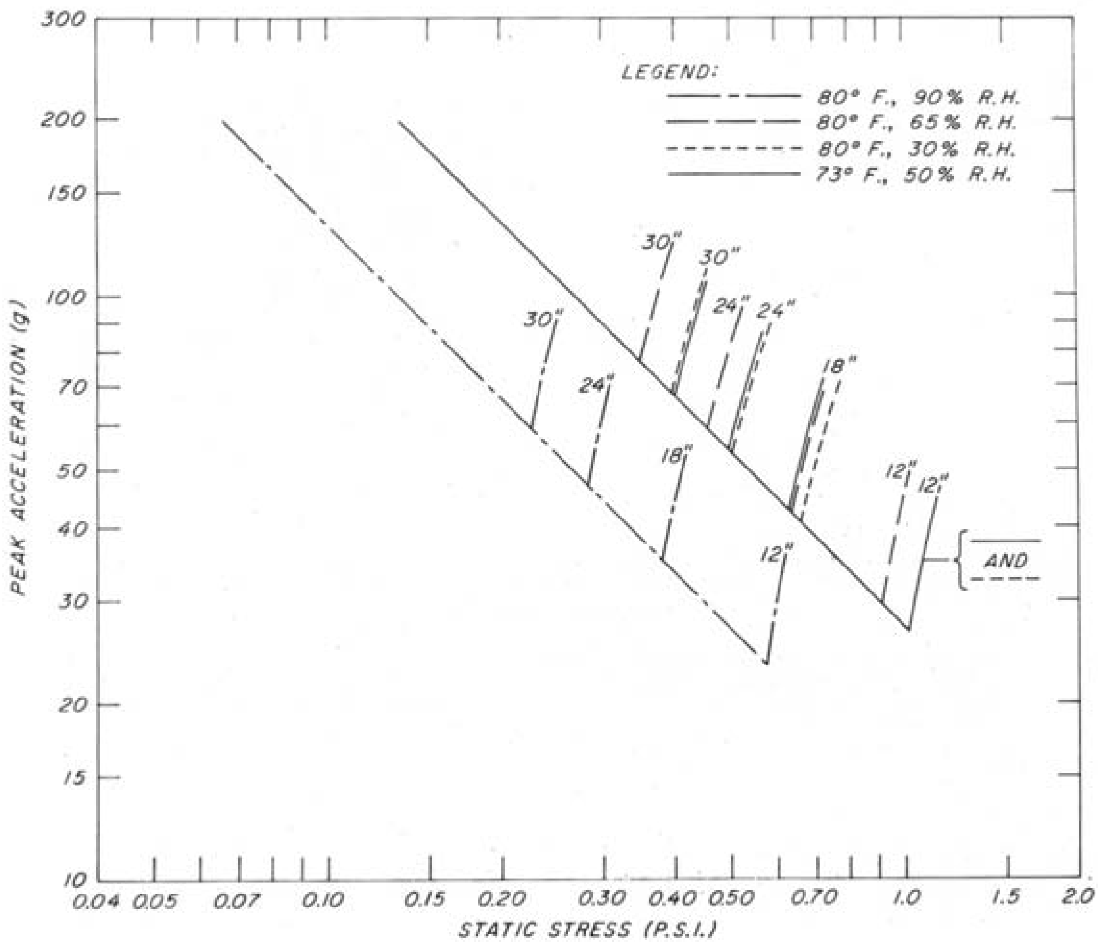

Figure 9.––The average change in shock absorption characteristics of five-layer, A–flute corrugated fiberboard pads equilibrated with different atmospheres common to service. Drop heights indicated are for theoretically frictionless drops.

(M 136 635)

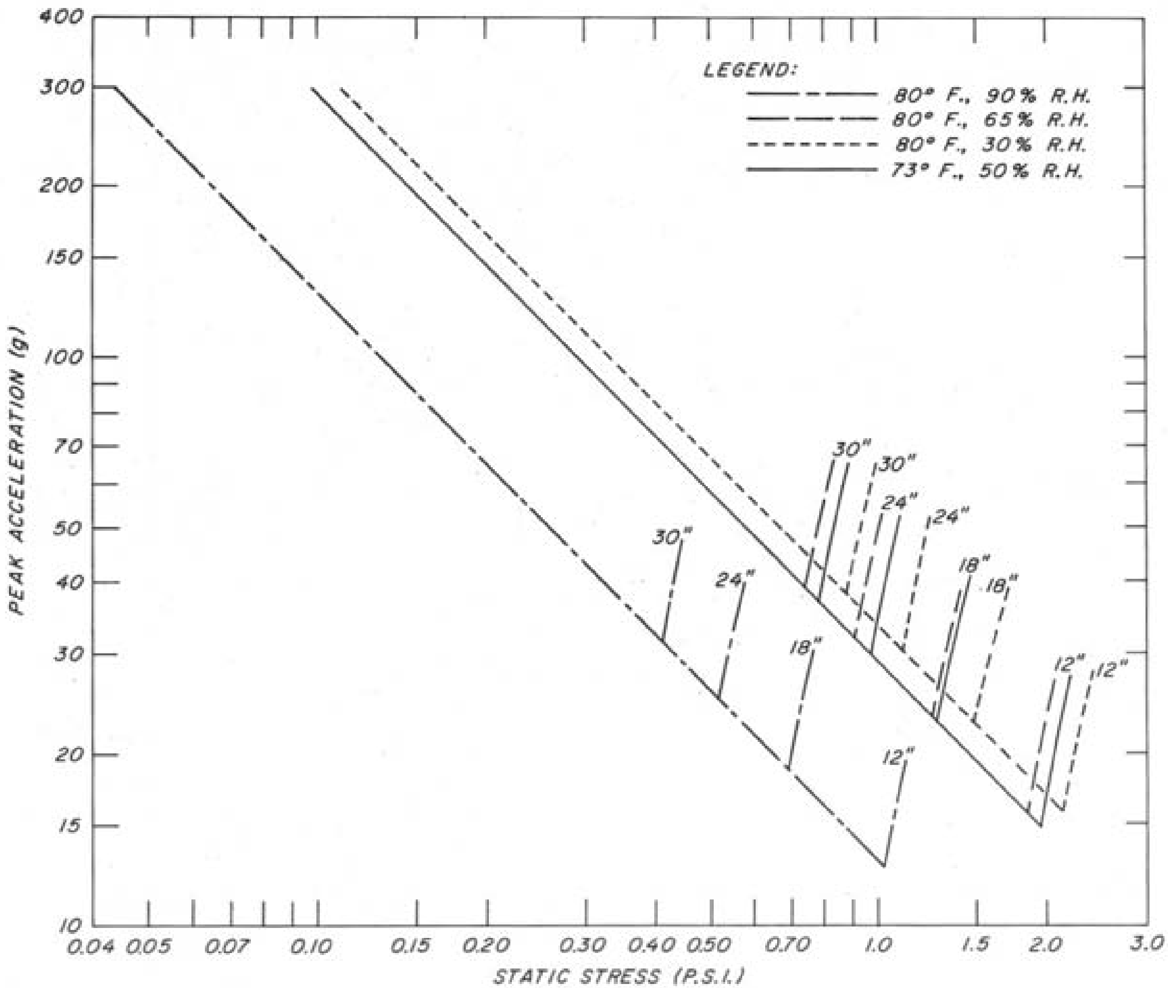

Figure 10.--The average change in shock absorption characteristics of ten-layer, A-flute, corrugated fiberboard pads equilibrated with different atmospheres common to service. Drop heights indicated are for theoretically frictionless drops.

(M 136 634)

Table 3.--Maximum variation of $\underline{G_m}$ at intercepts[1]

Conditioning atmosphere		Peak acceleration at intercepts			Range of difference[2]
Temperature	Relative humidity	Arithmetic mean	High	Low	
°F.	Pct.	g.	g.	g.	Pct.
		FIVE-LAYER PADS			
80	30	45.05	48.70	35.50	+8.1 to -21.2
73	50	44.33	52.60	38.00	+18.7 to -14.3
80	65	41.14	48.20	32.00	+17.1 to -22.2
80	90	21.39	24.50	19.50	+14.5 to -8.8
		TEN-LAYER PADS			
80	30	33.35	46.90	24.90	+40.0 to -25.3
73	50	28.29	35.90	22.00	+26.9 to -22.2
80	65	29.19	42.60	22.80	+46.0 to -21.9
80	90	12.38	16.30	9.60	+31.7 to -22.4

[1] 0.60 pound per square inch for five-layer pads and 1.00 pound per square inch for ten-layer pads.

[2] Based on the arithmetic mean.

CONCLUSIONS

There is little ox no change in the shock-absorbing characteristics of untreated corrugated fiberboard pads at equilibrium with the drier conditions, e.g., at 80° F., and 30 to 65 percent relative humidity. Under more humid conditions, such as 80° F., 90 percent relative humidity, the pads soften appreciably and are compressed more easily. The quantitative changes in shock isolation capability accompanying change in pad moisture content are defined by work described in this report.

Based on this work, individual specimen shock absorption performances at particular static stresses can differ widely from the group arithmetic mean.

RECOMMENDATION

Because corrugated fiberboard pads initially change rapidly in moisture content with humidity and time, it is recommended that the designer of vapor-permeable packages design for equilibrium moisture content. Furthermore, it is probably wise to design the shock isolation system of pads so that each is expected to absorb more than one severe impact.

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