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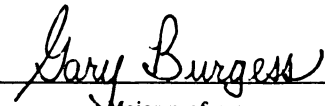
A COMPARISON OF PEAK ACCELERATION IN CUSHIONED DROPS:
ACCELEROMETERS VS. HIGH-SPEED VIDEO METHOD

presented by

Jeffery S. Waldeck

has been accepted towards fulfillment
of the requirements for

M.S. degree in Packaging


Major professor
Gary Burgess

Date April 28, 1989



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**A COMPARISON OF PEAK ACCELERATION IN CUSHIONED DROPS:
ACCELEROMETERS VS. HIGH-SPEED VIDEO METHOD**

**By
Jeffery S. Waldeck**

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

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ABSTRACT

A COMPARISON OF PEAK ACCELERATION IN CUSHIONED DROPS: ACCELEROMETERS VS. HIGH-SPEED VIDEO METHOD

By

Jeffery S. Waldeck

A quick summary is presented of some conventional methods for measuring the deceleration of a cushioned product in an impact and their limitations. A new method involving a high-speed video camera is developed. The procedure involves filming the compression-expansion process of the cushion during impact and afterwards measuring displacement values over time from the video screen. By fitting a high order polynomial function to this data and then obtaining its second derivative, the peak deceleration produced during the impact is obtained. The peak deceleration value obtained with an accelerometer is compared to that obtained using the high-speed video camera. The peak compression values of the cushions during the impact are also measured.

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JEFFERY SCOTT WALDECK

1989

DEDICATION

I would like to dedicate this thesis to my mother, Carol Hart Melvin, in recognition of the constant support she gave me and the sacrifices she made throughout my education.

ACKNOWLEDGEMENTS

I would like to thank Dr. Gary Burgess for acting as my advisor on this study. The constant assistance and direction he provided was greatly appreciated, especially at those times when all did not proceed as planned. Above all I cherish his friendship and humor, without which I would have been hard pressed to finish this study.

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LIST OF SYMBOLS

g		Peak Deceleration (G's)
p.s.i.	..	Pounds per Square Inch static loading of cushion
V		Impact Velocity of test platen
G		Acceleration due to gravity (386.4 in/sec ²)
h		Equivalent Drop Height
Pixel	...	The size of 1 display dot on the CRT screen
Y		Cushion Displacement at time n
s		Sampling Time Separation (3 msec in this study)
P		Conversion of Inches/Pixel
T		Cushion Thickness
S-L		Static Loading of cushion
t		Time

CHAPTER 1

INTRODUCTION

Cushioning is often the only way to protect a product in many situations. If a product is not sturdy enough to withstand the rigors of the distribution environment by itself, some form of protection, hereafter referred to as package cushioning, is generally required. However, since package cushioning can be expensive and depends on product fragility, it is important to use only enough cushioning to adequately protect the product. For a given packaging material and product fragility it can be shown that a trade off generally exists between the cost of excessive packaging and the cost of excessive damage. This is shown in figure 1. Ideally, the amount of protection built into a package should just make up for the difference between the hazards of the environment and the ability of the product to withstand these hazards. This is graphically illustrated in Figure 2. If the product can withstand the rigors of the distribution environment, no cushioning is needed. The product's fragility may be determined using the procedure outlined in ASTM procedure D-3332 [1]. The hazards of the distribution environment may be determined using measurement techniques on actual test shipments of the product

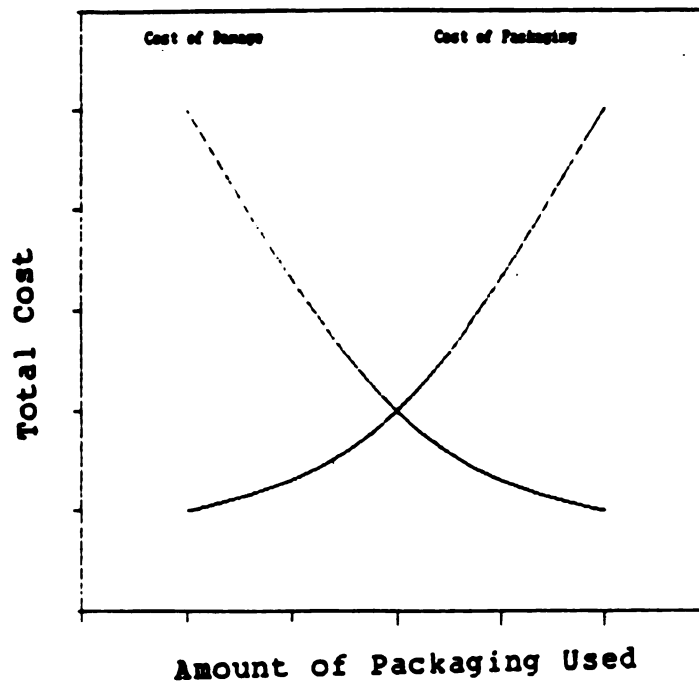


Figure 1. Trade-off between package costs and damage costs.

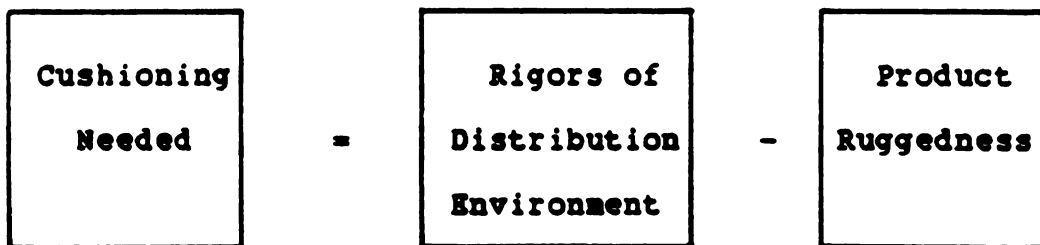


Figure 2. Methodology for determining cushioning needed

[2,3,4]. This allows for the amount of package protection required to then be determined.

The function of a cushion is to protect a fragile product by dissipating the free fall energy accumulated in a drop more slowly than would be dissipated in an unprotected drop. This energy is dissipated by a number of mechanisms such as heat transfer from the air in the cushion to the surrounding cell structure [5], damping [6], and plastic deformation of the cushioning material [7]. The peak deceleration in the impact is commonly used as a measure of cushion effectiveness. A larger peak deceleration indicates that the free fall energy is dissipated too rapidly and therefore, less protection is offered.

The standard method of portraying the protection potential of a cushion in an impact is the "cushion curve" as shown in figure 3. A cushion curve relates cushion thickness, load bearing area, and product weight to the peak deceleration (g's) that can be expected in a free-fall drop from a certain height. The method for generating cushion curves can be found in ASTM procedure D-1596 [8]. As the material properties of a cushion often change somewhat with repeated drops,

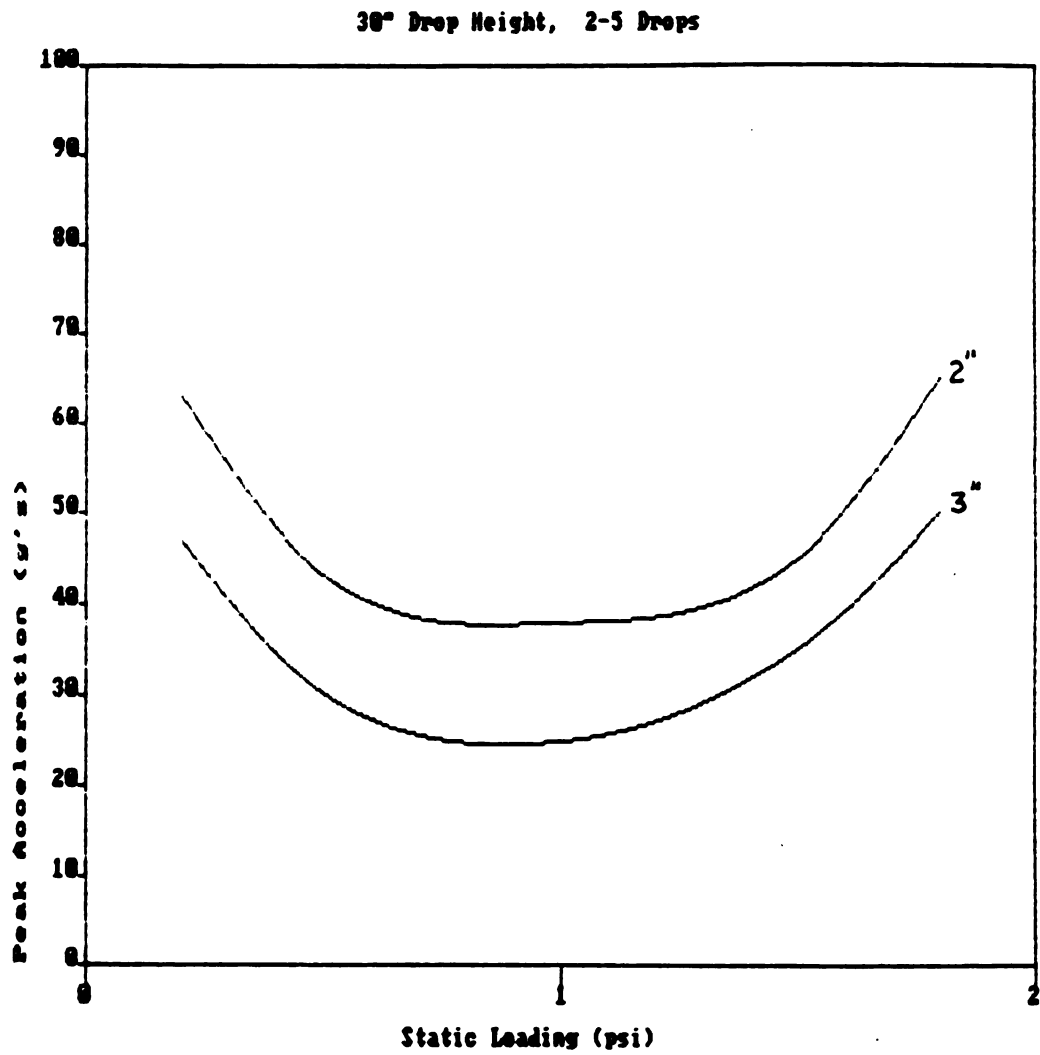


Figure 3. Typical Cushion Curve

the cushion curve will depend on the number of drops. The curves most often used in actual package design are the '2 - 5 drop' curves which represent the average deceleration experienced for the 2nd, 3rd, 4th, and 5th impacts under the same conditions. For this reason, the results of this study will be presented in the standard format of cushion curves, with static loading (P.S.I.) on the X-axis, and shock (g's) on the Y-axis. The curves generated from the video results will then be compared to published cushion curves for '2 - 5 drops' at the indicated drop height. The results should not be interpreted as new cushion curve data to be used for design purposes. This format is used merely for comparison purposes.

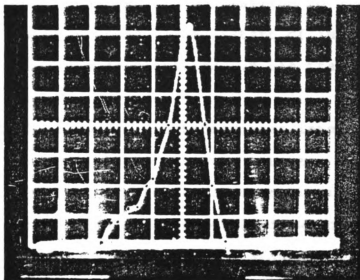
The standard method for developing a cushion curve requires some technique for measuring the peak deceleration during the cushioned impact. There are many used to measure this. Mechanical shock measuring devices include spongy balls, cantilevered beams, and in general any spring-mass system whose response to shock can be measured and translated into peak deceleration. The problem with all mechanical devices is that their response is slow and is determined to a great extent by the duration of the shock [9]. The

response time of a spring-mass type of mechanical accelerometer is governed by its natural frequency. If the response time is comparable to the shock duration, then the mechanical accelerometer will provide useless results. Only mechanical accelerometers with natural frequencies that are high enough to avoid this problem will produce accurate results. The piezo-electric accelerometer is such a device which relies on the deformation-dependent electrical properties of a crystal to measure deceleration. In spite of the widespread use of these types of accelerometers, they are still plagued with problems, some of which are outlined below:

1. **CALIBRATION ERRORS:** Accelerometers are transducers that produce minute voltages in proportion to the forces they are subjected to. Since force is proportional to acceleration through Newton's Law, the voltage produced becomes a measure of the deceleration experienced. While relatively reliable, they nevertheless require calibration to determine the ratio of voltage output to the deceleration experienced. The accuracy of the results will depend on the technique used and the

skill of the operator, which makes exact calibration difficult.

2. CONNECTION IMPEDANCE: If an accelerometer is not properly connected to the test item, inaccurate measurements will result. The high strains generated when the impact occurs may alter the electrical resistance of the connection. This may alter the output voltage and introduce an error in the measured deceleration.
3. COUPLER ERRORS: A piezo-electric accelerometer requires a capacitance coupler in order for an oscilloscope to measure the output. This coupler has an associated error. Also, as in #2 above, the connections to and from the coupler may induce an error. The power source for the coupler may magnify this error.
4. OSCILLOSCOPE ERRORS: Since the trace width of the accelerometer signal displayed on an oscilloscope is typically on the order of 1 mm at the very least, the peak height of the trace will be in error by this amount. See Figure 4. In addition,



The divisions in the photo are each 1 cm x 1 cm. The width of the shock pulse trace is appx. 1 mm (determined visually).

The settings for the oscilloscope in this photograph were 5 ms/division horizontally, 20 mv/division vertically. The drop height was 42", the static loading 1.0 p.s.i., and the cushion sample tested was 3" thick Ethafoam 220. The sensitivity of the accelerometer used was 2.0 mv/g (see Appendix D).

Figure 4. Typical shock pulse recorded by an accelerometer

the oscilloscope itself has inherent errors such as drift (the gradual shifting of the ocsilliscope's beam over time), connection errors, and calibration errors. The user may also induce an additional error by failing to differentiate between the base line (start of impact) and the peak (maximum deceleration) on the trace.

5. **AMBIENT ERRORS:** Electromagnetic interference from overhead lights, power sources, and nearby equipment can induce a current in the cable through induction, the result of which is to alter the signal from the accelerometer. This may be minimized but not completely eliminated by shielding the cables or reducing nearby electrical activity in the environment. An improper ground loop between equipment may also result in an error. Temperature variations may cause errors in virtually all of the equipment involved due to temperature dependent electrical properties of the types of electrical components found in the equipment.
6. **TRIBO-ELECTRIC NOISE:** Since the signal cable cannot be entirely immobilized throughout the

impact, cable flexing will alter the signal. This error can be reduced by using a signal cable with no more slack than necessary for the operation of the test equipment.

7. TRANSVERSE ACCELERATION ERRORS: Accelerations not confined to the axis of the accelerometer will cause an output error. These can be reduced by maintaining alignment of the accelerometer in the vertical direction during impact and by using well-braced mounting and proper test equipment.
8. OFFSET DUE TO DAMAGE: When overloaded with accelerations beyond their measurement capabilities, accelerometers may be permanently affected in the form of an offset from the calibration value. While this error can be prevented through careful handling of accelerometers, it is often impossible to know the complete handling history of an accelerometer beforehand.
9. RINGING OF THE TEST FIXTURE: During impact, the test fixture and associated support equipment will

"ring", or vibrate at their natural frequencies. This causes transverse vibrations which affect the signal from the accelerometer and lessen the impact by dissipating some of the impact energy which the cushion would otherwise have to absorb. This effect may be reduced by eliminating free play within the equipment as much as possible. If this is not possible, the output of the coupler may be electronically filtered to take out the undesirable high frequency components in the signal associated with externally induced noise, transverse accelerations, and fixture ringing. The positioning of the accelerometer can also effect the transmitted shock pulse.

Taking into account all of the above possible sources of error, the accelerometers used to generate deceleration data are likely to give results which are accurate to $\pm 14\%$. This figure was calculated as outlined in Appendix B.

As mentioned earlier, some of the sources of error may be removed electronically through filtering. The remaining sources of error still exist however. For

this reason, a new method for determining the peak deceleration in cushioned drops is desired.

The purpose of this study is to compare the peak deceleration obtained in an impact in a cushioned free-fall drop using a piezo-electric type accelerometer to the peak deceleration obtained using the high-speed video method outlined in Chapter 2. Although certain test conditions were used, it is not the intent of this study to generate any conclusions about the cushioning materials based on the results obtained under these conditions. Rather, the intent is to compare the two methods under the same set of arbitrary test conditions.

CHAPTER 2

A NEW METHOD

This chapter evaluates a new and simpler visual method for determining the deceleration in a cushioned impact. The technique uses a real time plot of product displacement versus time obtained from a high-speed video camera. The camera used in this research was a Kodak Ectapro 1000 which is capable of capturing images separated by 1 millisecond intervals [Fig. 5]. When a suitable mathematical function is fitted to this discrete displacement vs. time data, the deceleration function may be obtained as the second derivative of the displacement function. This method offers several key advantages over the conventional accelerometer method, such as:

1. NO CONNECTION ERRORS: The very nature of the video recording system eliminates connection errors by eliminating the connections themselves.
2. NO COUPLER ERRORS: There is no coupler.
3. NO TRIBO-ELECTRIC NOISE: Again, there is no physical connection to the test sample. This of

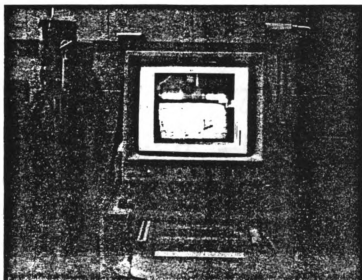


Figure 5a. Cushion as it appears before compression.

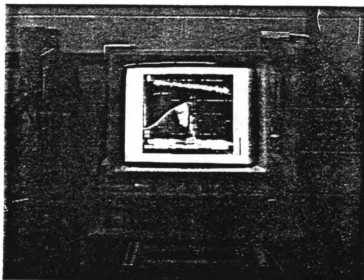


Figure 5b. Cushion as it appears during compression.

Figure 5. View screen of Kodak's Ectapro 1000 system.

course assumes that the cable between the camera and recorder does not move appreciably during the shock.

4. FEWER AMBIENT ERRORS: Ambient conditions can only effect the high-speed video recording system and this possibility has been reduced by the manufacturer by enclosing the electronics of the recording system in a metal enclosure (a Faraday Cage) which essentially eliminates electromagnetic interference.
5. NO TRANSVERSE VIBRATION ERRORS: The high speed video system may be used to analyze motion in one direction only by orienting the camera so that the on-screen grid system coincides with this direction.
6. NO RINGING ERRORS: Unless the amplitude of vibration of the test fixture is greater than the resolution of the camera (approximately .03"), which is rarely the case, the displacement measured by the camera will be essentially that of the product on the cushion.

7. NO ADDED MASS: Even though present day accelerometers are relatively light-weight, certain applications are precluded because of their weight. An example would be measuring the dynamic characteristics of thin films. The high-speed video method is ideal for such applications.

In spite of the obvious advantages, there are disadvantages, few of which however affect the accuracy of the technique. These include:

1. HIGH COST: The current price of the necessary test equipment is around \$80,000, far greater than the cost required for all of the equipment used in the accelerometer method. This limitation can be expected to decrease as high-speed camera technology and use improves.
2. LIMITED USAGE: Because of the strict set-up requirements of the high-speed video system, this technique is limited to laboratory use only except in special cases.

3. FREQUENCY CUT-OFF: Since the video system has a maximum "capture speed", displacement resolution decreases with increasing speed of the event to be captured. This limiting capture speed effectively acts as a low-pass filter which eliminates high-frequency motion superimposed on the dominant compression/expansion motion during the impact. This limitation may actually be regarded as an advantage since it automatically eliminates ringing problems with the test fixture.
4. CAMERA RESOLUTION: The amount of detail, or displacement resolution, of the camera will limit its accuracy. Movements less than the resolution of approximately .03" for the camera used here cannot be accurately displayed as this is the approximate size of a "pixel" on the video screen. This becomes critical around the peak displacement, when the change in displacement is less than the camera resolution. This most likely accounts for the greatest source of error in the method. A possible solution would be to focus in on the lower 1/3 of the cushion in order to record only the critical moments during peak displacement.

5. SCREEN ERRORS: Both image blurring and reading errors also limit the accuracy. Blurring may be minimized by proper lighting and adequate camera speed. In the tests performed here, the speed of the Kodak video system was adequate but less than optimal. This resulted in occasional blurring at critical moments during measurement. It may be assumed that some degree of reading error was also present.

6. ANGULAR OFFSET: Since the camera must capture continuous motion through a range of elevations, it must film at an angle most of the time. The actual displacement will therefore be distorted by the changing camera angle. Angular offset tends to make the perceived compression about 2% greater than the actual compression. This is illustrated in Figure 6. This may be minimized during the critical moment of peak displacement by adjusting the height of the camera lens to that of the bottom of the test cushion. In any event, if necessary this error can be removed by using trigonometric principles. See Figure 6. This error will not be present at all if the dimension of the cushion sample being tested is the same

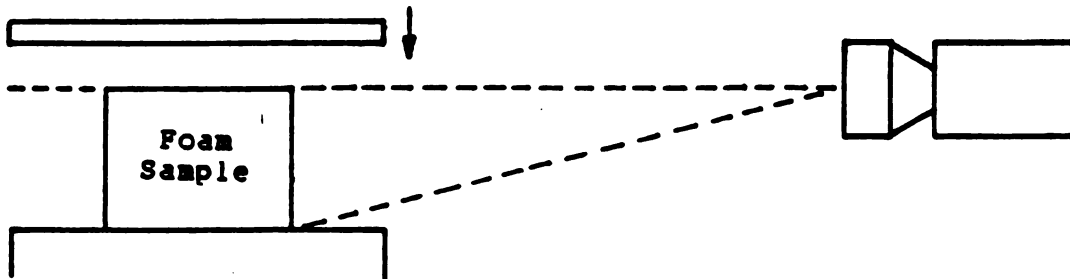


Figure 6a. High-speed video set-up

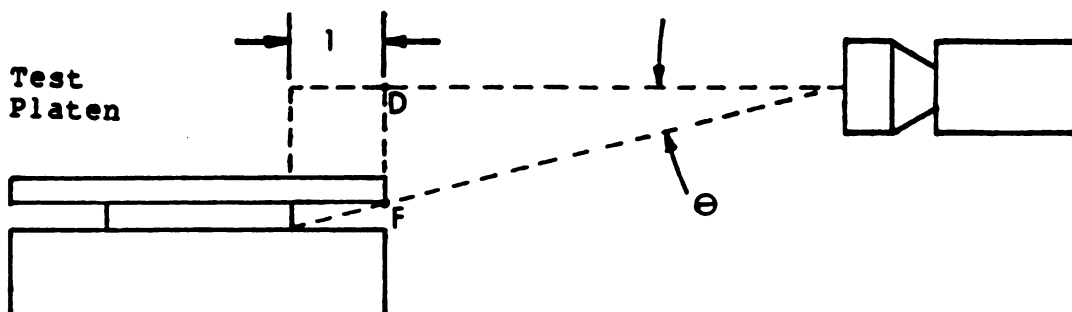
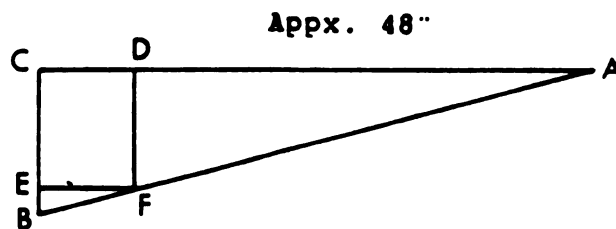


Figure 6b. Test platen interference



Line DA = Distance of camera to sample = 48"
 Line EF = CD = Distance from platen edge to sample = 1"
 Line DF = Perceived compression
 Line BC = Actual compression

$$\frac{CD}{EB} = \frac{DA}{DF} \quad \text{Error} = EB = \frac{CD \cdot EF}{DA} = \frac{(1'')(\text{perceived comp.})}{(48'')}$$

Therefore, Actual Compression = 1.02 x Perceived Comp.

Figure 6c. Trigonometric error analysis

Figure 6. Illustration of angular offset error

from front-to-back as the test platen.

7. GROUND-BORN VIBRATIONS: Vibrations of sufficient magnitude transmitted through the ground to the camera by the force of the impact can cause the camera's aperture to move. This could result in a displacement error which can be minimized through the use of a proper seismic mass to anchor the test equipment and by isolating the camera from the ground.

To utilize the high-speed video method in determining the peak deceleration experienced during a cushioned drop, the following equipment and materials are needed;

TEST MATERIALS

Although the test samples may be any material of a resilient nature, as described in ASTM D-1596 [8], the material used in these tests was Ethafoam 220, a product of Dow Chemical Company. Test samples are usually 8" x 8" x Thickness, but for these tests, it was necessary to reduce the surface area to 6" x 6" to reach the upper static loadings used.

TEST APPARATUS

The test apparatus used was a model 23 free-fall drop tester manufactured by Lansmont. A piezoelectric accelerometer mounted to the platen was used in conjunction with a digital storage oscilloscope to record the shock pulse. This set-up is illustrated in Figure 7. A Kodak Ectapro 1000 high-speed video recording system was used to gather the displacement versus time data. The camera was set up so that the entire compression range of the cushion from first contact to maximum deformation was within view of the camera lens. This is shown in Figure 8.

TEST PROCEDURES

The procedure to record a single drop using the high-speed video method is as follows;

1. RESET VELOCITY DETECTOR ON DROP TESTER: This is standard on most drop testers in order to ensure that the proper impact velocity is reached for the desired free fall drop height.

1. Lifting mechanism
2. Test weight
3. Test Platen
4. Accelerometer
5. Guide rods
6. Cushion sample
7. Seismic mass
8. Coupler or amplifier
9. Oscilloscope

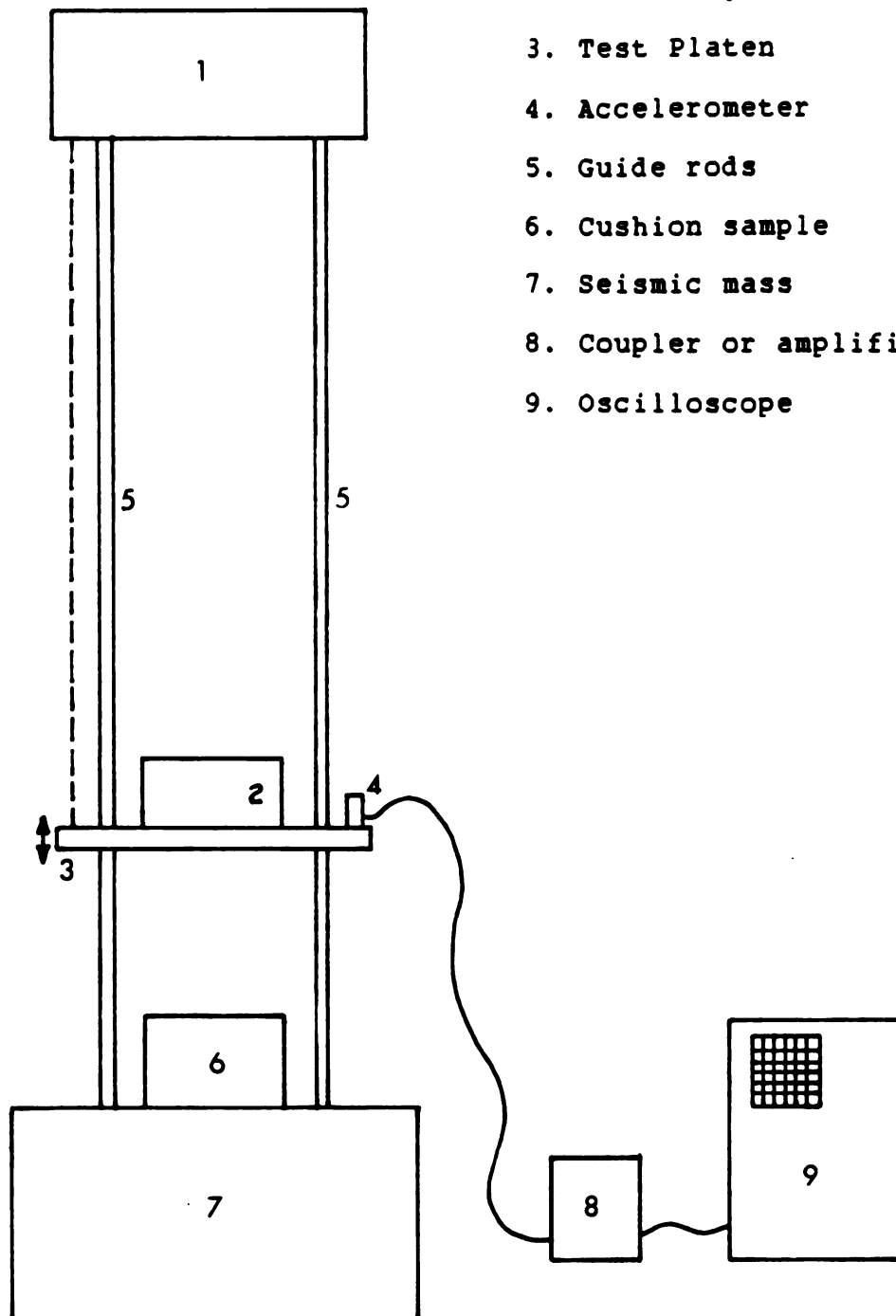


Figure 7. Test set-up for the accelerometer method.

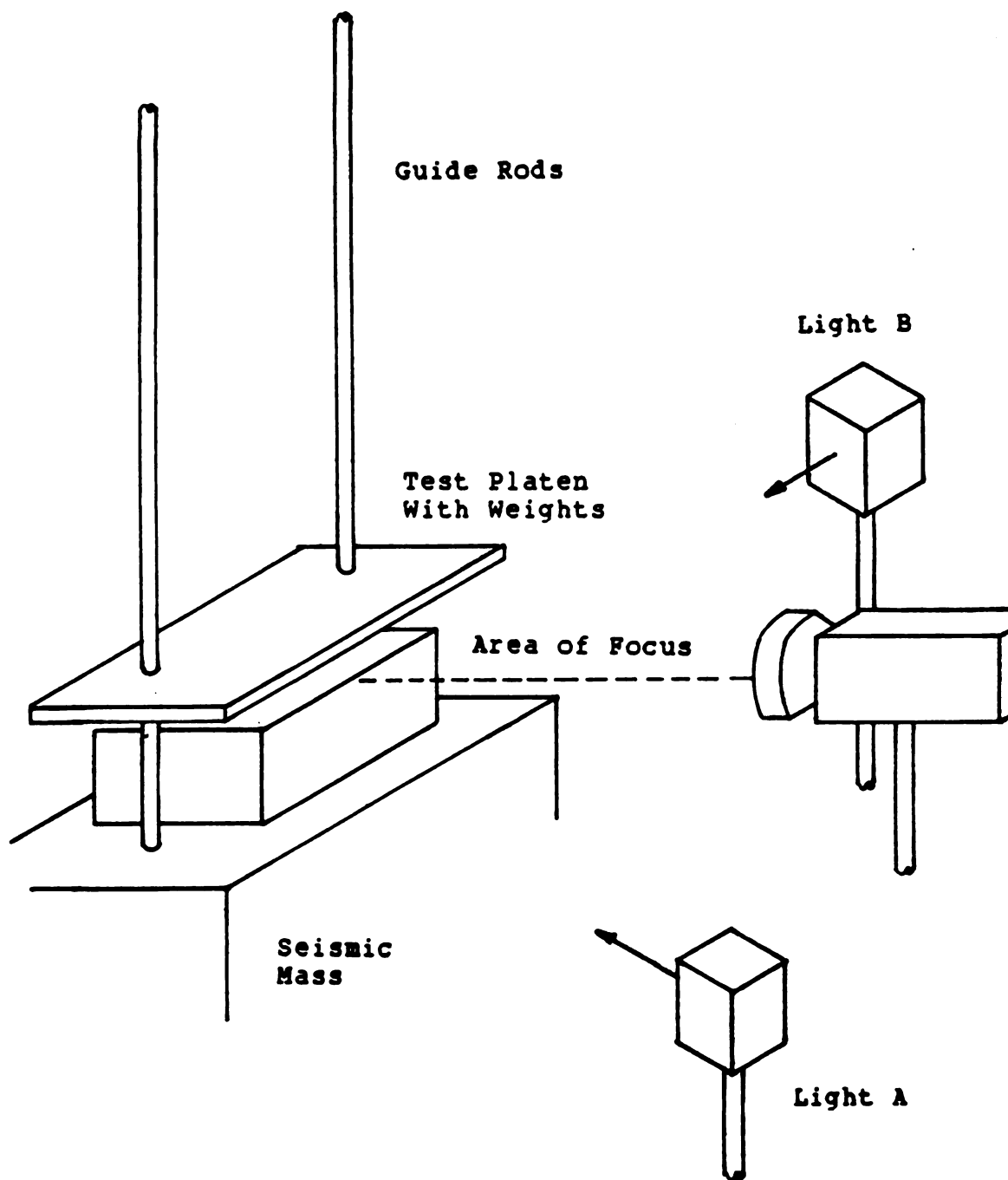


Figure 8. Test set-up for the high-speed video method

2. RESET STORAGE OSCILLISCOPE: (optional) The use of a storage oscilloscope is required only if it is desired to compare the result with that obtained from an accelerometer.
3. TURN ON CAMERA LIGHTS: The high-speed camera requires very bright lighting for proper filming. As such lights are very hot, it is desirable to leave them on only when required for filming.
4. ADJUST CAMERA POSITION: In the "live" or camera-on mode, the view can be lined up precisely. This should be checked before each drop to avoid possible loss of data due to an accidental bump to the camera. At this time the optimum focus can also be obtained.
5. START HIGH-SPEED CAMERA RECORDING: The high-speed camera uses up video tape very quickly. When running at the speed used in these experiments (23 ft/sec), a single tape can hold approximately 30 seconds of real-time data. For this reason it is desirable to film as little as possible for each drop.

6. INITIATE DROP TEST: Self explanatory.
7. TURN OFF HIGH-SPEED CAMERA: See #5 above.
8. TURN OFF CAMERA LIGHTS: See #3 above.
9. READ VELOCITY DETECTOR: This is done to verify that the impact velocity was correct for the desired free fall drop height, where;

$$v_i = \sqrt{2Gh}. \quad [\text{Eq.1}]$$

10. READ OSCILLISCOPE: Optional, see #2 above.
11. TRANSCRIBE CUSHION DISPLACEMENT DATA: The high-speed video system used was equipped with a cursor location readout system which allows for measurements of events to within 1 pixel (.03" for these tests). By selecting a reference point, such as the test platen edge, the displacement of this point can then be measured to within .03" at 1 millisecond intervals. Continue measurements throughout the displacement cycle, noting where the peak displacement occurs. Since the read-out system measures displacement in pixels, these

values can be converted to inches only after the entire sequence is viewed.

12. PICKING DATA POINTS: The mathematical analysis used here requires that displacement data be sampled at regular time intervals. There should be the same number of points on either side of the peak displacement, determined upon viewing the recording. In these tests, the sampling time interval used was 3 milliseconds. A typical transcription of the data appears in Figure 9. This method requires a conversion from pixels to inches. To determine this, one must measure the thickness of the sample cushions before testing. After the video record has been made, the reticle location system can be used to determine the locations for the top and bottom of the cushion on screen. The value for inches per pixel can then be determined as shown in Figure 10 and determined as follows:

$$P = \frac{\text{Thickness of cushion (inches)}}{\text{Pixels from btm to top of cushion}} \quad \text{eq. (2)}$$

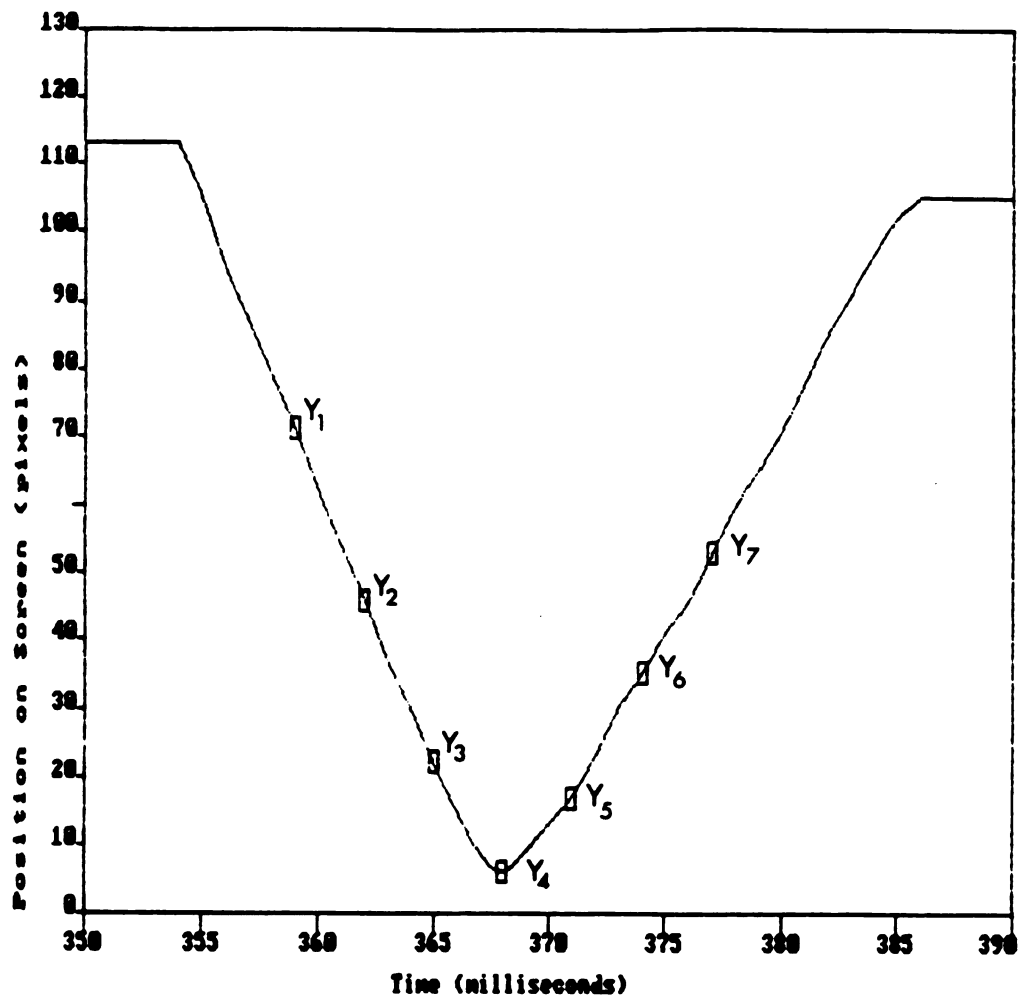
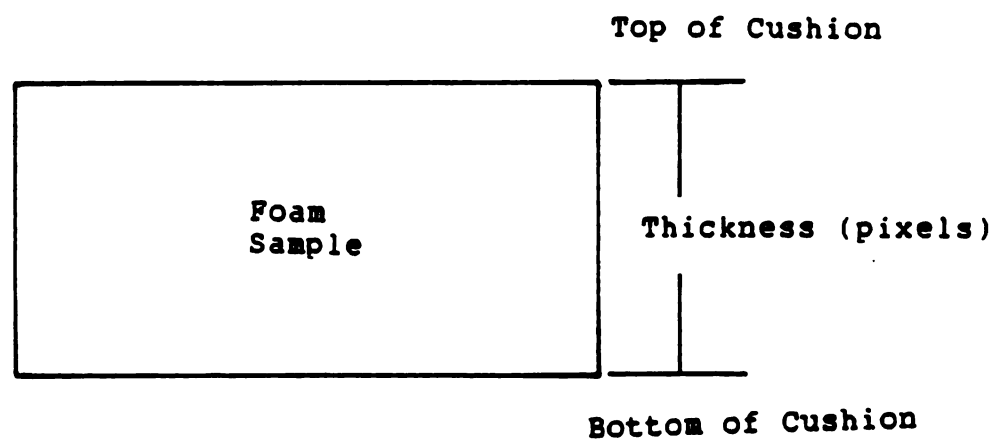


Figure 9. Typical displacement plot of cushion compression



**Figure 10. Determination of P (inches/pixel) from
sample**

Table 1. Values of inches/pixel calculated in study

30" drop height, 2" cushion	.024 in/pixel
36" drop height, 2" cushion	.024 in/pixel
42" drop height, 2" cushion	.026 in/pixel
30" drop height, 3" cushion	.032 in/pixel
36" drop height, 3" cushion	.031 in/pixel
42" drop height, 3" cushion	.030 in/pixel

13. FINITE DIFFERENCE ANALYSIS: The method of splines involves fitting a polynomial function to any number of displacement versus time data points. For greater accuracy, such a spline was fitted to the 7 equally spaced data points obtained in #12 and shown in Figure 9. Such a function represents the displacement of the cushion over time during the impact, and its second derivative is the instantaneous acceleration. The details of the derivation are carried out in Appendix C and the result is that the peak deceleration experienced during the impact in terms of the displacement values $y_1, y_2, \dots$ etc in pixels taken at evenly spaced intervals t seconds apart is ;

[Eq.15]

$$g = \frac{2(y_1) - 27(y_2) + 270(y_3) - 490(y_4) + 270(y_5) - 27(y_6) + 2(y_7)}{180(s^2)(386.4 \text{ in/sec}^2)(P)}$$

See Appendix C for the derivation of this equation.

For this study, s was .003 seconds. The values for inches/pixel are shown in table 1. This value is also the effective resolution of the system, as discussed earlier in disadvantage #4. The value for inches/pixel changed from test-to-test due to camera relocation between most tests. Therefore, it was calculated for every drop test recorded. This procedure is illustrated in Figure 10.

The procedure for recording a single drop using the accelerometer method is detailed in ASTM D-1596 [8].

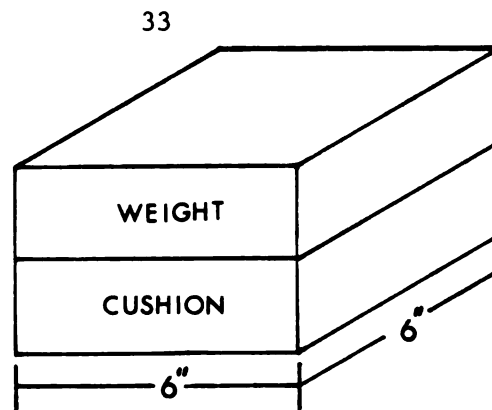
Tests were conducted using the above procedures to determine how closely the results of the high-speed video method compared to the results obtained from the accelerometer method. The following test conditions were used.

STATIC LOADING : Static loads of 1.0, 1.5, 2.0, and 2.5 P.S.I. were used. This represents the upper range of static loadings that are normally used in cushion design and was singled out for testing not only for this reason but also since accelerometers are likely to have the greatest difficulty in gathering data under these high G conditions. Since the static loadings were

chosen to be in this upper range, a smaller than normal cushion sample size was required due to the weight limitations of the test equipment used. The cushion size used was 6"x6" and the weights and static loadings produced are shown in Figure 11.

DROP HEIGHTS : Actual drop heights of 30", 36", and 42" were chosen since they are typical of industry cushion curves. The distance the test platen actually falls during the tests must be made somewhat higher than these values since friction between the guide rods of the drop tester and the test platen slow the test platen down as it falls. For this reason, an impact velocity gate was utilized to set the platen drop heights so that the desired free fall drop heights listed above were achieved. The platen drop height is adjusted until the target impact velocity for each of the drop heights is achieved

$$\text{Impact Velocity } (V_i) = \sqrt{2Gh} \quad \text{eq. (1)}$$



$$\frac{36\#}{36 \text{ sq. in.}} = 1.0 \text{ p.s.i.}$$

$$\frac{54\#}{36 \text{ sq. in.}} = 1.5 \text{ p.s.i.}$$

$$\frac{72\#}{36 \text{ sq. in.}} = 2.0 \text{ p.s.i.}$$

$$\frac{90\#}{36 \text{ sq. in.}} = 2.5 \text{ p.s.i.}$$

Figure 11. Weights and static loadings used in tests

For the desired test drop heights of 30", 36", and 42" the required impact velocities are 152 inches per second, 168 inches per second, and 180 inches per second respectively.

SAMPLE CHARACTERISTICS : The samples used were 6" x 6" blocks of Ethafoam 220, a low density expanded polyethylene foam weighing 2.2 pounds per cubic foot made by Dow Chemical. Two and three inch thick cushions were chosen as typical thicknesses that would be used in industrial applications. Twice as many samples were constructed as needed for the testing and checked for accurate measurements. Any samples that failed to meet specifications were discarded. From the remaining samples, the actual test samples were chosen at random for each drop.

TEST REPETITIONS : In order to maintain a minimum degree of statistical significance, two repetitions of each test condition were performed. While this is perhaps insufficient to gather statistically valid data for plotting cushion curves, it was judged to be adequate for the comparison between the accelerometer and the video methods since both acceleration measurements were taken simultaneously during the same

drop. This allowed for a direct comparison of the results as conditions were identical for each method.

These test conditions are summarized in Figure 12.

Test Drop Heights	3	30" , 36" , 42"
Test Static Loadings	4	1.0, 1.5, 2.0, 2.5 p.s.i
Test Sample Dimensions	2	2" x 6" x 6" 3" x 6" x 6"
Test Samples	1	Ethafoam 220
Test Repetitions	2	

Total Drop Tests 48

Figure 12. Summary of test conditions

CHAPTER 3

DATA & RESULTS

The data for the displacement versus time observations obtained as described in step #12 of the high-speed video method can be found in Tables 5 and 6. This data can be used in Equation 15 to calculate the instantaneous acceleration values. The data obtained by using an accelerometer to measure the peak deceleration can be found in Tables 7 and 8.

The results of both methods are compared directly in Tables 2 and 3, and the data is displayed again in the format of cushion curves in Figures 13 through 15. Cushion curves generated from the data provided by the Dow Chemical Corporation are shown in Figures 16 through 18.

Table 2. Results of both methods using 2" cushions.

h / T / S-L	Video Method	Accelerometer Method
30" / 2" / 1.0 psi	98 g's 89 g's	95 g's 76 g's
30" / 2" / 1.5 psi	140 g's 139 g's	143 g's 140 g's
30" / 2" / 2.0 psi	185 g's 185 g's	175 g's 178 g's
30" / 2" / 2.5 psi	203 g's 203 g's	255 g's 260 g's
6" / 2" / 1.0 psi	129 g's 146 g's	105 g's 113 g's
6" / 2" / 1.5 psi	226 g's 201 g's	280 g's 275 g's
36" / 2" / 2.0 psi	236 g's 246 g's	310 g's 325 g's
36" / 2" / 2.5 psi	302 g's 255 g's	460 g's 460 g's
42" / 2" / 1.0 psi	159 g's 166 g's	140 g's 158 g's
42" / 2" / 1.5 psi	286 g's 226 g's	350 g's 345 g's
42" / 2" / 2.0 psi	256 g's 235 g's	430 g's 430 g's
42" / 2" / 2.5 psi	304 g's 284 g's	590 g's 570 g's

h = equivalent drop height in inches
T = cushion thickness in inches
S-L = cushion static loading in p.s.i.

Table 3. Results of both methods using 3" cushions.

h / T / S-L	Video Method	Accelerometer Method
30" / 3" / 1.0 psi	48 g's 46 g's	36 g's 35 g's
30" / 3" / 1.5 psi	43 g's 16 g's	47 g's 44 g's
30" / 3" / 2.0 psi	65 g's 52 g's	63 g's 65 g's
30" / 3" / 2.5 psi	85 g's 75 g's	103 g's 93 g's
36" / 3" / 1.0 psi	82 g's 106 g's	50 g's 54 g's
36" / 3" / 1.5 psi	146 g's 147 g's	93 g's 90 g's
36" / 3" / 2.0 psi	169 g's 133 g's	118 g's 110 g's
36" / 3" / 2.5 psi	190 g's 189 g's	158 g's 163 g's
42" / 3" / 1.0 psi	101 g's 99 g's	57 g's 63 g's
42" / 3" / 1.5 psi	171 g's 183 g's	125 g's 135 g's
42" / 3" / 2.0 psi	179 g's 202 g's	160 g's 168 g's
42" / 3" / 2.5 psi	236 g's 200 g's	245 g's 235 g's

h = equivalent drop height in inches
T = cushion thickness in inches
S-L = cushion static loading in p.s.i.

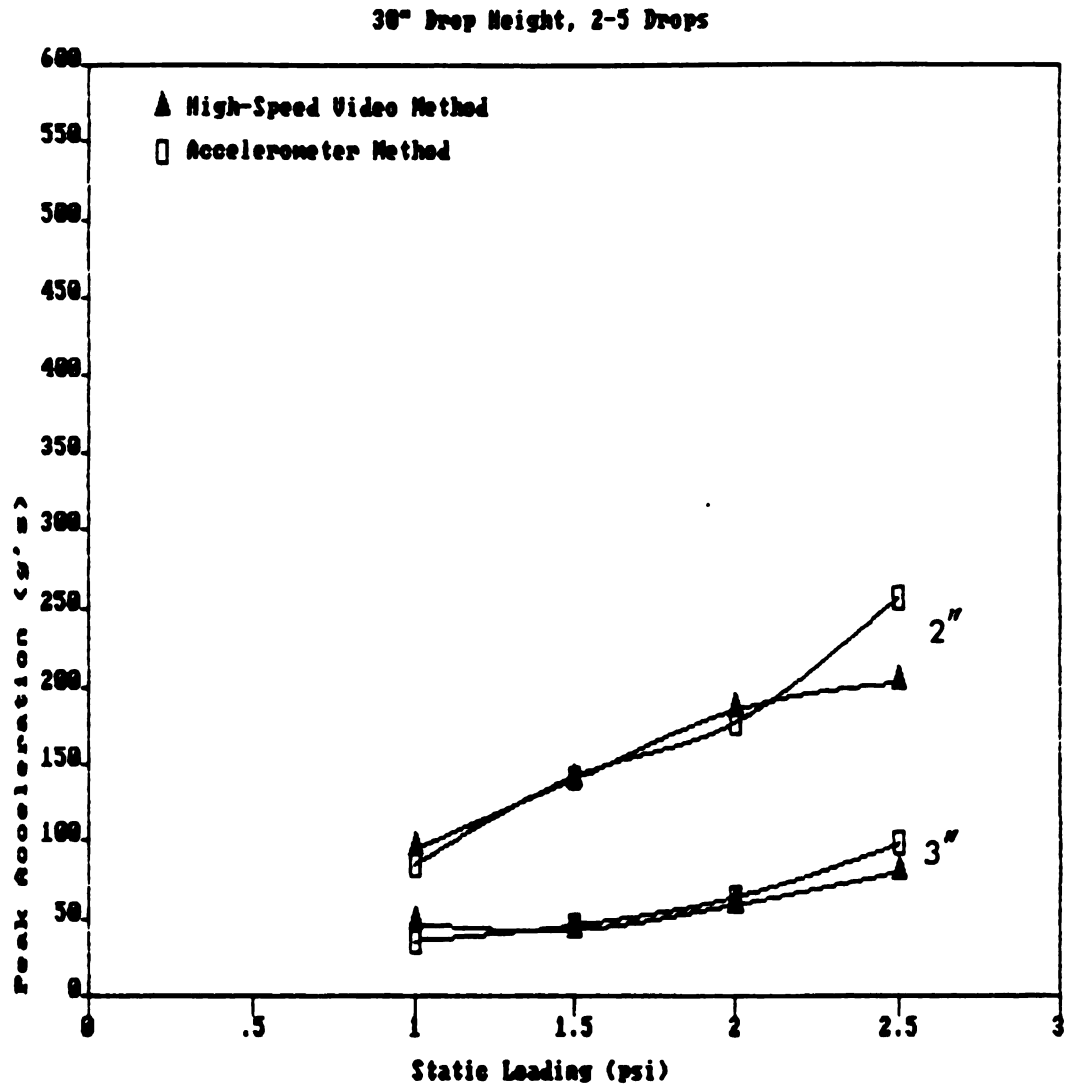


Figure 13. Results of both methods at a 30" drop height

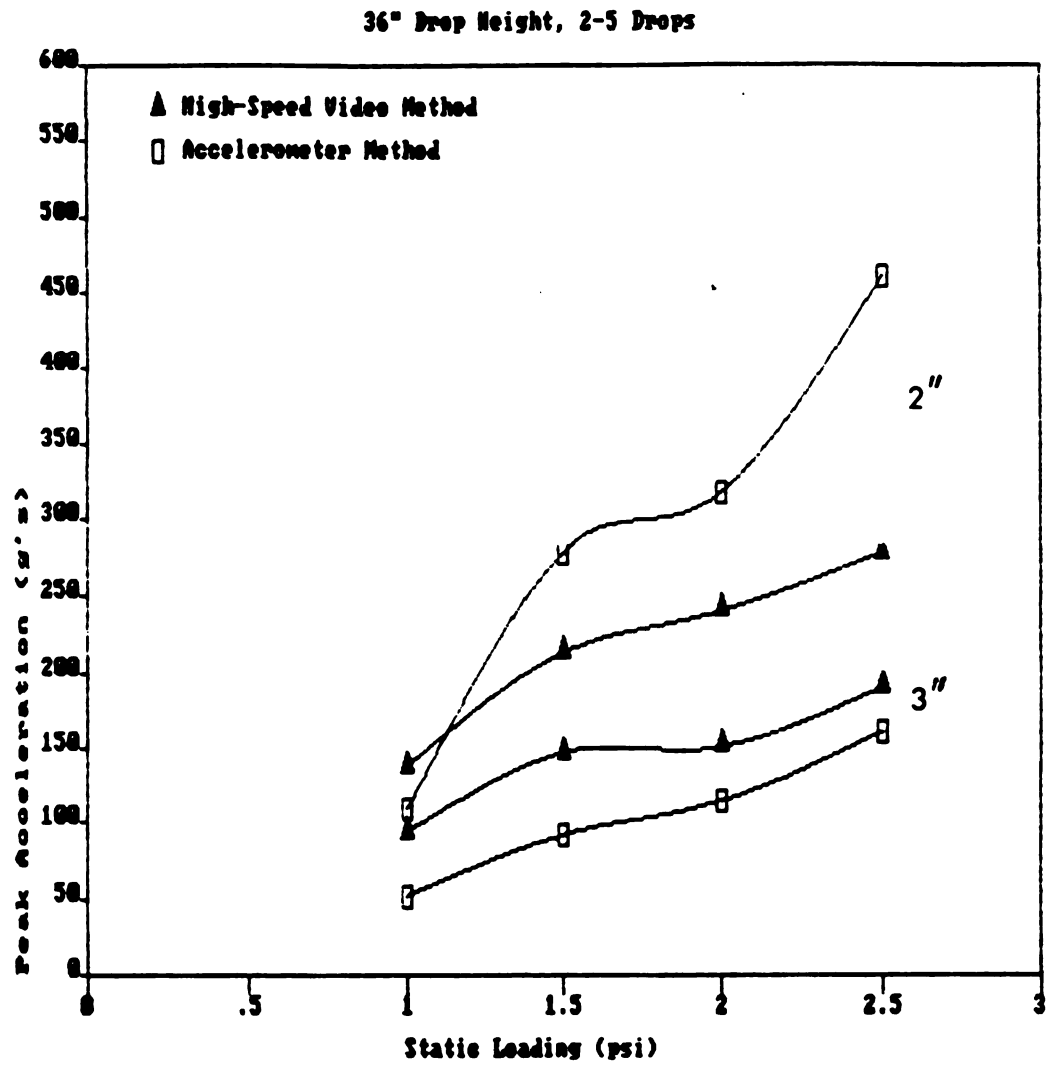


Figure 14. Results of both methods at a 36" drop height

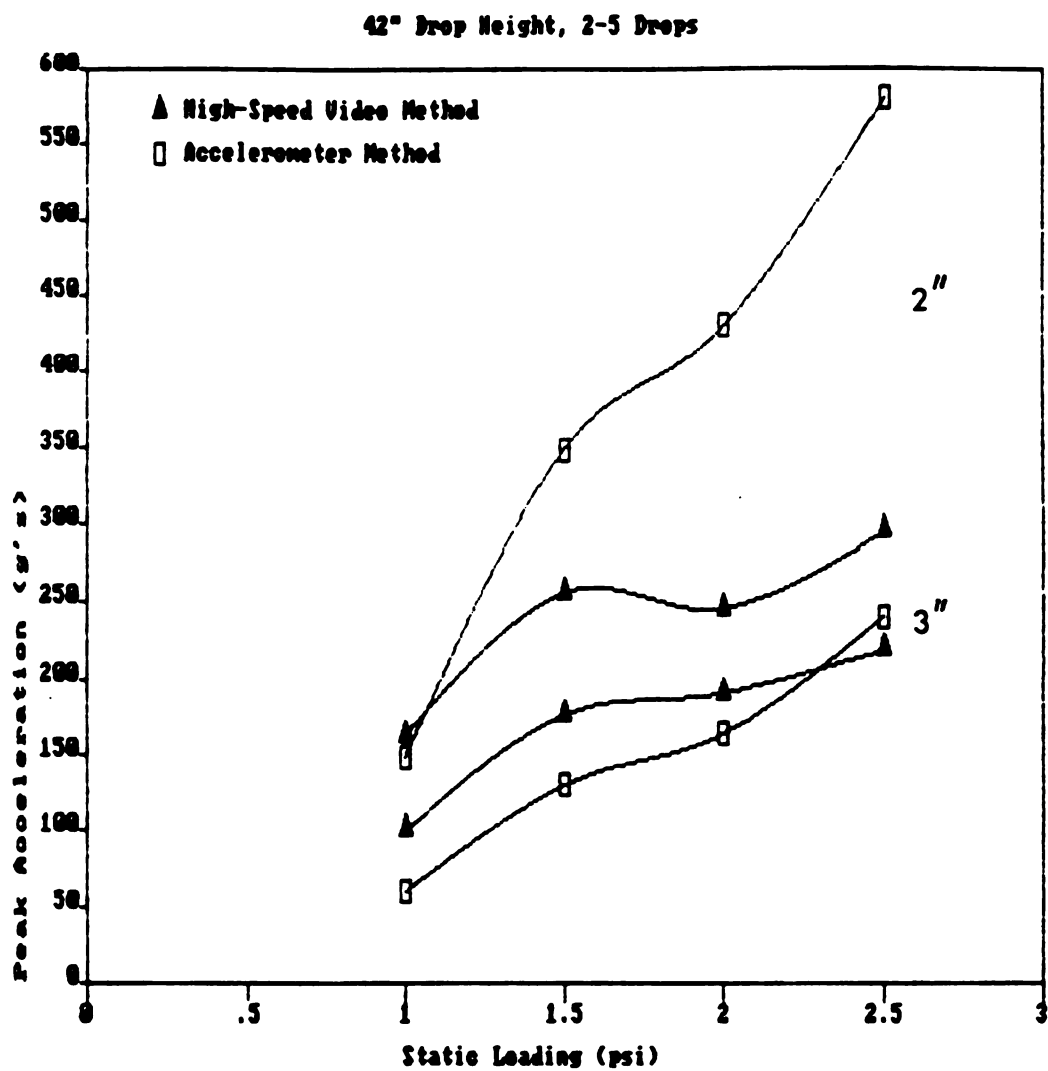


Figure 15. Results of both methods at a 42" drop height

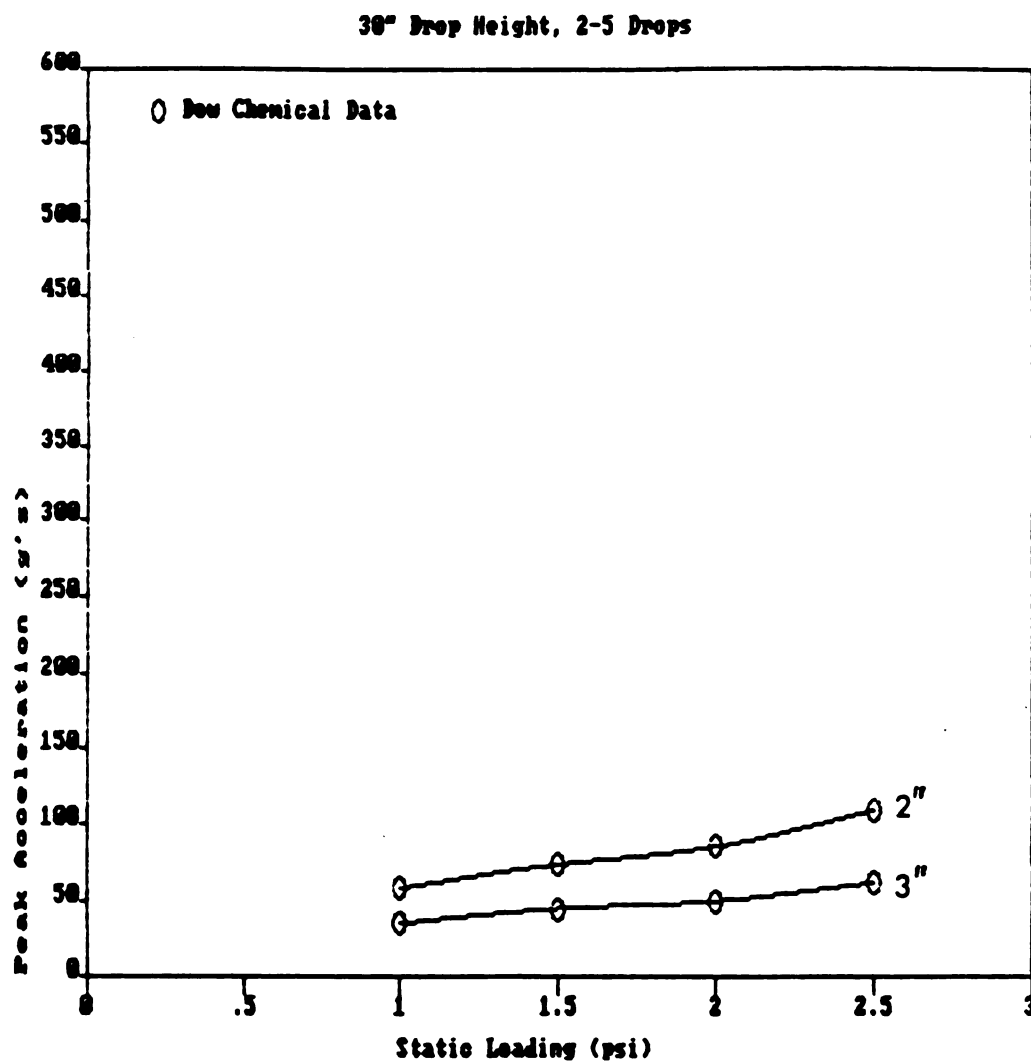


Figure 16. Dow Chemical Co. data for a 30" drop height

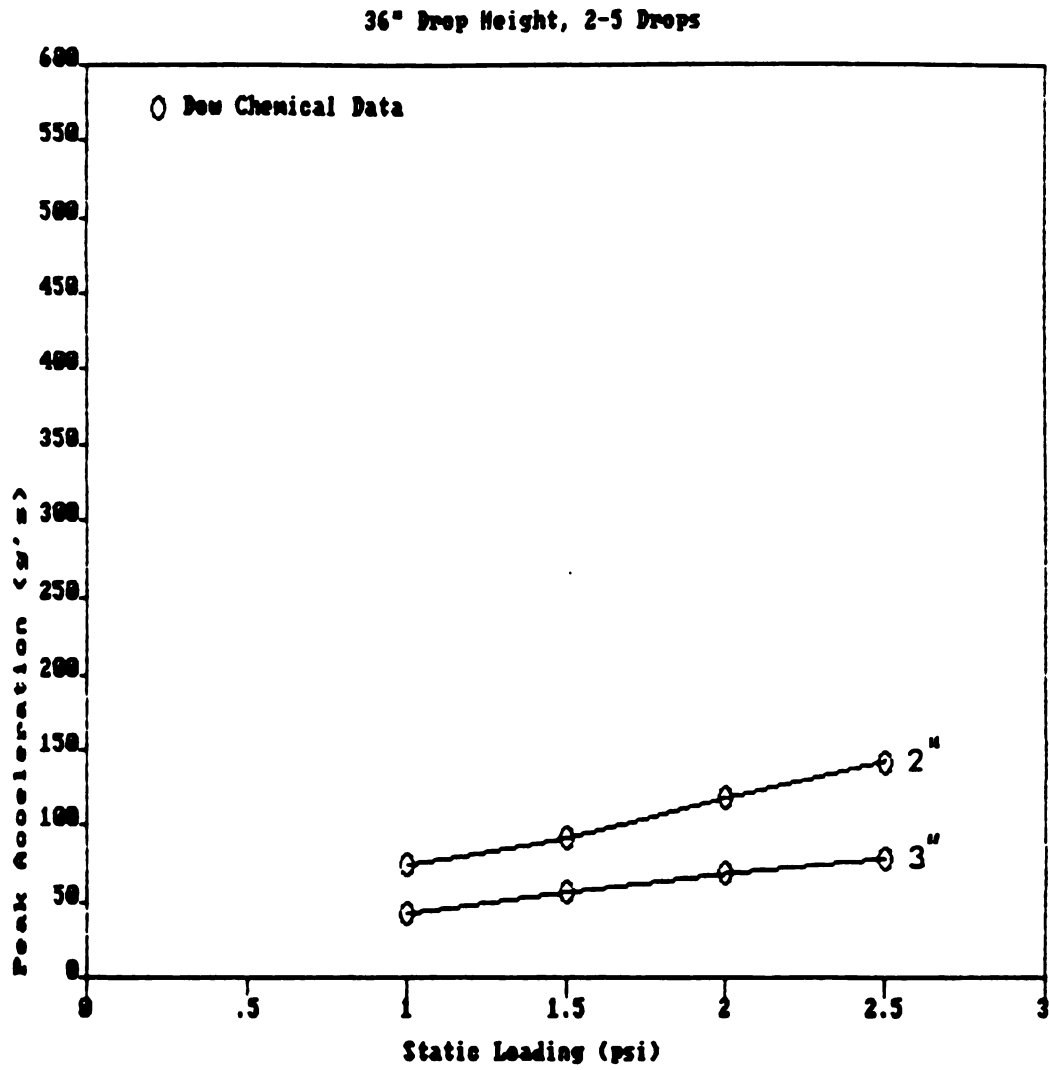


Figure 17. Dow Chemical Co. data for a 36" drop height

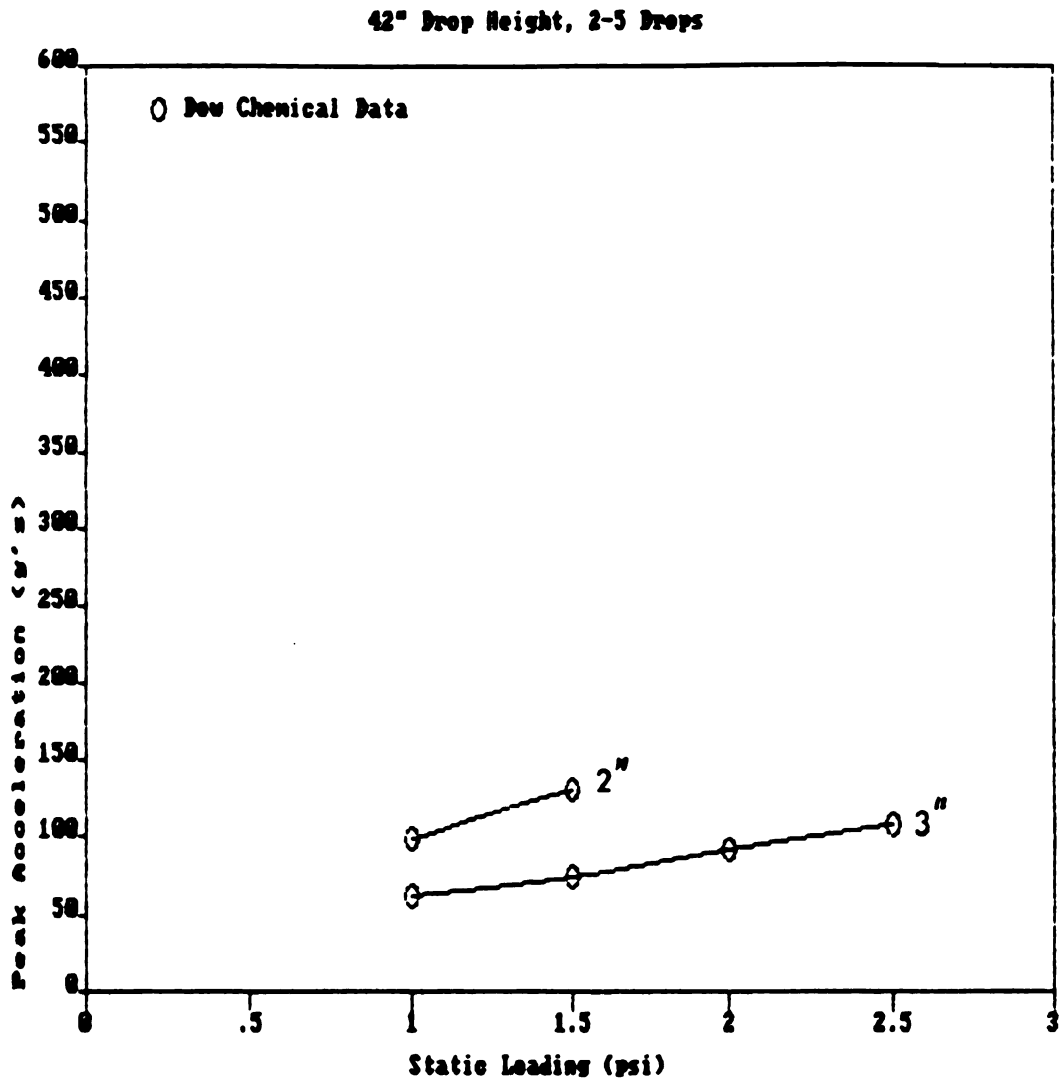


Figure 18. Dow Chemical Co. data for a 42" drop height

An additional benefit derived from using the high-speed video method is that the maximum cushion strain can be readily determined upon playback of the recording. In comparison, peak compression values are difficult to obtain, if not impossible, using the accelerometer method. The percent compressions during peak cushion deformation are calculated in Table 4 and shown in Figure 19. Note the extreme degree of cushion compression that occurs. Since the sides of the cushions were not observed to bulge appreciably during this compression, it follows that the volume of the cushion decreases dramatically. When this occurs, it is natural to assume that the density, and therefore the shock-pulse frequency experienced during the impact, increases dramatically.

Table 4. Percent total compression at peak cushion deformation for 2" and 3" thick cushions

S-L, sample		h=30"		h=36"		h=42"	
		T=2"	T=3"	T=2"	T=3"	T=2"	t=3"
1.0	A	82%	69%	89%	77%	91%	80%
1.0	B	83%	68%	90%	79%	92%	81%
1.5	A	92%	79%	99%	92%	99%	95%
1.5	B	95%	79%	97%	92%	99%	94%
2.0	A	96%	90%	99%	94%	99%	96%
2.0	B	98%	90%	99%	93%	99%	95%
2.5	A	99%	95%	99%	97%	99%	99%
2.5	B	99%	94%	99%	97%	99%	99%

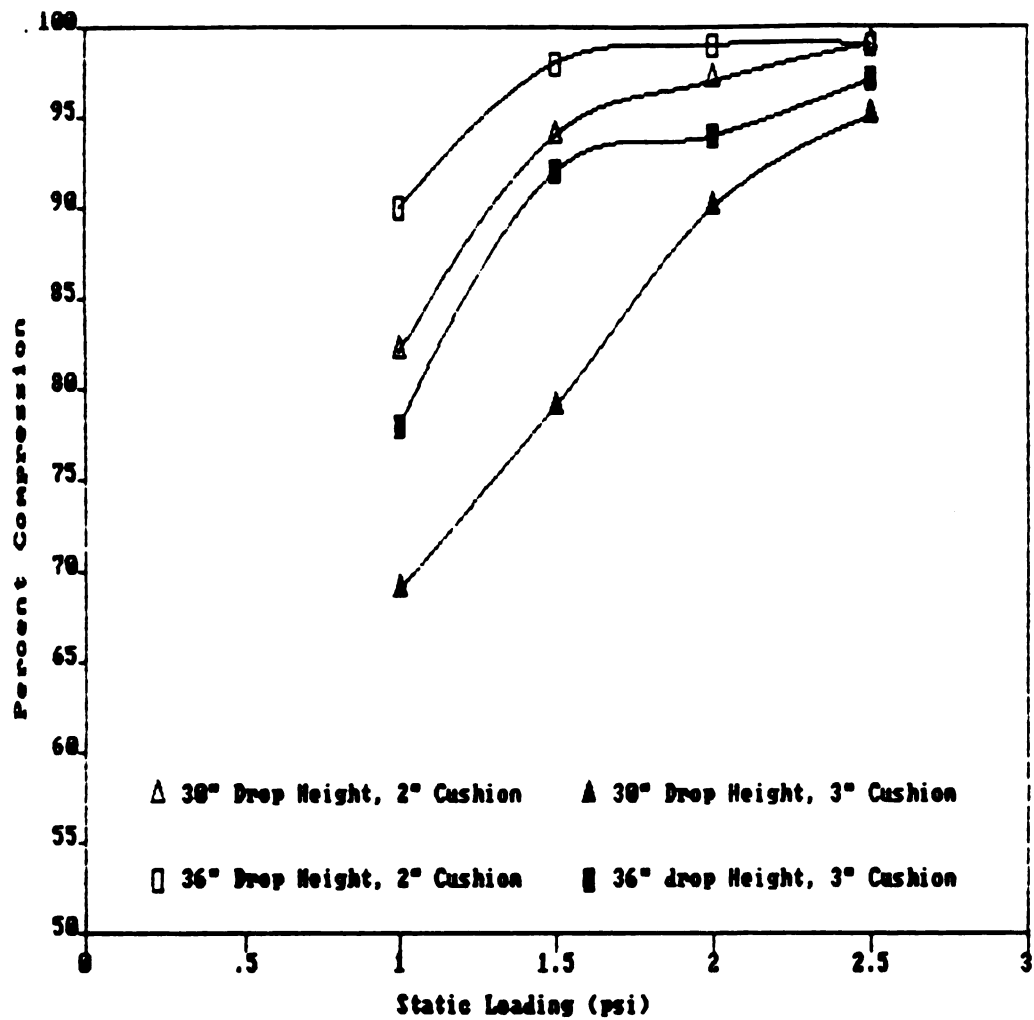


Figure 19. Percent compression at peak cushion displacement

CHAPTER 4
LIMITATIONS AND SUGGESTIONS
FOR FUTURE RESEARCH

When comparing the results obtained using the high-speed video method with the results obtained using the accelerometer method, it is clear that they may differ by as much as 100%. Only part of this discrepancy may be attributed to the high-speed video method. The remainder must be associated with the accelerometer method. Some obvious problems encountered during the drop tests using the high-speed video method that were not covered previously are covered below.

The contrast between the white cushion material and the moving test platen tended to decrease the most at peak displacement and this may have increased reading errors somewhat. Blurring or wash-out of certain "key" frames also resulted in greater reading errors. Ambiguous portions were double-checked in an attempt to reduce these errors.

Possible improvements include improving the contrast between the test platen and the cushion material, and using a faster camera speed (not currently possible on the camera used) with a greater resolution.

The contrast could also be improved by using the proper combination of surface characteristics. Both black-and-white paper, and black paper and aluminum foil were tried as platen coverings. The best results were obtained with the black-and-white paper. It is possible that other surface coverings may work better. This would have helped to positively locate the pixel corresponding to maximum cushion compression.

A faster camera speed would result in a smoother image on the video screen. Often the platen edge would "jump" 5 pixels or more in 1 "frame". While this occurred to a lesser extent at the critical moment of peak cushion deformation, it must still be assumed that reading errors occurred whenever the platen edge was blurred over a span of many pixels. A faster camera speed would also allow for greater resolution through "zooming-in" at the critical moment of peak cushion displacement. This assumes some prior knowledge of the approximate value of this peak compression however. Since a greater number of pixels would cover the smaller critical area, finer measurements could be made. This would in turn require a greater camera speed in order to maintain a reasonably smooth record.

The number of replications was limited by the availability of film for the Kodak video system. A test project using a greater number of replications may give better results but would require more film.

While the above arguments point to the high-speed video method as being responsible for the difference between the two methods, it is entirely likely that the accelerometer method is equally responsible for the discrepancy. The accelerometer method has an accuracy of $\pm 14\%$ (See Appendix B) which accounts for at least part of the difference.

The data shows a tendency towards greater disparity at higher static loadings with greater drop heights. See Figures 13 through 15. These impacts produce very high cushion strains (from 90% - 99%). In these instances, the density of the cushion increases dramatically (from 10 to 100 times in a very short time) which in turn raises the cushion stiffness and leads to high g values. The accelerometer must therefore be capable of responding to large changes in acceleration over small time periods and may not be able to do so depending on its natural frequency. The accelerometer may also be producing exaggerated data as

the result of shock amplification [10]. This may also help explain the variation in g's measured between the accelerometer results and the cushion curves for Ethafoam 220 provided by Dow Chemical. It does not however completely explain the variation between the high-speed video method and the other results. Further testing needs in order to more fully understand the errors inherent in each method.

CHAPTER 5

CONCLUSION OF RESULTS

The high-speed video method is a useful alternative for determining peak acceleration during cushioned impacts. While there are problems associated with this method, few affect the accuracy of the results. Furthermore these problems, outlined in Chapter 2, may be expected to decline as the technology of high-speed video becomes more prevalent. The high-speed video method also is capable of several functions not currently possible using the accelerometer method.

Since a time record is made of the entire compression-expansion cycle, peak displacement is very easy to obtain. This study shows that cushions deform much more upon impact than previously thought. This is shown in Figure 19. In addition, since there is no contact with the test sample, it is possible to record the dynamics of cushioned drops on extremely lightweight samples. One possible example would be to measure the dynamic characteristics of thin films without having to deal with the weight of an accelerometer. Any analysis situation where the weight of the accelerometer is a concern is a possible candidate for the high-speed video method.

APPENDIX A:
Experimental Data

Table 5. Position of Platen vs. Time for 2" cushions

h / T / S-L	Cshn				Peak	Cshn			
	Top	-9	-6	-3		+1	+6	+9	Btm
30"/ 2"/ 1.0 psi	93	66	46	30	23	29	41	56	8
	89	66	45	30	22	26	38	52	8
30"/ 2"/ 1.5 psi	92	68	47	27	15	21	34	50	8
	92	62	40	21	12	21	36	52	8
30"/ 2"/ 2.0 psi	92	69	47	27	11	18	33	49	8
	92	69	47	27	11	18	32	48	9
30"/ 2"/ 2.5 psi	91	68	45	24	9	19	34	50	8
	91	66	43	23	9	20	36	52	8
36"/ 2"/ 1.0 psi	94	71	46	27	18	26	42	60	9
	90	74	50	29	17	24	40	57	9
36"/ 2"/ 1.5 psi	89	76	51	27	11	23	41	60	10
	89	71	45	23	12	26	43	62	10
36"/ 2"/ 2.0 psi	93	74	49	26	9	21	39	58	9
	91	75	49	26	9	22	40	58	9
36"/ 2"/ 2.5 psi	90	76	53	28	7	22	38	56	6
	91	74	49	25	9	24	41	60	9
42"/ 2"/ 1.0 psi	86	70	47	25	13	20	35	53	6
	82	69	44	22	12	22	39	57	6
42"/ 2"/ 1.5 psi	81	73	47	23	3	15	33	49	3
	79	69	42	19	5	17	35	54	5
42"/ 2"/ 2.0 psi	82	75	48	25	8	20	38	57	8
	81	70	44	20	8	23	41	61	8
42"/ 2"/ 2.5 psi	107	102	76	51	31	45	64	81	32
	109	98	73	47	31	47	64	81	32

all measurements in pixels.

h = equivalent drop height in inches

T = cushion thickness in inches

S-L = cushion static loading in p.s.i.

Table 6. Position of platen vs. time for 3" cushions

h / T / S-L	Cshn				Peak	Cshn			
	Top	-9	-6	-3		+3	+6	+9	Btm
30"/ 2"/ 1.0 psi	118	61	50	43	41	44	50	61	~10
	116	64	54	46	44	47	53	63	~11
30"/ 2"/ 1.5 psi	118	59	46	36	33	35	42	52	~12
	115	57	44	33	32	34	42	52	~11
30"/ 2"/ 2.0 psi	117	52	37	27	24	28	37	48	14
	117	51	37	27	25	29	39	51	15
30"/ 2"/ 2.5 psi	113	53	37	24	20	25	35	48	15
	114	47	32	22	21	28	39	52	15
36"/ 2"/ 1.0 psi	117	67	50	37	33	38	48	62	8
	115	63	46	34	30	37	48	63	8
36"/ 2"/ 1.5 psi	116	62	42	25	17	24	37	52	8
	114	63	43	26	17	23	35	50	8
36"/ 2"/ 2.0 psi	114	63	42	24	14	21	34	50	8
	114	58	38	21	15	23	37	53	8
36"/ 2"/ 2.5 psi	114	63	41	22	11	19	33	50	8
	112	62	41	22	11	19	34	50	8
42"/ 2"/ 1.0 psi	121	69	49	35	29	34	45	60	6
	119	69	48	34	28	33	46	61	6
42"/ 2"/ 1.5 psi	116	66	42	22	11	18	33	51	5
	114	68	44	24	11	17	32	50	4
42"/ 2"/ 2.0 psi	112	63	40	18	8	17	33	52	4
	113	70	45	23	9	16	32	49	4
42"/ 2"/ 2.5 psi	114	71	45	23	8	17	34	53	8
	116	69	44	22	9	17	35	54	9

all measurements in pixels

h = equivalent drop height in inches

T = cushion thickness in inches

S-L = cushion static loading in p.s.i.

Table 7. Data for accelerometer method, 2" cushions

h / T / S-L	Oscilloscope	Pulse	Acceleromtr	Accl.
	Setting	Height in Div.	Sensitivity	(g's)
30"/ 2"/ 1.0 psi	50 mv/div	3.8 div	2.0 mv/g	95 g
	20 mv/div	7.6 div	2.0 mv/g	76 g
30"/ 2"/ 1.5 psi	50 mv/div	5.7 div	2.0 mv/g	143 g
	50 mv/div	5.6 div	2.0 mv/g	140 g
30"/ 2"/ 2.0 psi	50 mv/div	7.0 div	2.0 mv/g	175 g
	50 mv/div	7.1 div	2.0 mv/g	178 g
30"/ 2"/ 2.5 psi	100 mv/div	5.1 div	2.0 mv/g	255 g
	100 mv/div	5.2 div	2.0 mv/g	260 g
36"/ 2"/ 1.0 psi	50 mv/div	4.2 div	2.0 mv/g	105 g
	50 mv/div	4.5 div	2.0 mv/g	113 g
36"/ 2"/ 1.5 psi	100 mv/div	5.6 div	2.0 mv/g	280 g
	100 mv/div	5.5 div	2.0 mv/g	275 g
36"/ 2"/ 2.0 psi	100 mv/div	6.2 div	2.0 mv/g	310 g
	100 mv/div	6.5 div	2.0 mv/g	325 g
36"/ 2"/ 2.5 psi	200 mv/div	4.6 div	2.0 mv/g	460 g
	200 mv/div	4.6 div	2.0 mv/g	460 g
42"/ 2"/ 1.0 psi	50 mv/div	5.6 div	2.0 mv/g	140 g
	50 mv/div	6.3 div	2.0 mv/g	158 g
42"/ 2"/ 1.5 psi	200 mv/div	3.5 div	2.0 mv/g	350 g
	100 mv/div	6.9 div	2.0 mv/g	345 g
42"/ 2"/ 2.0 psi	200 mv/div	4.3 div	2.0 mv/g	430 g
	200 mv/div	4.3 div	2.0 mv/g	430 g
42"/ 2"/ 2.5 psi	200 mv/div	5.9 div	2.0 mv/g	590 g
	200 mv/div	5.7 div	2.0 mv/g	570 g

h = equivalent drop height in inches

T = cushion thickness in inches

S-L = cushion static loading in p.s.i.

Table 8. Data for accelerometer method, 3" cushion

h / T / S-L	Oscilloscope Setting	Pulse Height in Div.	Acceleromtr Sensitivity	Accl. (g's)
30"/ 2" / 1.0 psi	20 mv/div	3.6 div	2.0 mv/g	36 g
	20 mv/div	3.5 div	2.0 mv/g	35 g
30"/ 2" / 1.5 psi	20 mv/div	4.7 div	2.0 mv/g	47 g
	20 mv/div	4.4 div	2.0 mv/g	44 g
30"/ 2" / 2.0 psi	20 mv/div	6.3 div	2.0 mv/g	63 g
	20 mv/div	6.5 div	2.0 mv/g	65 g
30"/ 2" / 2.5 psi	50 mv/div	4.1 div	2.0 mv/g	103 g
	50 mv/div	3.7 div	2.0 mv/g	93 g
36"/ 2" / 1.0 psi	50 mv/div	2.0 div	2.0 mv/g	50 g
	20 mv/div	5.4 div	2.0 mv/g	54 g
36"/ 2" / 1.5 psi	50 mv/div	3.7 div	2.0 mv/g	93 g
	50 mv/div	3.6 div	2.0 mv/g	90 g
36"/ 2" / 2.0 psi	50 mv/div	4.7 div	2.0 mv/g	118 g
	50 mv/div	4.4 div	2.0 mv/g	110 g
36"/ 2" / 2.5 psi	50 mv/div	6.3 div	2.0 mv/g	158 g
	50 mv/div	6.5 div	2.0 mv/g	163 g
42"/ 2" / 1.0 psi	20 mv/div	5.7 div	2.0 mv/g	57 g
	20 mv/div	6.3 div	2.0 mv/g	63 g
42"/ 2" / 1.5 psi	50 mv/div	5.0 div	2.0 mv/g	125 g
	50 mv/div	5.4 div	2.0 mv/g	135 g
42"/ 2" / 2.0 psi	100 mv/div	3.2 div	2.0 mv/g	160 g
	100 mv/div	6.7 div	2.0 mv/g	168 g
42"/ 2" / 2.5 psi	100 mv/div	4.9 div	2.0 mv/g	245 g
	100 mv/div	4.7 div	2.0 mv/g	235 g

h = equivalent drop height in inches

T = cushion thickness in inches

S-L = cushion static loading in p.s.i.

Appendix B
Measurement Errors

The errors associated with this study may be divided into accelerometer method errors, drop tester errors, and video method errors.

Accelerometer method errors:

Accelerometer: $\pm 2\%$

Coupler: $\pm 5\%$

Oscilloscope: $\pm 3\%$

Reading error: $\pm 4\%$

Sensitivity error: unknown

(See Appendix C)

Total Error : $\pm 14\%$

Drop tester height errors:

Drop height error: $\pm 2\%$

Total Error : $\pm 2\%$

Video method errors:

An obvious technique error resulting in the blurring of some of the recorded video images is known to have occurred. When this occurred, the exact position of the platen edge was not easily determined. The range of uncertainty was at most 1 pixel. To maximize the effect of this uncertainty on the instantaneous acceleration [eq.15], the displacements y_1, y_3, y_5 , and y_7 should be increased by 1 pixel, and the displacements y_2, y_4 , and y_6 should be decreased by 1 pixel. This is illustrated in Figure 20. Likewise, to minimize the instantaneous acceleration, the displacements

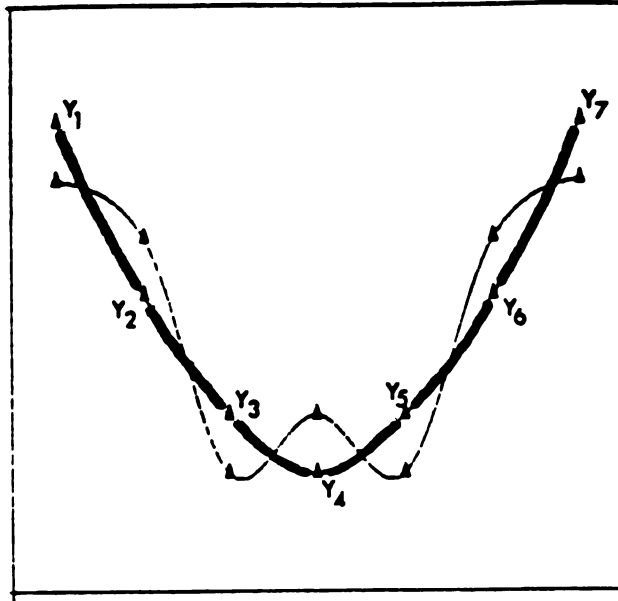


Figure 20. Video error analysis, maximum case

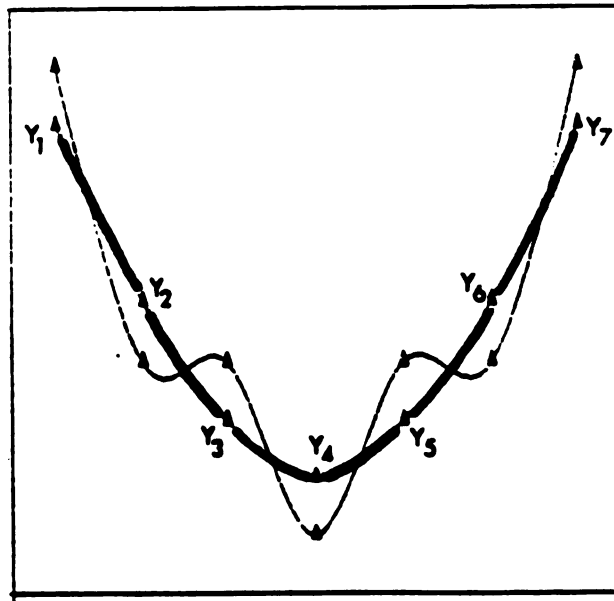


Figure 21. Video error analysis, minimum case

y_1 , y_3 , y_5 , and y_7 should be decreased by 1 pixel and displacements y_2 , y_4 , and y_6 should be increased by 1 pixel. This is shown in Figure 21. Since the maximum and minimum accelerations obtained in this way represent the two extremes (assuming no more than a ± 1 pixel error) the actual acceleration is expected to be somewhere in between them. The average error for the acceleration associated with this range of values using the test data is $\pm 25\%$. A more accurate assessment of the position error is .5 pixels, which would reduce the error to $\pm 12.5\%$.

Another source of error the changing camera angle. See Figure 6. This error is greatest at peak displacement if the camera is initially focused on the top of the cushion (as in these tests). By focusing on the cushion bottom, this error would have been less. This error was estimated to be $\pm 2\%$ for a typical drop.

Total Error : $\pm 27\%$

Appendix C
Finite Difference Analysis

The method of splines involves fitting a polynomial function to a collection of equally spaced data points. The degree of the polynomial is determined by the number of data points to be fitted. In general, if there are N points to be fitted, the degree of the polynomial is $N-1$. The greater the degree of the polynomial, the better it is expected to represent the data. For example, to fit a quadratic spline to the 3 data points represented in Figure 22.;

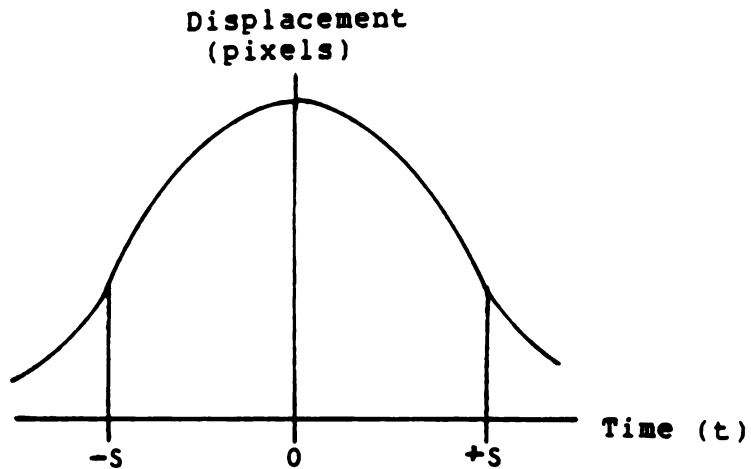


Figure 22. Typical 3-point data spread

A quadratic spline can be fitted to these points by forcing the displacement vs. Time equation,

$$Y = a + b(t) + c(t)^2 \quad [\text{Eq.4}]$$

to fit the data, which requires that:

$$\text{When: } t = -s, \quad Y = a - b(s) + c(s)^2 \quad [\text{Eq.5}]$$

$$\text{When: } t = 0 \quad Y = a + b(0) + c(0) = a \quad [\text{Eq.6}]$$

$$\text{When: } t = +s \quad Y = a + b(s) + c(s)^2 \quad [\text{Eq.7}]$$

The solution of this system of equations for c gives:

$$c = \frac{y + y - 2y}{2(s^2)} \quad [\text{Eq.8}]$$

The values of a and b are not needed as the acceleration is the second derivative of Eq.4 with respect to time and this involves only c;

$$Y = a + b(t) + c(t) \quad [\text{Eq.4}]$$

$$Y' = 0 + b(1) + 2c(t)$$

$$Y'' = 0 + 0 + 2c = \frac{y - 2y + y}{(s^2)} \quad [\text{Eq.9}]$$

The value of y'' in Eq.9 is the peak deceleration associated with the 3-point finite difference approximation to the true acceleration.

An improved finite difference expression for the acceleration uses a 5-point data spread as illustrated in Figure 23.

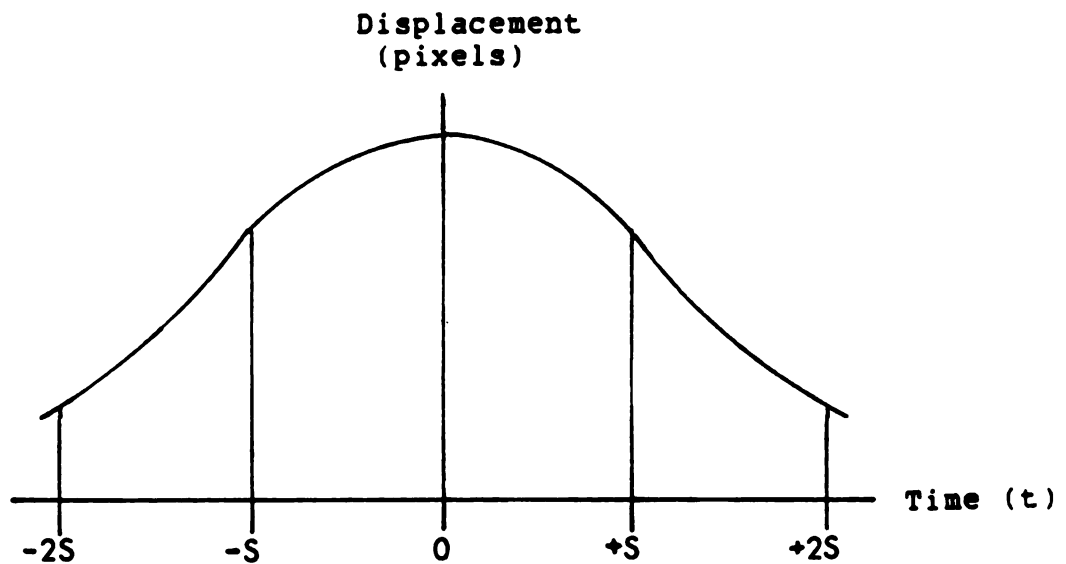


Figure 23. Typical 5-point data spread

The spline to be fitted to this data is a quadratic polynomial,

$$Y = a + b(t) + c(t^2) + d(t^3) + e(t^4) \quad [\text{Eq.10}]$$

$$Y'' = 0 + 0 + 2c + 6d(t) + 12e(t^2) \quad [\text{Eq.11}]$$

Eq. 11 is the instantaneous acceleration at any given moment in time, (t). At t=0 where the deceleration is desired, the result is seen to be dependent again only on c;

$$Y'' = 2c \quad [\text{Eq.12}]$$

The solution to the system of equations obtained by forcing the spline in Eq.10 to fit the displacement y at the five sampling times in Figure 23 gives;

$$c = \frac{-y + 16y - 30y + 16y - y}{24(s^2)} \quad [\text{Eq.13}]$$

Therefore, by substituting Eq.13 into Eq.12;

$$g = Y'' = \frac{-y + 16y - 30y + 16y - y}{12(s^2)} \quad [\text{Eq.14}]$$

Fitting a 7-point data spread as in Figure 24 to a 6th order polynomial gives an even better finite difference approximation to the true acceleration,

$$[\text{Eq.15}]$$

$$g = \frac{2(y_1) - 27(y_2) + 270(y_3) - 490(y_4) + 270(y_5) - 27(y_6) + 2(y_7)}{180(s^2)}$$

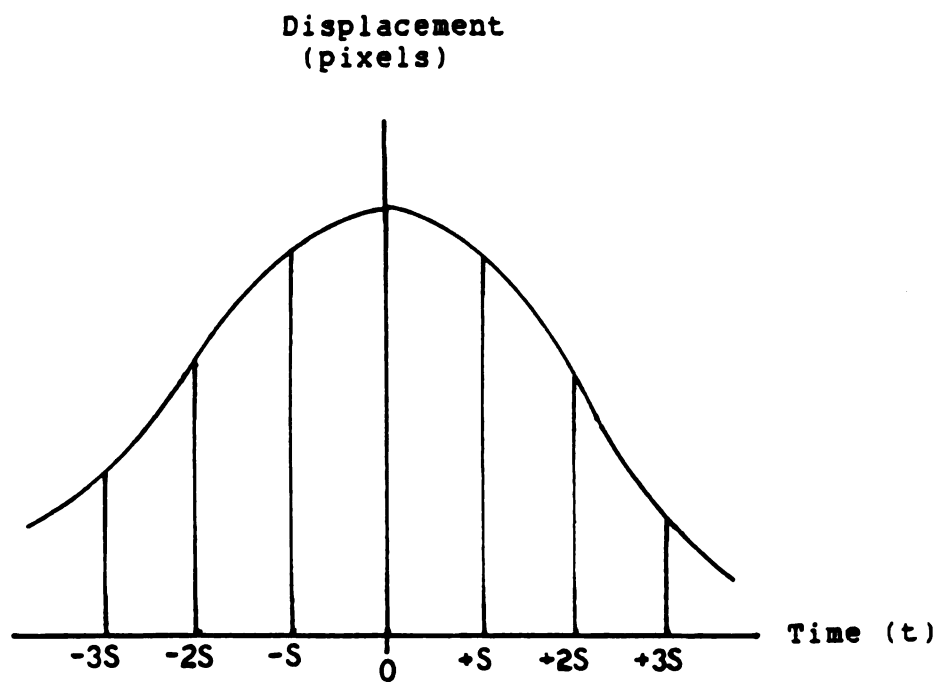


Figure 24. Typical 7-point data spread

APPENDIX D
EQUIPMENT SPECIFICATIONS

Cushion Test Machine: Lansmont model 23 cushion tester

Machine Type	Free-fall
Platen Size	9" x 9"
Platen Weight	12.8 lbs.
Ballast Kits	1 x 6.4 lbs. 1 x 12.8 lbs. 2 x 25.6 lbs. 2 x 32.0 lbs.
Controls	24 vdc control system (standard)
Table Lifting/Positioning	By electric hoist
Maximum Equivalent Free-Fall Drop Height	45 inches
Power Requirements	115 vac, 60 hz, 8 amps.
Pneumatic Requirements	Air or nitrogen at 80 - 120 p.s.i.

Accelerometer: PCB model 305 A05 piezoelectric

Resonant Frequency	40 khz
Reference Voltage Sensitivity	2.00 mv/g @100 hz

Note: Although this value was used for this study, it must be assumed that an error due to the frequency response characteristics of the accelerometer was present. For best results, the accelerometer used should be calibrated over the entire range of shock frequencies expected.

Range	1000 g's
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Coupler: Kistler model 5116

Frequency Response	5% from .5 hz to 250 khz
Input/Output Coupling	Input is AC coupled to output buffer amplifier.
Full Scale Signal	20 v p-p
Impedance	20 ohms
Noise	.18 mv rms
Power Source	110 vac, 60 hz, 10 mA

Oscilloscope: Kikusui model D55 6520

Screen Type	Direct viewing, bi-stable storage tube.
Acceleration Voltage	Appx. 3.15 Kv
Writing Speed	25 div/msec
Vertical Sensitivity	5 mv at 5v/div
Frequency Bandwidth	DC - 20 mhz, -3 dB
Rise Time	17 nsec
Input Impedance	1 Mega-Ohm
Maximum Allowable Input Voltage	400 v

High-Speed Video Camera: Kodak Ectapro 1000

Imager Resolution	192 x 240 pixels
Imager Lens Mount	C-mount
Tripod Mount	1/4-20 and 3/8-16 standard ANSI
Recording Technique	Linear FM
Recording Medium	1/2" high-density magnetic tape
Tape Handling	Cassette (700 ft)
Recording Rates	30,60,125,250,500, 1000 frames/sec
Recording Time	From 30 seconds to 16 minutes based on speed used
Playback	Continuous, jog, or single step
Video Output	NTSC and PAL
Power Requirements	110 vac, 60 hz, 8 amps

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