PACKAGE ENGINEERING, DESIGN AND TESTING

A STEP-BY-STEP APPROACH FOR PROTECTION OF FRAGILE PRODUCTS

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I. INTRODUCTION

The purpose of this paper is to assist engineers and designers in the analysis of requirements for protective package systems. The basics of product fragility testing, package design, and package testing from a dynamics standpoint will be covered.

There are numerous sources that one can turn to for precise technical data on the behavior of products and materials in a dynamic environment. But how does one use this information to help design a better package? How does one determine what is important and what is not? How does one go about designing an optimum package system or even recognizing when that system has been designed? Finally, how does one know if the final numbers are believable or if significant questions exist which would benefit from further analysis? These and other areas will be investigated.

Packaging dynamics is a relatively straightforward application of simple physics. However, one does not need a working knowledge of calculus in order to understand dynamics in packaging. Knowledge of a few physical laws and the relationship between variables is all that's necessary to begin designing effective and optimum dynamic package systems.

II. DEFINITION OF TERMS

Packaging Dynamics refers to active forces; that is, it implies motion rather than static forces. Types of dynamic input include **SHOCK** or **IMPACT** which is defined as a sudden severe non-periodic excitation of an object, and **VIBRATION** which is defined as oscillation of an element or system about some fixed reference point. While other inputs including temperature, humidity, compression and static electric discharge may be important for a particular design, they are not dealt with here. Refer to Appendix I for a complete definition of terms list.

Note that metric units are cited as primary values with English units included in brackets whenever feasible.

SHOCK

In order to properly understand the phenomenon of shock, it is necessary to define the terms **DISPLACEMENT, VELOCITY** and **ACCELERATION,** all which play a role in talking about a shock pulse.

DISPLACEMENT (D) is a measure of distance, typically in millimeters or meters in the Metric system, inches or feet in the English system. (It is the integral of velocity.)

VELOCITY (V) is the rate at which displacement changes. It is measured in meters per second, kilometers per hour (inches/sec, miles per hour) or similar units. It is a vector quantity which means it has both magnitude and direction. (It is the integral of acceleration and the differential of displacement with respect to time.)

ACCELERATION (A) is the rate at which velocity changes. It is measured in meters/sec^2, inches/sec^2 or similar units. It is generally defined as a multiple of Earth's gravitational acceleration at sea level (g) = 9.8 m/sec^2 (386 in/sec^2) which is a constant. Therefore, 10 G equals 10 (ten) times 9.8 m/sec^2. Peak acceleration is also the peak or the high point of the acceleration vs. time pulse. Note that **DECELERATION** is negative acceleration. The two terms are often used interchangeably although acceleration properly refers to an increasing rate of velocity change whereas deceleration describes a decreasing rate of velocity change. (Acceleration is the differential of velocity with respect to time.)

VELOCITY CHANGE (ΔV) is another unit often used in dynamic packaging work. It refers to the difference between initial and final velocity and can be thought of as a measure of energy dissipated at impact. It is equal to the area under the acceleration vs. time pulse (the integral of the pulse).

ΔV = Peak acceleration x effective duration

For a body in freefall, the following also applies:

$$\Delta V = V_i - (-V_r) = V_i + V_r = (1+e)\sqrt{2gh}$$

where: $e = V_r / V_i$ (coefficient or restitution)
$g = 9.8$ m/sec^2 (386 in/sec^2)
h = freefall drop height in meters (or inches)
i = impact
r = rebound

Velocity change is a crucial concept which can help determine the accuracy of test results and help predict the required shock response characteristics for a given package system.

VIBRATION

VIBRATION is periodic or repetitive motion with respect to a fixed reference point.

AMPLITUDE refers to the maximum excursion from a reference point measured in acceleration units (m/s^2 or G's).

FREQUENCY is a measure of the number of cycles per time period, typically cycles per second or hertz (Hz).

PERIOD refers to the time necessary to complete one cycle. This is the inverse of frequency.

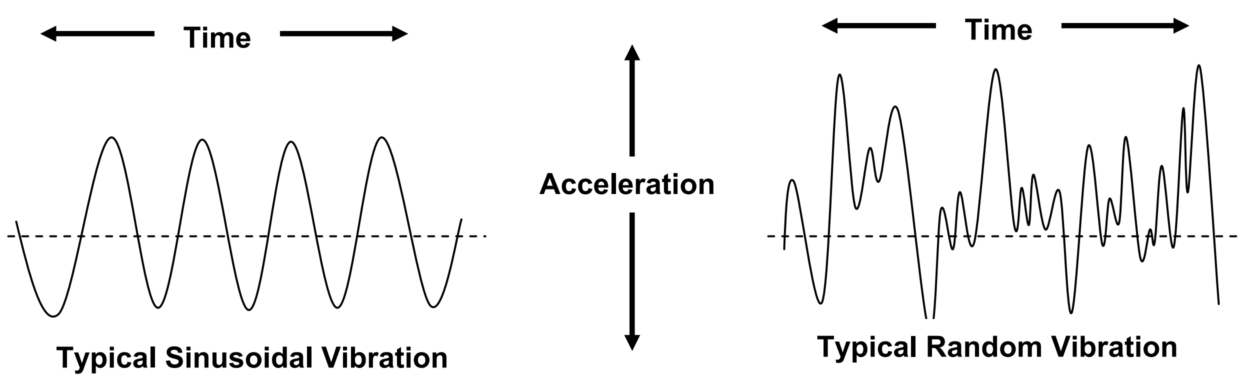
SINUSOIDAL VIBRATION refers to repetitive motion which can be traced as a sinusoidal curve on an acceleration vs. time plot. (See Figure 1)

RANDOM VIBRATION refers to periodic motion where the frequency and amplitude change randomly with respect to time. (See Figure 1)

RESONANCE is that characteristic of all spring/mass systems where the response of the system to (forced) vibration input is greater than the input itself. The frequency where this occurs is called the natural frequency or resonant frequency of that system.

TRANSMISSIBILITY is a measure of the maximum response acceleration of a spring/mass system in resonance. It is normally expressed as a ratio of the input (A_r / A_i). It is a measure of the damping (See Appendix I) exhibited by a spring/mass system in resonance.

FIGURE 1
SINUSOIDAL AND RANDOM VIBRATION



(Source: WESTPAK, Inc.)

III. THE CONCEPT OF A PROTECTIVE PACKAGE

A protective package can be thought of conceptually as that device which provides a protective interface between a fragile product and a potentially harmful environment. The potentially harmful input from the environment can generally be categorized in terms of physical forces such as shock, vibration, compression or similar inputs. **It is the job of the packaging engineer to determine what level of input is likely when a product is shipped from the point of manufacture to its ultimate destination, and to provide the protection necessary. This includes the assessment of basic product ruggedness as well.**

The process of designing an efficient protective package requires knowledge of three distinct areas:

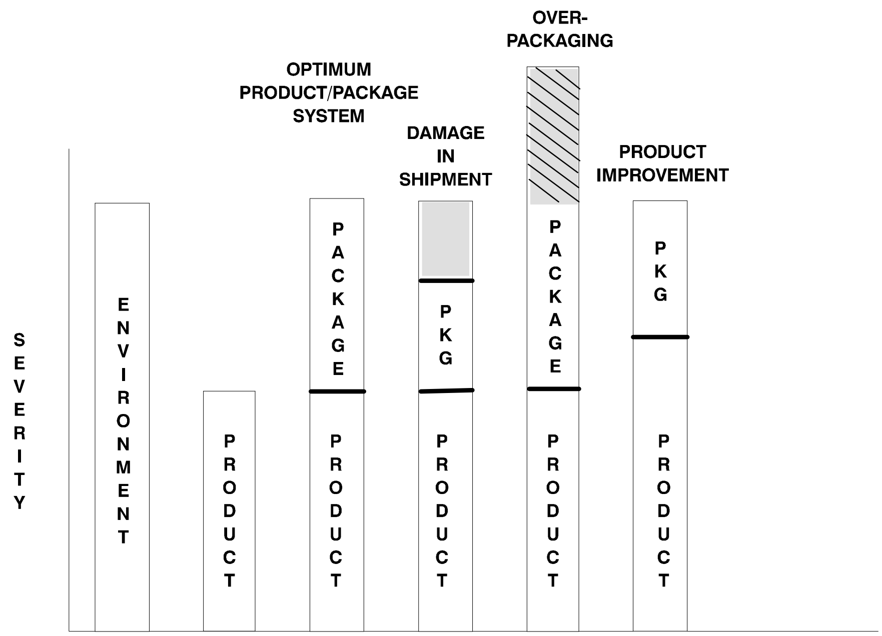
A. The severity of the distribution environment in terms of its damage-producing potential.

B. The ruggedness or sensitivity of the product to the effects of potentially harmful inputs identified in A above.

C. The capability of package materials or designs to mitigate or "filter out" the harmful effects of those inputs.

The "optimum" package system consists of a product of known ruggedness and a package which together provide sufficient resistance to damage from those inputs likely to be encountered in the distribution environment. The chart in Figure 2 graphically demonstrates this concept.

Figure 2



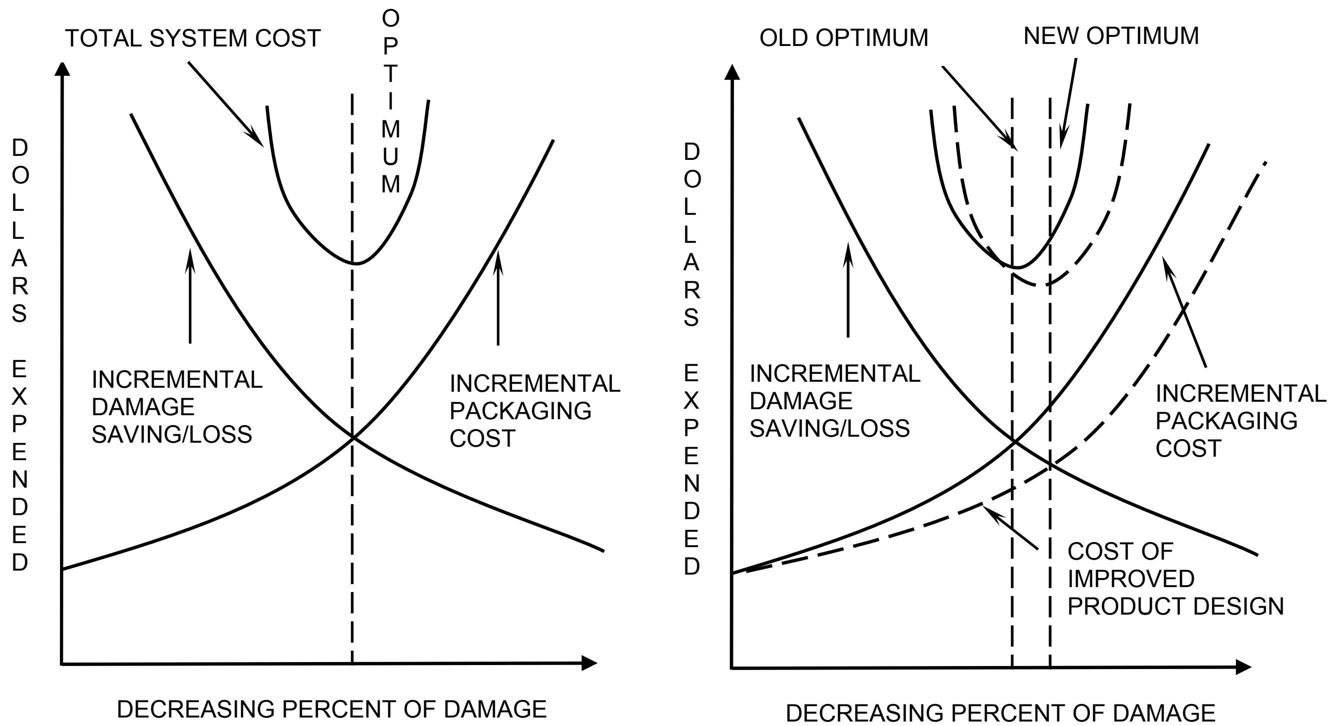
PROTECTIVE PACKAGE: **That device which limits environmental input to a level below product fragility**

(Source: Lansmont Corporation)

The relationship between these areas has been expressed by the equation **PDE = PR + P** (Physical Distribution Environment = Product Ruggedness + Package). Thus the job of package design for fragile products amounts to defining and quantifying the variables in this simple equation.

Since the product and package must work together as a system to resist the forces of the distribution environment, it is obvious that a tradeoff can be made between the amount of ruggedness built into the product and the amount of protection designed into the package. The exact tradeoffs between product ruggedness and package protection should be a matter of economic analysis between the product designers and the package engineer. In an ideal world, this tradeoff would be based on economic considerations where the total delivered cost of the product is a minimum. This concept is graphically demonstrated in Figure 3.

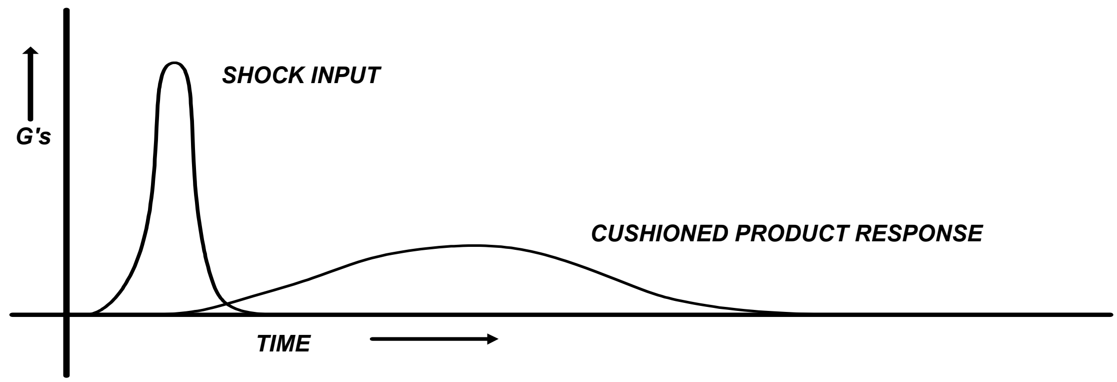
Figure 3



(Source: R. M. Fiedler & Associates)

One of the most severe physical input that a protective package must mitigate is the shock input associated with drops or other mishandling of a packaged product. In this case, the job of the package system is to transform the relatively high peak G short duration input typical of dropping a package onto a rigid surface into a long duration low G shock pulse which is below the fragility level of the product. See Figure 4.

Figure 4



(Source: Westpak, Inc.)

The package does this generally by means of a cushion system which deflects in response to the mass of the product and the deceleration produced by the impact. The cushion can deflect in compression, in shear, in torsion or any other spring mode, although generally the compressive mode is used in packaging design work. All cushion systems work in this way; namely, they deflect and in doing so, trade peak acceleration for duration.

IV. A BRIEF HISTORY OF PROTECTIVE PACKAGE DEVELOPMENT

Initially, package cushions were analyzed as mechanical springs and were designed to protect against the maximum potential energy delivered by an impact. This energy was determined from the mass of the product and the likely drop height. The stress-strain curve (See Appendix I) for the particular cushion would give the proper thickness and area of cushion necessary to reduce the energy at impact below what was believed to be a safe value for the product. Cushion materials were assigned "cushion factors" in order to aid in this process.

During the 1950's, considerable attention was focused on the general area of shock response testing as well as the equipment and techniques useful to describe the phenomenon of shock and shock response. The Firestone Aerospace Division was active in designing and testing cushion systems (primarily rubber airbags) for military applications. One of the big drawbacks was the lack of reliable fragility information on various military hardware. Another was the inadequate sophistication of equipment used to determine shock fragility.

In the early 1960's several companies, including Monterey Research Laboratories, were formed for the express purpose of building sophisticated shock test equipment geared to the military and aerospace testing markets. In the mid-1960's instructors at Michigan State University School of Packaging suggested that this equipment and test approach could be used for commercial and industrial products and that money could be saved with efficient package designs using this approach.

To determine its feasibility and to simplify the procedure, Dr. Robert Newton at the Naval Postgraduate School in Monterey, California, was asked to formulate a test procedure which would utilize shock response spectrum analysis for commercial products with an eye towards improving the packaging procedure for these products. The result of his effort is the now famous Damage Boundary Theory for product fragility testing.

Michigan State University then ran a lengthy series of tests on a wide variety of consumer products during the late 1960's. Equipment to run this testing was leased from Monterey Research Laboratories and the results were published in Technical Report Number 17 from the multi sponsored research group at Michigan State University. The results showed that the theory was indeed workable and did provide an accurate means of assessing product fragility.

The Damage Boundary Theory was simplified and put in an easy to follow five step procedure by the MTS Corporation, which had acquired the Monterey Research Laboratory facilities in the late 60's. The "five step" also incorporated dynamic cushion testing, which had been developed through the efforts of the ASTM D-10 Committee on Packaging.

It was therefore significant that in the early 1970's, for the first time, package development could seriously be considered an engineering discipline. The tools and procedures were now in place to effectively and efficiently design protective packages. Refinements have occurred since that time but nothing rivals the significance of the Damage Boundary Theory. Vibration testing for both products and cushion systems has also been added to the package design and test procedures.

V. DEFINE THE ENVIRONMENT

A necessary prerequisite for package system development is a precise definition of the distribution environment through which the packaged product is likely to travel from the time it is manufactured until it reaches its ultimate customer. It is during this part of the product's life cycle that the package system must perform its job.

Note that the environment must be quantified in terms of all potentially harmful inputs. These inputs may include temperature and humidity extremes, atmospheric pressure changes, compression, shock, vibration, and electrostatic discharge among others. Only the effects of shock and vibration are covered here. However, the designer must be aware of all likely hazards in the environment and quantify them in terms of their ability to cause damage to the product.

SHOCK ENVIRONMENT

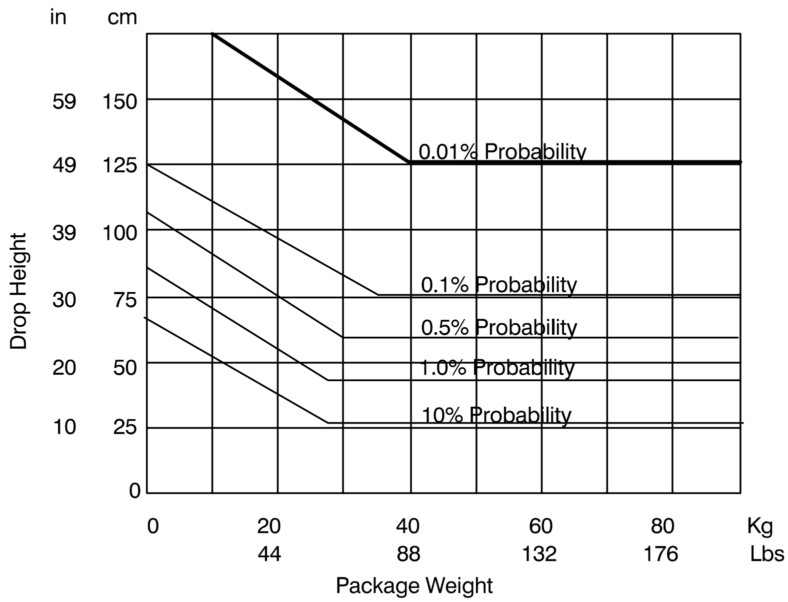
Most shock inputs occur during physical handling, especially the loading and unloading of transport vehicles. Defining this environment amounts to quantifying the drop height experienced by packages. Studies have attempted to define drop height as a function of the package size and weight. (Figure 5) Much literature is available with similar information.

Other methods of obtaining this data are direct observation and measurement of the environment with appropriate devices. Whether taken from published literature or direct observation and measurement, this data has a certain probability associated with it and must be properly interpreted. Arbitrarily increasing the severity of the "assumed environment" to achieve a hypothetical increase in the confidence level leads to costly overpackaging.

FIGURE 5

TYPICAL DESIGN DROP HEIGHT CHART

(CAUTION: This chart shows trends only, not actual values)

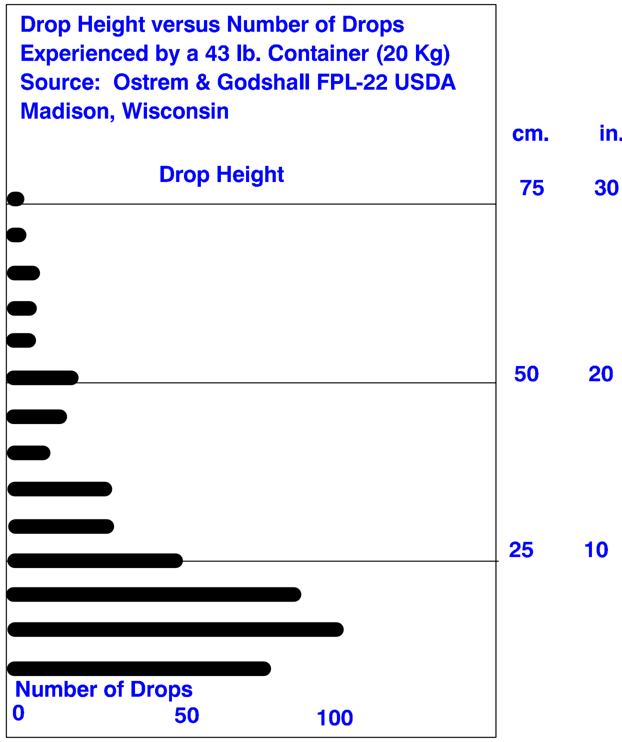


(Source: MTS Corp.)

In general, the following apply to package drop heights:

1. Severe drops are rare. Most packages are subjected to many low drops while relatively few packages receive more than one drop from greater heights (See Figure 6).
2. Unitized loads are subjected to fewer and lower drop heights than individual packages.
3. Most packages are dropped on their base; over 50% of the total number recorded.
4. The heavier the package, the lower the drop height.
5. The larger the package, the lower the drop height.
6. Warning labels such as "Fragile" and "Handle with Care" have little effect on package handling.
7. Hand holds on the sides of packages appear to reduce the incidence of higher drop heights.

FIGURE 6
DROP HEIGHT vs. PROBABILITY



(Source: FPL22)

VIBRATION ENVIRONMENT

The vibration environment is complex and random. The primary source of this vibration input is the various transport vehicles in which products travel from the time they are produced until they reach the final consumer. To quantify it, the acceleration vs. frequency profiles (spectra) of transport vehicles must be determined.

Once the likely transportation mode has been defined, envelope or composite spectra such as that shown in Figures 7 and 8 can be assigned to the environment. This information can be used to program a random vibration spectrum for package testing. It is also useful to note at which frequencies the highest dynamic inputs occur. A well designed package system will attenuate vibration input at these frequencies.

In summary, defining the distribution environment for shock and vibration amounts to defining the design drop height and the vibration profile likely to be encountered. Information presented here is not intended to define the total transportation shock and vibration environment. Rather it is meant only to give a brief overview of the formats used to present such data.

FIGURE 7
TRUCK SPECTRA

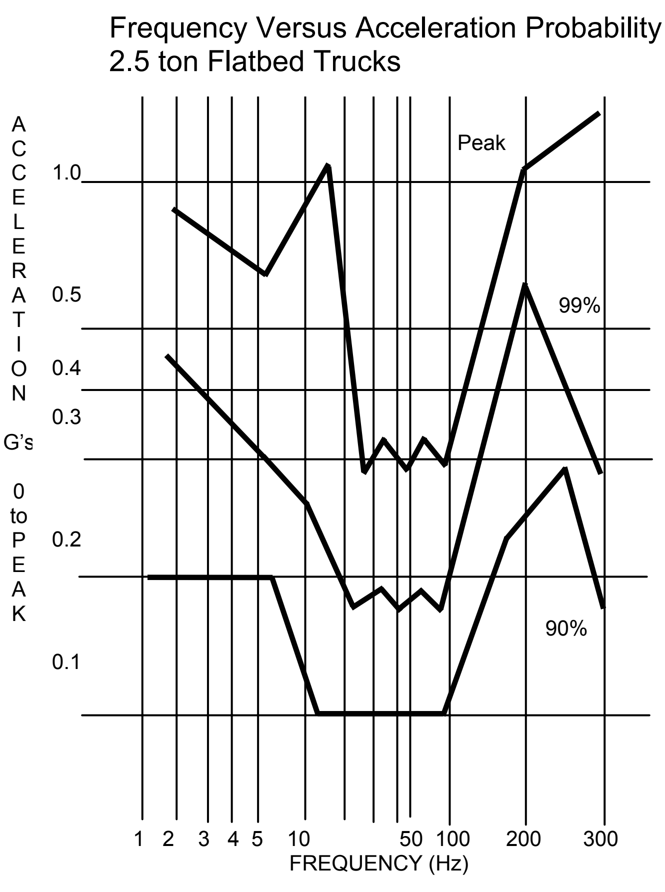
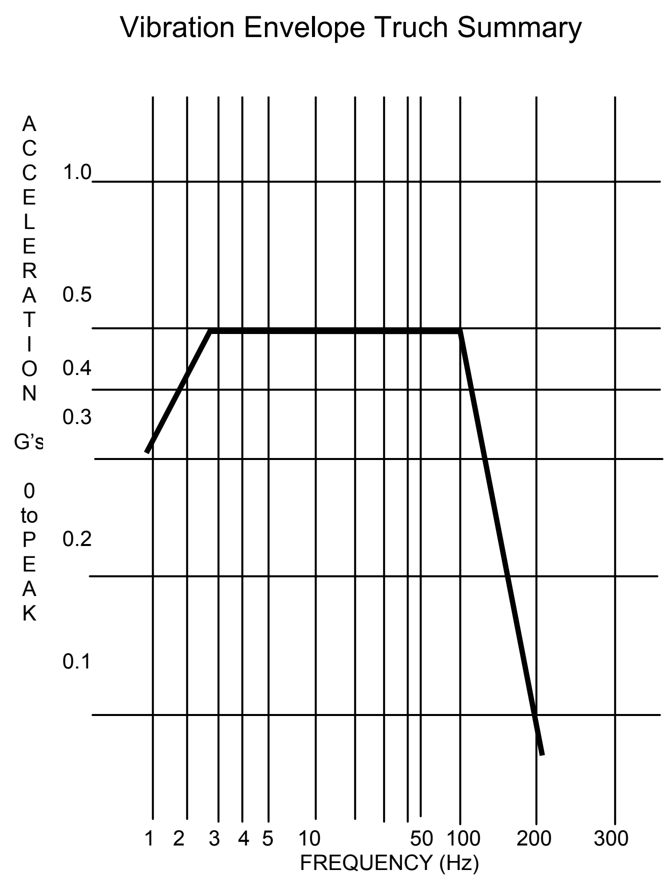


FIGURE 8
ENVELOPE SPECTRUM



(Source: FPL-22)

VI. DETERMINE PRODUCT FRAGILITY

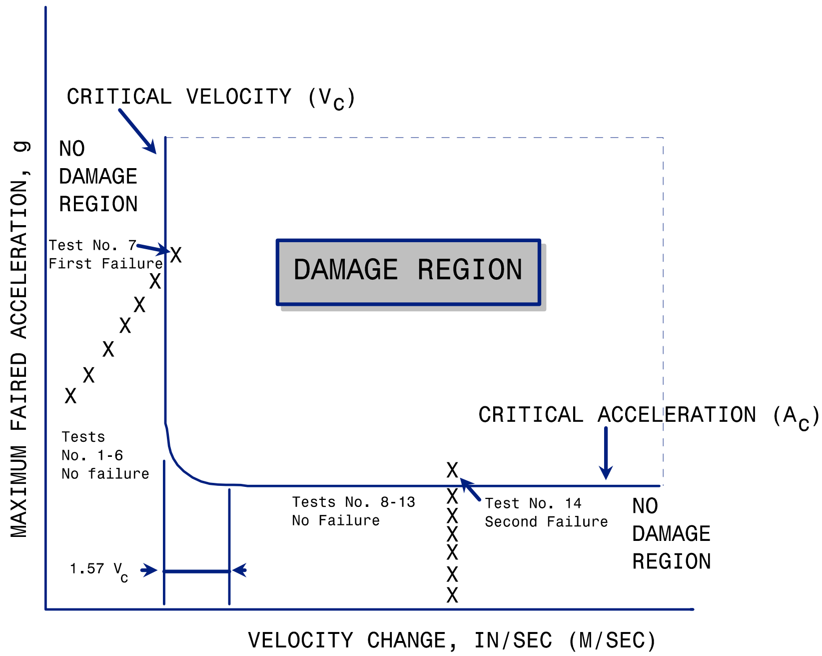
The term "Product Fragility" is often misunderstood. Images of destroyed products, broken bottles and similar events normally come to mind. In reality, product fragility is yet another product characteristic, just as size, weight and color. These characteristics are determined by measurement, and in a similar way, product fragility can be "measured" with shock inputs. This measurement takes the form of a Damage Boundary Curve for shock sensitivity and Resonant Frequency Plots for vibration response.

The importance of determining these characteristics cannot be overemphasized. Most people would not think of buying a pair of shoes based on guessing their foot size. It is just as shortsighted to design a package system by guessing at product fragility.

SHOCK FRAGILITY

The Damage Boundary is the principal tool used for product shock fragility assessment. The Damage Boundary Plot takes the general shape of that shown in Figure 9. It defines an area on a graph bounded by Peak Acceleration on the vertical axis and Velocity Change on the horizontal axis. Any shock pulse experienced by the product which can be plotted inside this boundary will cause damage regardless of whether the product is packaged or not. (Remember this is a **product** test.)

FIGURE 9
DAMAGE BOUNDARY



(Source: ASTM D3332)

To run a Damage Boundary test, mount the product on the table of a shock test machine (Figure 10). Support the product by a fixture similar in configuration to a package. The fixture should be as rigid as possible so that it does not distort the shock pulse transmitted to the product.

FIGURE 10
SHOCK TEST MACHINE

Set the shock machine to produce a low velocity change pulse with a duration of approximately 2 msec (a half sine waveform is generally used for this test). After the test, examine the product to determine if it is damaged. If not, set the shock machine to produce a slightly higher velocity change and repeat the test. Continue this process with small increases in velocity change until damage occurs. The last non-failure shock input defines the **critical velocity change** (ΔV_c) for the product in that orientation. (Refer to Figure 9)

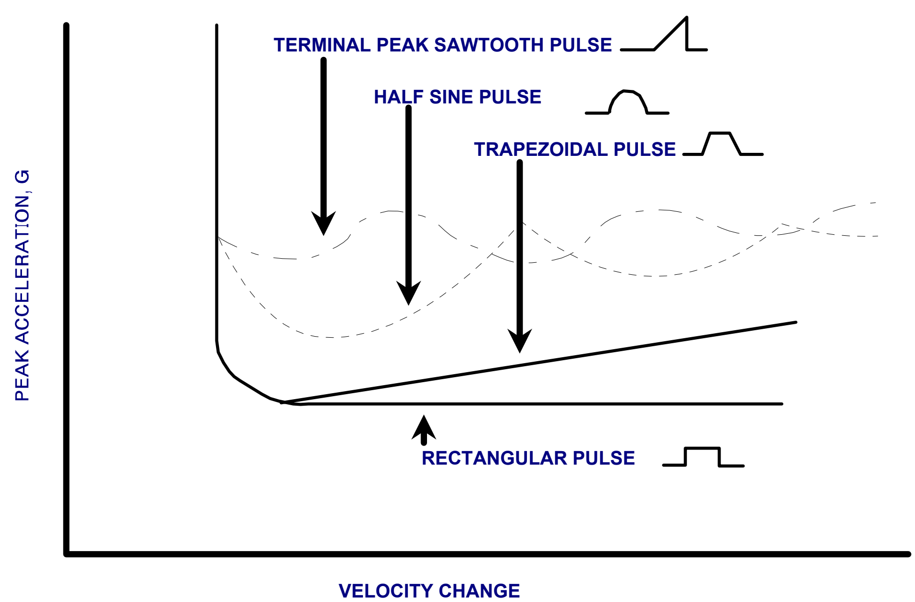
Fixture a new test specimen to the shock machine and set the machine to produce a trapezoidal pulse with low acceleration and a velocity change of (2)ΔV_c. After the shock pulse, examine the product to determine if damage has occurred. If not, set the shock machine to produce a higher acceleration level at constant velocity change. Repeat this process with small increments in acceleration until the failure level is reached. The last non-failure shock input defines the **critical acceleration** (A_c) for the product in that orientation. (Refer to Figure 9.)

The Damage Boundary may now be plotted by drawing a vertical line through the critical velocity change point and a horizontal line at the critical acceleration point. The intersection of these two lines (the knee) is a smooth curve as Figure 9 shows. A rectangular corner approximates the damage region.

Critical acceleration determined by a trapezoidal pulse is conservative compared to other waveforms. That is, a trapezoidal pulse is more damaging than other waveforms of identical peak acceleration and duration (See Figure 11). Since the shape of a shock pulse transmitted through packaging cushion materials during impact is not known, the use of the trapezoidal pulse for Damage Boundary testing results in higher confidence in the finished package system and is recommended for this reason.

The use of the trapezoidal wave results in a (near) linear abscissa on the Damage Boundary. This means that it is necessary to determine only one point to define the critical acceleration for the product in that orientation. Other waveforms result in critical accelerations which are a complex function of the natural frequency of components within the product. Figure 11 shows Damage Boundaries for various waveforms.

FIGURE 11
DAMAGE BOUNDARIES FOR VARIOUS WAVE SHAPES



(Source: Newton, *Fragility Assessment*)

The Damage Boundary is a valuable and powerful tool. Critical velocity change is related to freefall drop height from the formula:

$$\Delta V = (1 + e)\sqrt{2gh}$$

where e = coefficient of restitution of the impact surfaces

g = acceleration of gravity, 9.8 m/sec^2 (386 in/sec^2)

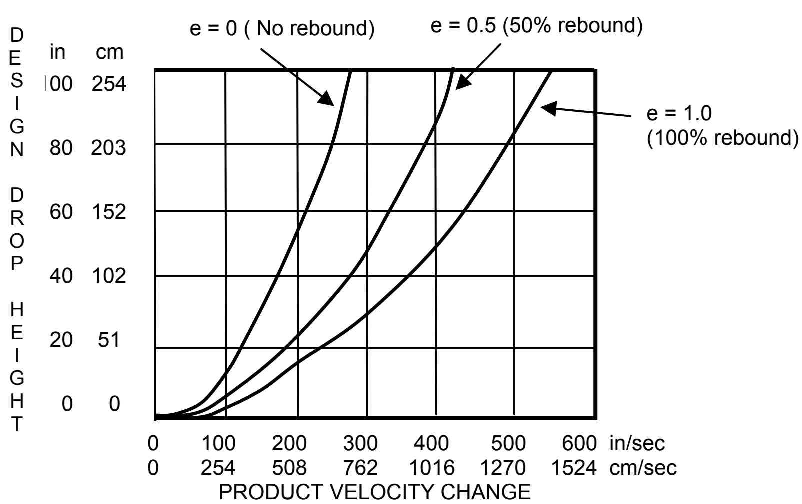
h = equivalent freefall drop height in meters (inches)

Critical velocity change tells the designer how high the **unpackaged** product can fall onto a surface before damage occurs. If this drop height is likely to be exceeded in the distribution environment, then the product must be cushioned. The performance requirements of the cushion are that no more than the critical acceleration be transmitted to the product.

In theory the value of e (coefficient of restitution) varies between 0 and 1. A value of zero implies a totally elastic impact with no rebound whereas a value of 1 indicates a perfectly plastic impact where rebound velocity is equal to impact velocity. As a practical matter, a range of .25 to .75 produces good accuracy. The chart in Figure 12 shows the effect of e with various velocity changes and drop heights.

FIGURE 12

DROP HEIGHT vs. PRODUCT VELOCITY CHANGE

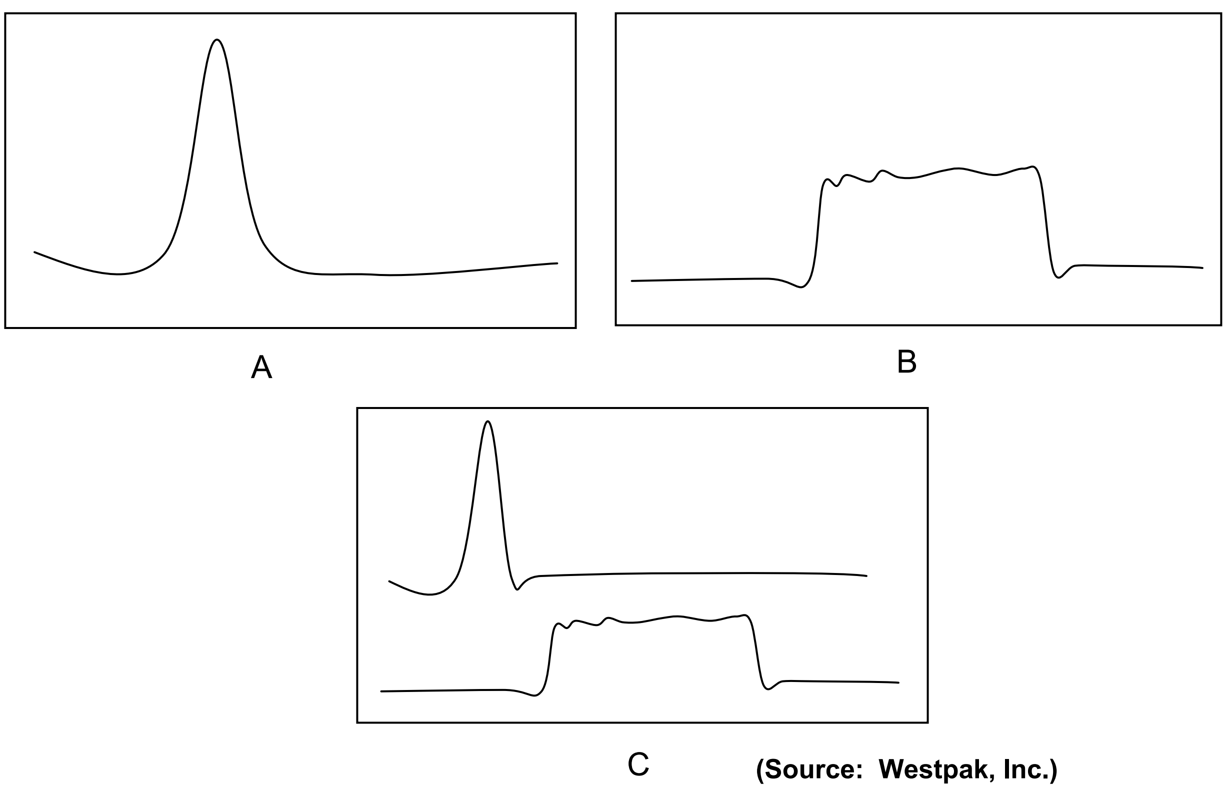


(Source: ASTM D3332)

The Damage Boundary also tells the engineer that at low velocity changes, infinite accelerations are possible without damage. Conversely, at low acceleration levels infinite velocity change is allowable without product damage. This means BOTH critical acceleration and critical velocity change are necessary to properly characterize product fragility.

The shock pulse used to determine critical velocity change (ΔV_c) may look like that in Figure 13A. While it is often called a half sine pulse, its shape is more characteristic of a versed sine rather than a true half sine. Figure 13B shows the trapezoidal pulse used for the Critical Acceleration test. Note that this pulse is often called a square wave or rectangular wave. In reality, it is a trapezoid because the rise and fall times are not infinitely short. Shown together on the same scale these two pulses would look like those shown in Figure 13C, with the velocity change pulse on top and the acceleration pulse below.

FIGURE 13
DAMAGE BOUNDARY WAVEFORMS



(Source: Westpak, Inc.)

Before running the Damage Boundary test, the engineer must define what constitutes **damage** to the product. Damage may be catastrophic failure or less severe damage modes which make a product unacceptable to the customer. In some cases damage can be determined by looking at the product or it may involve running sophisticated functional checks. Once the determination of **damage** is made, the definition must remain constant throughout the test and must be consistent with what is unacceptable to the customer.

In general, Damage Boundary tests must be run for each axis in each orientation of the product. In the case of a rectangular product such as a television set, this means a total of 12 specimens for a rigorous test (6 for critical velocity change and 6 for critical acceleration). However, since the testing is normally done in the prototype stage, rarely is this number of product available for a potentially destructive test. As a practical matter, much information can be gained from a limited number of units.

Another procedure for determining product fragility, often overlooked, is a test method for the assessment of mechanical shock fragility using package cushion materials instead of a programmable shock test machine. It was developed in response to those who consider the Damage Boundary procedure to be too elaborate and expensive for most applications.

To conduct this (simplified) test, the product is supported on a cushioning pad inside a shipping container and is subjected to a series of shock inputs (drops) of increasing severity. This is accomplished by decreasing the thickness of the cushion under the product or by increasing the drop height. The shock levels experienced by the product are recorded and the level at which damage occurs is taken to be the fragility of the product in that orientation. Although this procedure doesn't have the high tech image of the Damage Boundary method, it can be an effective means of determining product fragility.

It is imperative that the fragility level of the product be clearly established prior to designing a package system. In general, the amount (thickness) of cushion increases exponentially as the fragility of the product decreases linearly. The result may be a tremendous waste of material if an engineer decides to use

20 G's as the "assumed fragility" of the product just to be conservative when the actual fragility of the product is 30 G's or more.

VIBRATION

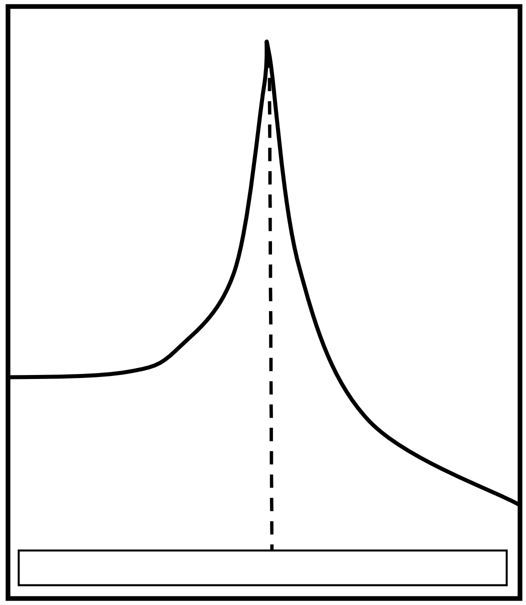
Determining product vibration sensitivity involves identifying resonant frequencies of critical components. As a general rule, a product will not be damaged due to non-resonant inertial loading (forces) caused by vibration input from distribution vehicles. The acceleration levels of most vehicles are relatively low when compared to the critical acceleration of most products. It is only when a component within the product is excited by vibration at (or near) its natural or resonant frequency that damage is likely.

Vibration sensitivity is determined by running a Resonance Search Test as outlined in ASTM D3580. The result of this test is a resonant frequency plot such as that shown in Figure 14. This plot describes the natural frequency and transmissibility (amplification) of a component monitored during the test. The engineer should monitor all critical components in all three axes of the product.

At frequencies below the resonant frequency, the response of a component is roughly equal to the input (the response/input ratio is 1). At frequencies greater than the resonant or natural frequency, the response acceleration is lower than the input. In this region the component acts as its own isolator and results in a condition known as **attenuation**.

At (and near) the product resonant frequency, the response acceleration can be very much greater than the input, causing the product fatigue and failure in a short time. **Amplification** occurs in this frequency band. The purpose of vibration sensitivity assessment is to identify those critical frequencies likely to cause damage to the product.

FIGURE 14
PRODUCT RESONANT FREQUENCY PLOT



(Source: ASTM D3580)

The Resonant Frequency Search Test is run by fixturing a product to the table of a vibration test machine and subjecting it to a sinusoidal low level constant acceleration input (typically .25 to .5 G's) over the frequency range of the distribution environment, typically 3 to 500 Hz (cycles per second). Random vibration can also be used for this purpose. The response/input ratio (transmissibility) is plotted as a function of frequency. This ratio reaches a maximum at the component resonant frequency. The test usually involves monitoring many components in each axis of the product in order to characterize its overall vibration sensitivities.

The importance of vibration testing cannot be over-emphasized. Any product that is shipped is subjected to vibration because of the vehicle in which it is riding. **The probability of this input is 100%.** In contrast, the probability of a shock input because of a drop is exactly that, a **probability function**. In some cases the drop height experienced by a package may be severe. In most cases, the impact will be barely measurable.

Not only is vibration input a certainty, but **its damaging effects can be severe.** This is particularly true if a package cushion amplifies vibration input at the product natural frequency. This can result in a rapid build up of acceleration leading to component failure in a very short period of time. Thus, it is possible for an **improperly designed package to actually destroy the product** it is intended to protect. Without adequate vibration data on the product and the package, it is impossible to know if this situation exists prior to shipment.

Real products behave more like complex spring/mass systems rather than the single-degree-of-freedom (See Appendix I) model implied by the simplex transmissibility plot of Figure 14. Actual data shown in Figure 15 reveals the more normal interactive nature and the constructive and desctuctive interferences that are typical for electronic products. Sub-harmonic peaks are normally benign and should not be mistaken as a true product resonance. Likewise, harmonics will often occur at integer multiples of the primary resonant frequency.

It is customary to ignore harmonics and sub-harmonics unless their response levels are equal to or greater than the fundamental or primary resonant frequency response level. As a practical matter, the lowest primary resonance in each axis is generally the most important information from this test. The reasons are discussed later in Section IX, Package System Design.

Recent studies have found that random vibration excitation of products results in better and more predictive data from a resonance search test as compared to sinusoidal vibration. The reasons appear to be associated with the fact that random inputs excite all resonances simultaneously at approximately the same levels as will occur on transit vehicles. Normally, this random vibration resonance search results in lower amplification levels and slightly lower resonant frequencies as compared to sine vibration. This is probably due to normal destructive interferences between spring/mass systems within the product.

Care must be exercised when attaching transducers (accelerometers) to a product under test to avoid loading the monitored components and thereby altering the true resonant responses. Use the lightest accelerometers appropriate for the measurement to reduce the effect of the instrumentation on the test results.

VII. CUSHION MATERIAL PERFORMANCE

The ability of various cushions to mitigate shock and vibration input is an important characteristic. It is necessary to know exactly what to expect when using certain materials in a particular design situation.

SHOCK PERFORMANCE

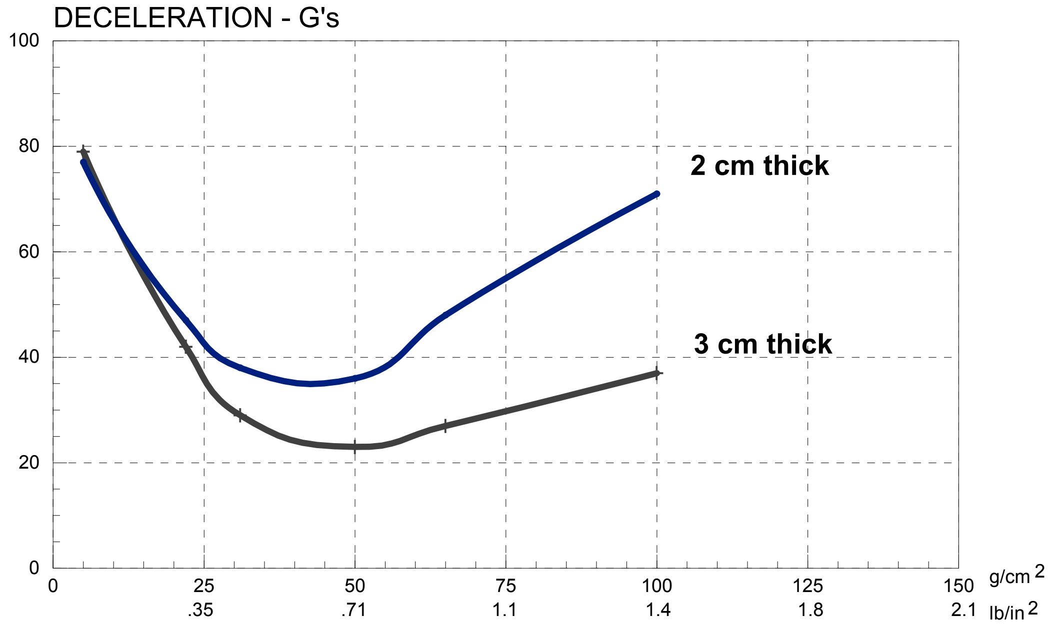
This characteristic is measured using instrumented impacts resulting in a **cushion curve** such as that shown in Figure 15. This curve describes the amount of acceleration (or, more correctly, deceleration) transmitted through a given thickness of material as a function of static stress (loading) on the cushion and the drop height. The test procedure is covered by ASTM D1596. It involves dropping a guided platen of predetermined mass onto a cushion of known thickness and area from a known drop height. The amount of acceleration (deceleration) transmitted through the cushion is measured by an accelerometer mounted on the platen. The results are displayed on a readout device.

The resulting cushion curve shows peak acceleration on the vertical axis and static stress on the horizontal axis (static stress = weight/bearing area). Each curve is drawn from a minimum of 5 test points (static stress levels) and each test point is the average of the last 4 of 5 acceleration readings (impacts) of the cushion material.

FIGURE 15

TYPICAL CUSHION CURVE

75 cm (30 in.) DROP HEIGHT



(Source: Westpak, Inc.)

Most cushion curves have the general shape of those in Figure 15. The left-hand portion shows a relatively high deceleration transmitted through the cushion. In this area the static stress is low because of the light weight on the cushion; the object (platen) does not have sufficient force to deflect the cushion and therefore the effect resembles dropping a product onto a rigid surface.

In the center portion of the curve (where the cushion is being used effectively), the object has sufficient force to deflect the cushion and cause the deceleration to be spread over a longer period of time. The result is a lower deceleration level.

On the right-hand portion of the curve, the cushion material is overloaded and the object continues right through the cushion (it bottoms out) and impacts with the surface on which the cushion is resting. Thus, it approaches using no cushion at all resulting in, once again, high deceleration levels.

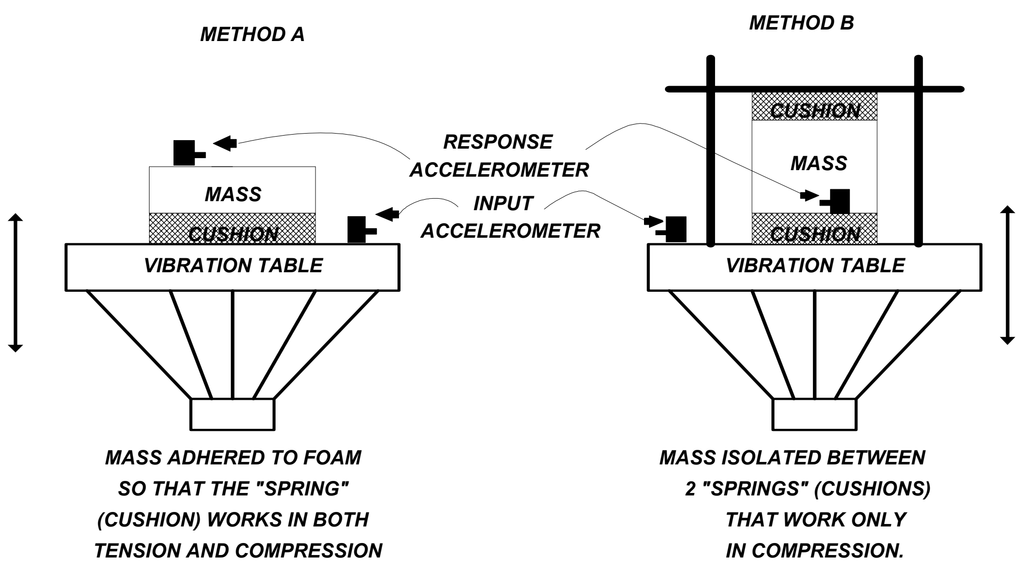
It is desirable to use cushions in the lower portion ("belly") of the curve where performance is optimum. When the product critical acceleration, weight and design drop height are known, the usable static stress range of cushion area can be determined for a given material and thickness.

VIBRATION PERFORMANCE

The vibration performance characteristics of cushion materials are determined by subjecting them to vibrational inputs over the frequency range of interest. In this case, the cushion and a test block on top of it form a spring/mass system with resonant frequency characteristics as described earlier.

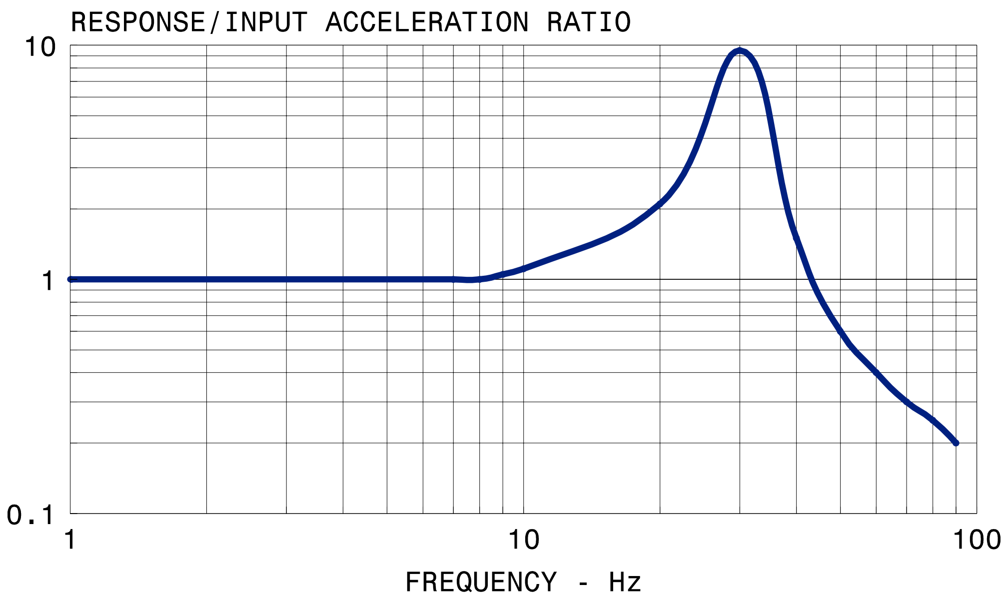
Figure 16 shows the possible test setups and Figure 17 the transmissibility plot for a typical cushion. The mass of the test block is changed in order to vary the loading on the cushion material and the test is repeated. Different plots are obtained in this fashion (see Figure 18). A series of 5 vibrational sweeps at different loadings are recommended to construct the Amplification/Attenuation plot shown in Figure 19.

FIGURE 16
TYPICAL CUSHION VIBRATION TEST SETUPS



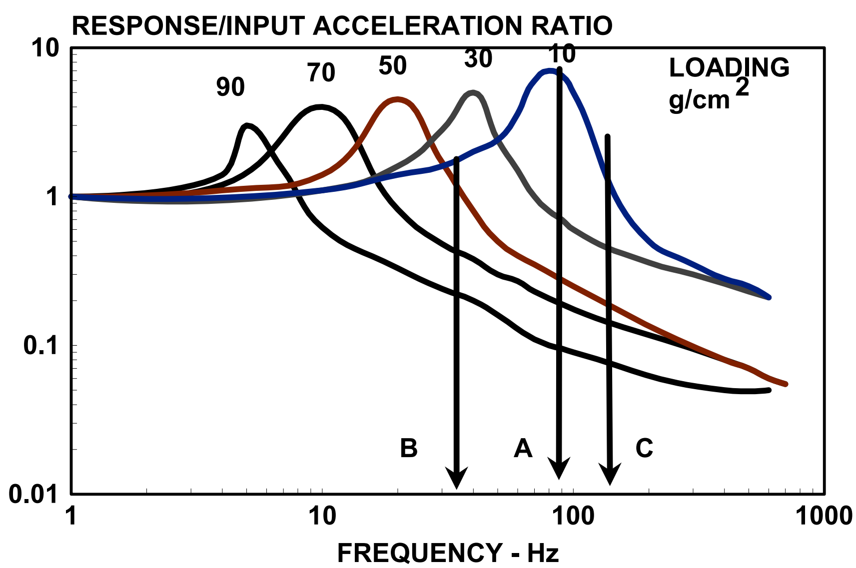
(Source: Westpak, Inc.)

FIGURE 17
CUSHION RESONANT FREQUENCY PLOT
(TRANSMISSIBILITY)



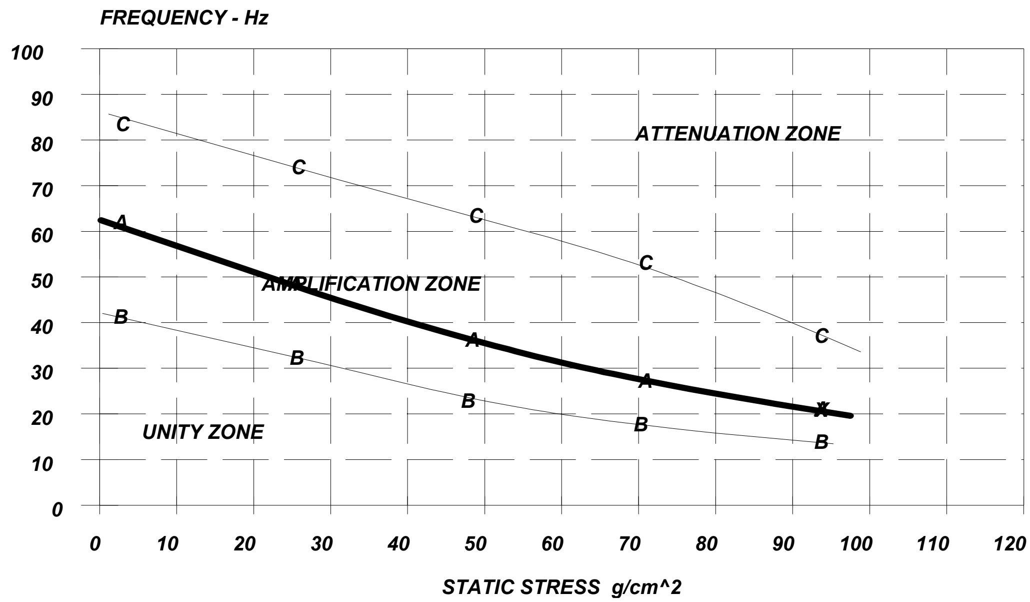
(Source: Westpak, Inc.)

FIGURE 18
MULTIPLE RESONANT FREQUENCY PLOTS
(different cushion loadings)



(Source: Westpak, Inc.)

FIGURE 18
AMPLIFICATION/ATTENUATION PLOT



(Source: Westpak, Inc.)

The Amplification/Attenuation plot describes an area on a graph bounded by frequency on the ordinate (vertical axis) and static stress (loading) on the abscissa. The center portion is that combination of frequency and loading which results in amplification of the vibrational input.

The plot in Figure 19 may be interpreted as follows: for a given frequency, low static stress levels result in the same acceleration transmitted to the product as the input. In other words, the response/input ratio is approximately 1. As the loading increases, there is a range over which the cushion material amplifies the vibrational input. In this region the response/input ratio is greater than 1. At higher static stress levels, the cushion material attenuates (reduces) the vibrational input and the response/input ratio is less than 1.

The producers and users of cushion materials should be familiar with cushion curves (impact) and Amplification/Attenuation plots (vibration) both in terms of the data and how it is obtained. This is important. For example, information obtained from procedures like ASTM D1596 will likely be different from the Enclosed Test Block method described in ASTM D4168 for testing of foam-in-place materials.

Users of cushion materials should insist on shock and vibration data when designing with a given material. Without adequate performance data, the package designer cannot optimize performance. It is possible to design a package system that will destroy a product rather than protect it, particularly if the cushion amplifies vibrational input at product critical frequencies.

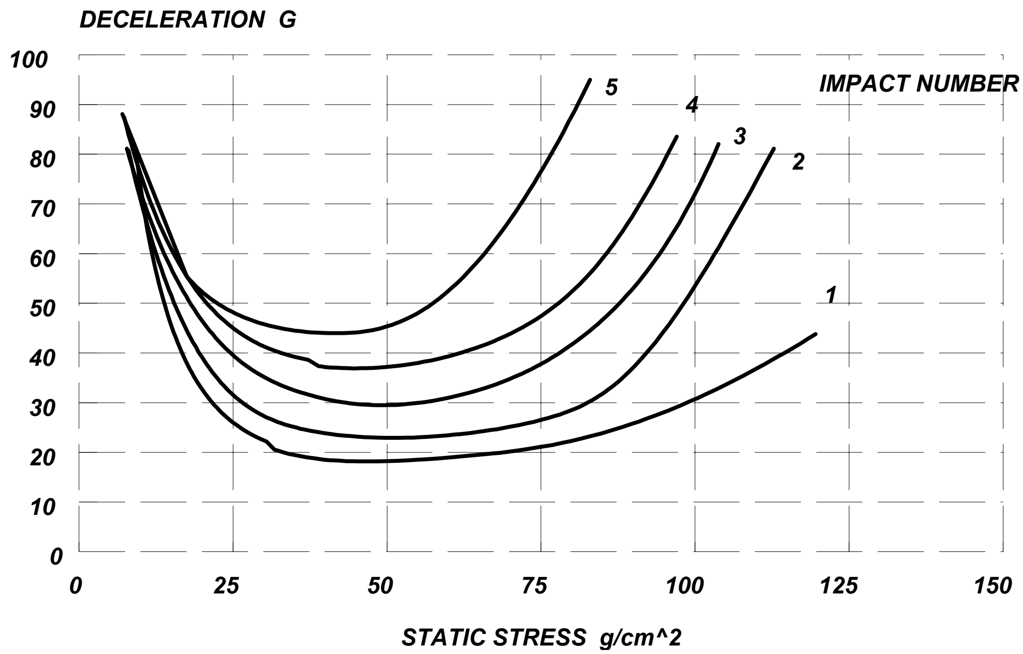
VIII. PACKAGE TEST PROCEDURES

Before a package system is designed or tested, it is vital to establish the exact procedure used to judge its performance. This should include the design drop height and the test procedure used to evaluate vibration performance. The amount or duration of input must also be specified. For example, will the package be subjected to one, two, or three impacts on each face from the design drop height? Or one impact on each face, corner and edge? Or a procedure such as ASTM D4169?

The reason for establishing the test procedure before designing the package comes from the characteristic of many cushion materials where they transmit higher levels of deceleration with increasing drops. For example, a close look at Figure 20 shows that the first drop will often result in lower transmitted deceleration than succeeding drops. This is especially true for "semi-resilient" cushions such as expanded polystyrene (EPS). Heavier loadings necessary to achieve lower deceleration levels will also have a negative effect on the cushion's ability to withstand repeated impacts. On the other hand, more resilient materials such as polyethylene foam generally show very little change with repeated impacts.

The result is that the design process is dependent on the material used and the test procedure. An EPS pack for a single impact verification test procedure would be different than if the test procedure required multiple impacts on the same face. However, if one were using polyethylene foam cushions, it would probably make little difference if the test procedure called for single or multiple impacts on each face. The end result of this step should be a clearly established test procedure.

FIGURE 20
CUSHION CURVE SHOWING THE EFFECT OF MULTIPLE IMPACTS



(Source: Westpak, Inc.)

PERFORMANCE vs. DESIGN VERIFICATION TEST PROCEDURES

There is subtle, though distinct differences between the **performance** and the **engineering design** characteristics of a package system, both in terms of design criteria and the testing to verify compliance. Package **engineering design** refers to the ability to mitigate shock and vibration to levels below product fragility. Package **performance** refers to the ability of the package system itself to withstand the normal forces involved in the distribution process. It is very possible to design a package which has the proper engineering design characteristics but will not withstand the forces typical of the shipping environment.

Package impact design verification is tested with a series of instrumented flat impacts. Package performance is verified by non-instrumented flat, corner, and edge impacts typical of the ISTA or ASTM D4169 test procedures.

Vibration design verification refers to the ability of a package system to attenuate vibration input at and near product natural frequencies. It is tested by subjecting an instrumented package to vibration input in a sinusoidal sweep test (ASTM D999) or similar procedure. The normal vibration performance test involves one or more resonance dwells at package resonant frequencies. Random vibration testing may be used in place of or in addition to sinusoidal resonance search and dwell tests.

It is interesting to note that engineering design is something that is taught in universities and can be verified by analytical techniques. The performance of a design, however, is something which must be learned by experience and is probably more art than science. It is rare to find a designer who can successfully integrate both performance and engineering design requirements into package cushions.

IX. PACKAGE SYSTEM DESIGN

A. DETERMINE CUSHION THICKNESS

The process begins with determining cushion material thickness necessary to achieve the desired results. For this, assume the cushion material behaves as a linear spring and look solely at the total deflection necessary to achieve the required deceleration from the design drop height. This deflection is estimated by:

$$\Delta x = 2h / (A - 2)$$

where:

Δx = cushion deflection in cm (or inches)
h = drop height in cm (or inches)
A = the required deceleration level (G's)

This gives the **theoretical deflection necessary, not the overall cushion thickness.** In general, materials such as expanded polyethylene foam will compress approximately 40 to 60% of total thickness before "bottoming out" starts to occur. More flexible materials such as polyurethane foam will compress up to 80% before it bottoms out.

DESIGN EXAMPLE:

A product has a fragility of 50 G's and a design drop height of 90 cm. (35 inches). Calculate the deflection necessary and the resulting total cushion thickness for expanded polystyrene, polyethylene, and polyurethane foam materials.

The theoretical deflection is calculated from the formula: ($\Delta x = 2 (90) / (50-2) = 3.75$). The resulting theoretical deflection is 3.75 cm. Total cushion thickness necessary for the individual materials is:

MATERIAL	OPTIMUM STRAIN %	TOTAL THICKNESS	
		cm	inches
EPS foam	40%	9.4 (3.75/.4)	3.7
PE foam	50%	7.5 (3.75/.5)	3.0
Polyurethane foam	70%	5.4 (3.75/.7)	2.1

As we shall see later, these numbers can be adjusted through the use of ribs. However, the numbers provide a good guideline for estimating cushion thickness. For example, if a designer wants to achieve a 50 G response from a 90 cm (35 inch) freefall using a 2 cm (.75 inch) thick polystyrene pad, the numbers clearly show this is impossible.

B. ESTABLISH OPTIMUM LOADING

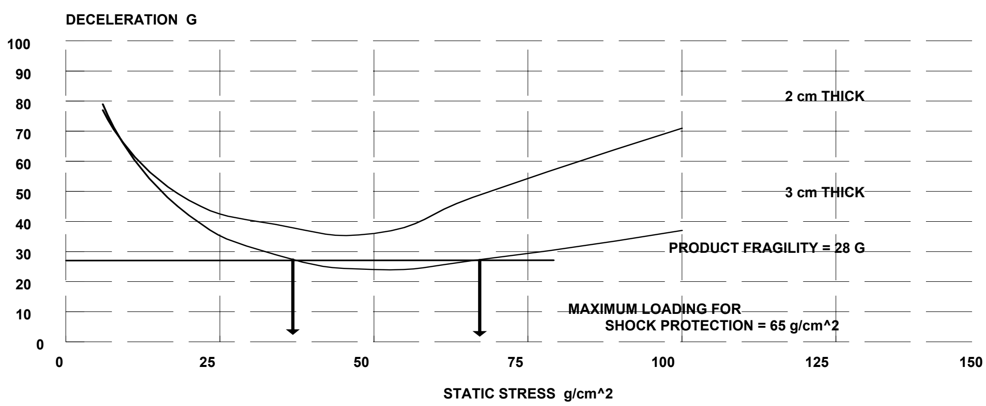
The optimum static stress loading (weight/bearing area) for a given material, thickness and drop height combination is determined from a cushion curve. (Figure 21) Theoretically, any portion of the cushion curve that lies below the product fragility level will define a static stress loading capable of transmitting less than the critical acceleration to the product. For optimum material usage, it is normally desirable to load the cushion to the highest static stress allowed by the curves. However, many designers find it desirable to load the material at the low point (belly) of the cushion curve where transmitted deceleration is a minimum.

Note that the procedure used for running cushion curves may have a significant effect on the usefulness of the information.

The end result of this step should be the optimum static stress loading for the material thickness determined earlier.

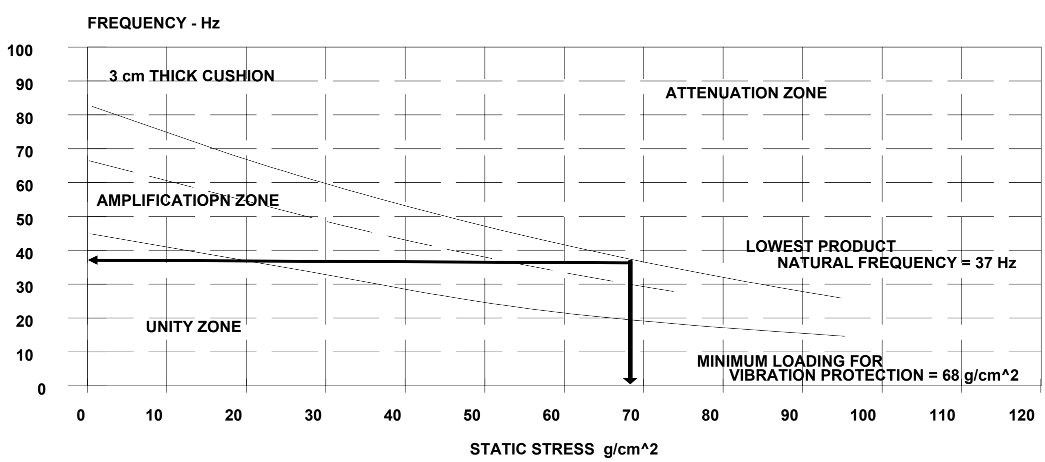
If vibration data will be used in the design (and it certainly should), the next step is to draw a horizontal line across the Amplification/Attenuation plot for this cushion material, tangent with the product natural frequencies. For most designs, the lowest product resonance in each axis is the most important. This plot must describe the same material and thickness as that described in the (shock) cushion curve.

FIGURE 21
DESIGN FOR SHOCK PROTECTION
75 cm (30 in) DROP HEIGHT ("DESIGN" DROP HEIGHT)



(Source: Westpak, Inc.)

FIGURE 22
CUSHION VIBRATION DESIGN
AMPLIFICATION/ATTENUATION PLOT



(Source: Westpak, Inc.)

The **minimum** static stress loading is determined from the intersection of the attenuation boundary and the lowest product critical frequency (See Figure 22). Higher static stress loading will result in **greater attenuation** (which is desirable) while lower static stress loading may amplify vibrational input.

The end result should be a static stress loading which will give good results for **both shock and vibration requirements**. Cushion thickness may have to be adjusted in order to achieve this goal.

While it is relatively straightforward, this process is not well understood by most package engineers and therefore vibration performance is sometimes not considered as part of cushion system designs. This is unfortunate since a compromise between the requirements of shock and vibration in a package system should normally be settled in favor of the vibration requirements. The reasons include the following:

1. The likelihood that the vibration environment will be as predicted is reasonably certain. However, the likelihood that the product will be subjected to impacts from the design drop height is a probability function and the probability of a severe drop is very low. (See Figure 6)

2. The fragility level established by Damage Boundary shock testing using a trapezoidal wave is conservative. It is normal for a product to survive a shock pulse of less damaging waveform at peak accelerations greater than the fragility level.

Testing of a package system will provide an evaluation of any compromises or tradeoffs made in the design of a prototype package. All things being equal, it should be remembered that **the likelihood of vibration input is 100%, while the likelihood of a shock input is a probability function and the probability of a severe input is low.**

C. CONSIDER THE USE OF RIBS

It is instructive to investigate why ribs have been used in package cushions for many years. In general, the use of ribs will result in less material in the design and therefore, higher loading on the material which remains. Ribs can also result in greater deflection from a given cushion thickness.

There are no recognized procedures which would guide a designer to a certain rib configuration. Most of the work done in this area has been intuitive in nature. After reviewing the available literature (and considerable practical experience), the following guidelines are offered for establishing rib configurations:

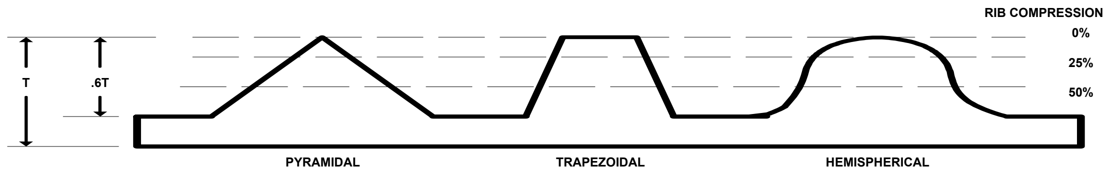
1. In general, the depth of a rib should be approximately 1/2 to 2/3 total cushion thickness.

2. The cross sectional area of material at zero deflection should yield a static loading of 2 or more times the optimum static stress obtained from a cushion curve for that material, thickness and drop height. For example, using the 50 G response requirement from a 90 cm (35 inch) freefall, the optimum static stress for a material 8 cm (3.1 inch) thick may be 50 g/cm^2 (0.7 psi). Using this guideline, the area of the top of the rib would yield a static stress loading of 100 g/cm^2 (1.4 psi) or greater (see Figure 23).

3. The cross sectional area of a rib at 25% total deflection should be approximately equal to that which would give the optimum loading for that material from a representative cushion curve. For the example above, the total cross sectional area at 25% deflection would give a static loading of 50 g/cm^2 (0.7 psi).

4. The cross sectional rib area at 50% total cushion compression should equal a static loading approximately 2/3 that called for by the applicable cushion curve (again refer to Figure 23).

FIGURE 23
VARIOUS RIB CONFIGURATIONS



It is interesting to note that most rib designs are trapezoidal in cross section and most literature treats this as a "standard" shape for ribs. From a theoretical standpoint the best rib design is a pyramidal cross section. A rib with a hemispherical cross section also is a good theoretical design. The reason is that at zero deflection, the static stress loading is (theoretically) infinite and therefore deflection occurs very rapidly at the onset of a dynamic input. As deflection of the cushion material continues in response to the input, the static stress decreases as the area of the cushion increases. Ideally this deflection and change in loading will occur at a rate which is optimum for the shock performance of the cushion.

Of greater significance is the fact that the vibration response characteristics of a cushion material can be substantially altered through the use of ribs. In particular, a high static loading at the peak of the rib will result in a lower natural frequency for the cushion system which is generally the most desirable situation for vibration sensitive products. The force levels associated with environmental vibration are relatively small and therefore the deflection of the cushion is correspondingly small. This deflection will occur at the point of maximum stress and if this is the peak of the rib, that area will strongly influence the vibration characteristics of the entire package system and can be designed to effectively attenuate (filter) higher frequency vibration from the product.

D. PACKAGE DESIGN SUMMARY

Once the total thickness, static loading and rib configurations are determined, the package must be designed using these numbers. This is the point where both the performance and the integrity requirements of the package system must be addressed. Certainly numerous other factors enter into the process of determining the best package design. These include fabrication requirements, end user constraints, ecological considerations, flammability and a host of others. The important requirement for dynamics is a static loading in each product axis which satisfies the product shock sensitivities and does not result in vibration amplification at product critical (resonant) frequencies.

X. PACKAGE PROTOTYPE TESTING

Once the design is complete and a prototype fabricated, it must be tested. Design Verification Testing and performance testing are the two most common procedures used for this step.

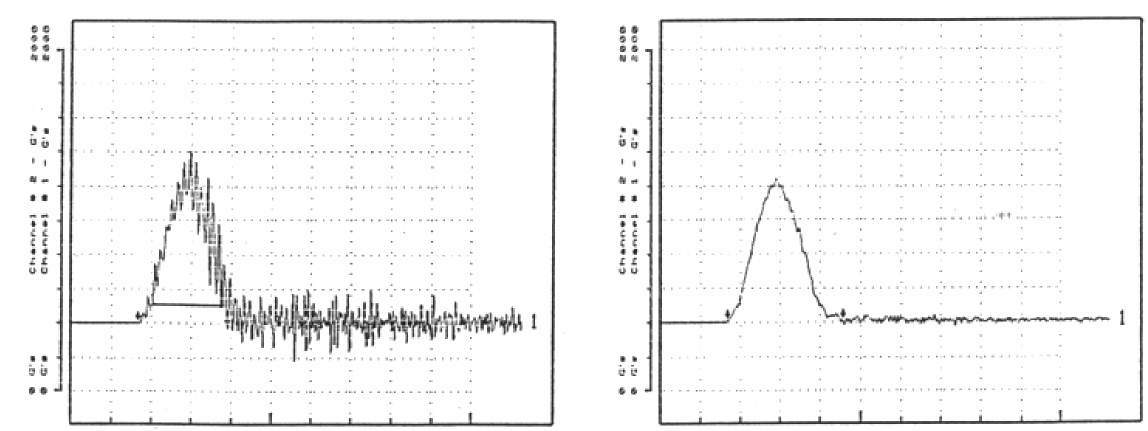
DESIGN VERIFICATION TESTING - IMPACT

For design verification testing of package systems, flat impacts (as opposed to corner or edge impacts) are generally used with the deceleration transmitted through the cushion measured by accelerometers mounted on the product. The test procedure should be that previously agreed to, but in most cases will follow ASTM D5276 or similar procedures. Take care to ensure flat impacts. This is important! The difference between a flat drop and an "almost flat" drop can be very drastic in terms of response deceleration.

It is also important that the monitored location (where the accelerometers are mounted) be as rigid as possible and ideally as close to the product/cushion interface as possible. The reason is to determine the **package input**, not the **product response** characteristics. In may cases these are difficult to separate. If the product were a solid uniform mass, it probably wouldn't make any difference where the accelerometers were located; the input from the cushion would be identical to the response of the mass. However, most products have suspended masses and other flexible components which will be excited (put into motion) by a shock input. The response of these various suspended components can cause such things as "chattering" or high frequency noise on the response waveform (see Figure 24).

Often the response peak deceleration is well above the input of the cushion. For example, a primary cushion response waveform may have a peak of 40 G's with superimposed high frequency on top of it which may double that number. It is sometimes important to identify the difference between package input and product response.

FIGURE 24
UNFILTERED AND FILTERED RESPONSE WAVEFORMS
UNFILTERED (LEFT), FILTERED (RIGHT)



(Source: Westpak, Inc.)

This is one of the most common problems in package response testing. Several methods of reducing this problem include:

1. Learn to mount the response accelerometers in the proper location, avoiding flexible elements and locating the transducers as close as possible to the cushion material.

2. Understand the use of electronic filters and how they can reduce the apparent affect of high frequency ringing superimposed on the primary response waveform. Exercise care to avoid overfiltering and distorting the response data. (See Figure 24) Remember that the best filter is no filter at all.

3. If possible, restrict flexible elements within the product in order to make it as homogeneous and rigid as possible. (It is sometimes instructive to perform two drop tests; one with the flexible elements unrestrained showing the high frequency response and the second with flexible elements restrained showing the difference this has on the product response characteristics.)

DESIGN VERIFICATION TESTING - VIBRATION

The vibration design of a package system is verified by subjecting it to a sine sweep or random vibration spectrum over the same frequency range likely to be experienced in the distribution environment. With an accelerometer mounted on a rigid part of the product, the designer can tell exactly where the cushion material amplifies vibration input and where it begins to attenuate that input. If the job was done correctly, the package will attenuate (reduce in amplitude) those frequencies where the product is most sensitive.

PERFORMANCE TESTING - IMPACT

Package shock performance tests typically involve a series of corner and edge impacts such as those called out in ASTM D4169. This procedure is perhaps the most up-to-date method incorporating much of the environmental input studies to date. This standard is highly recommended for package integrity testing.

PERFORMANCE TESTING - VIBRATION

The vibration performance characteristics of a package system are tested using a sinusoidal dwell test such as that called out in ASTM D999-B. More preferably, a properly designed random vibration procedure can be used to test both performance and design characteristics. Refer to ASTM D4728 for more details.

Under no circumstances should the "mechanical bounce" test (ASTM D999-A) be construed as a vibration procedure. The bounce test (conducted on a mechanical shaker) amounts to a series of repeated impacts with very short intervals between events. It may be referred to as a repeated impact test, a bounce test, a fatigue test or something else.....but it should **not** be mistaken for a vibration test.

If the package system meets all its requirements, then the job is finished. If not, further package system refinements are necessary. The following sections should help with those refinements.

XI. INTERPRETING PACKAGE RESPONSE DATA

A. WAVEFORM ANALYSIS

The response waveform generated during a package drop test contains a wealth of information useful to the package designer. A good designer should definitely learn to interpret this information.

The first piece of information taken from a response waveform is the total velocity change (or what can be thought of as the energy released during the impact). This can be determined by integrating the waveform. The integral, as described earlier, is the area under the deceleration vs. time pulse. This area can be estimated by multiplying the peak by the duration. Use the following formula:

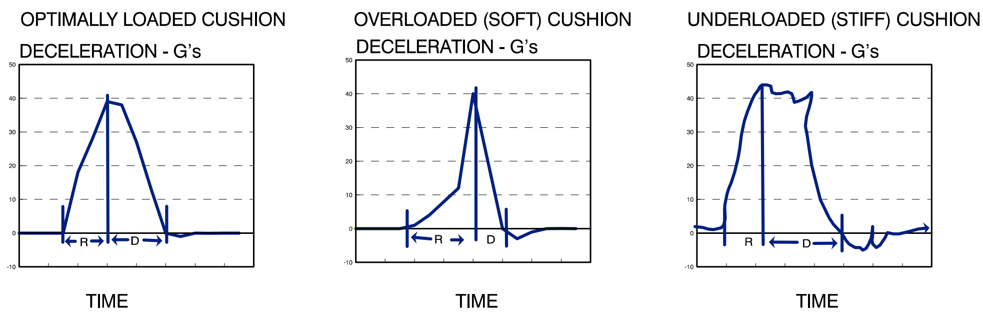
$$\Delta V = A_p \times g \times D \times .6$$

where A_p = Peak Pulse Deceleration in G's
g = 9.8 m/sec^2 (386 in/sec^2)
D = pulse duration in seconds

The ".6" is a factor to account for the shape of the waveform which is generally someplace between a halfsine and a haversine. The resulting estimate of velocity change should fall somewhere between the minimum and maximum lines on the drop height vs. velocity change chart shown in Figure 12. If it doesn't, there is something wrong with the test and it should be investigated.

In general, the rise time of a shock response pulse (the time from onset of the pulse until peak acceleration) should be 1/3 to 1/2 total pulse duration. If the rise time is shorter than this, it generally indicates that the cushion is too stiff or the loading too light. If the rise time is greater than 1/2 pulse duration, this generally indicates that the material is too flexible or is overloaded. In a similar way, if a sharp spike is seen at the very beginning of the waveform, it generally indicates that the cushion material is too stiff or too lightly loaded. Conversely, if a sharp spike is seen near the end of the waveform this indicates that the material is too flexible or too heavily loaded. Refer to Figure 25.

FIGURE 25



R = pulse rise time **D = pulse decay time**

(Source: Westpak, Inc.)

B. INCONSISTENT DATA

In some cases, repeated drops will produce different results with the same drop height and accelerometer location. This generally indicates that either the drop is not flat or that the product is rotating within the cushion on impact. One way to resolve this is to use two accelerometers at different locations within the product. Product rotation upon impact is normally an indication that the cushion material is not properly distributed in relation to the weight of the product. Another method of determining this is to use a triaxial accelerometer (3 accelerometers in one) to measure the cross axis deceleration during a package drop test.

Instrumentation problems can also cause inconsistent data during a drop test. Be sure that the acceleration monitoring system is connected properly and that there are no shorts or intermittence in the accelerometer cable(s). Of course, only recently calibrated instruments should be used for any serious testing.

XII. DESIGNING WITH NEW OR COMBINATION MATERIALS

As most people are aware, moldable polyethylene and polypropylene have been introduced worldwide. These two materials promise to revolutionize at least part of the foam cushion industry in that they are capable of being molded in configurations similar to expanded polystyrene and are easily recyclable. Although they have excellent shock and vibration characteristics, their high costs necessitate optimum material usage in order to be economically feasible. This often requires the use of flexure in a design situation rather than compression as in traditional cushion designs.

This means that standard cushion curves may no longer serve as the only guideline for determining proper static loading. Rather, the designer will first use a formula to determine the required deflection (and therefore overall cushion thickness) and following this, will use waveform analysis of a drop test in order to further optimize the cushion system. This will likely result in a substantial amount of trial and error until newer tools like Finite Element Analysis (FEA) and Statistical Energy Analysis (SEA) become available and widely used.

To reduce this effort to the absolute minimum, the designer must be knowledgeable in waveform analysis. The designer must be able to look at a response waveform and determine if more or less flexibility, more or less cushion thickness, or different cushion distribution is required.

Another interesting feature of cushion systems of the future will likely be the increased use of combination materials; for example, polyethylene and polyurethane foam used together, or polystyrene and polyethylene foam used in the same package system. Currently it is rare to find a design which uses combination materials, either in series or in parallel. On the few occasions that one finds it, the results are normally not encouraging.

The reason is that there are few guidelines to help the designer produce an optimum package system. Rather, it is generally a series of trial and error efforts that may or may not produce fruitful results. However, all this is changing.

Through the use of deflection equations, waveform analysis and microcomputers, the designer can more quickly determine if combination materials make sense in a given situation over conventional techniques.

Of the designs done to date, it appears that combination materials used in series make more sense than those used in parallel. It has also been noted that the more successful designs use materials that have approximately the same spring rates. On the other hand, those that use materials with vastly different spring rates such as polyurethane and polystyrene generally produce unsatisfactory results.

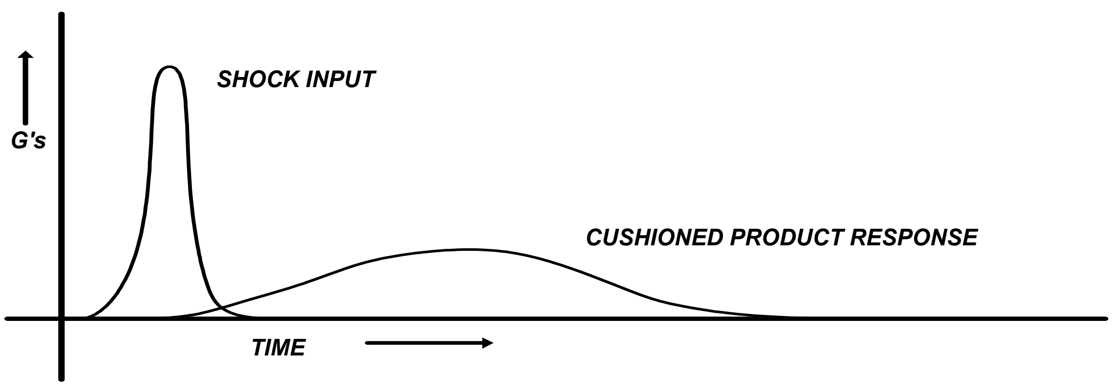
Ecological considerations must also be reviewed when choosing a cushion design, especially if different materials are bonded together making them difficult or impossible to recycle. The optimum design is one that can be reused without modification indefinitely. This rarely occurs. The next best option is a design that is easily recyclable back into components that become raw materials for the same basic design. This should be a high priority for all package systems. Governments will force this issue on package designers (normally in a painfully inefficient fashion) unless proper attention is paid to good ecology.

XIII. CONCLUSION

All cushion systems work in the same way, namely they trade peak deceleration for duration; that is, they trade a high peak short duration shock pulse for a longer duration lower peak shock pulse (See Figure 26). The longer duration is in response to the **deflection** of the cushion. This deflection can be the result of compression, shear, flexure, or other motion of the material. In any case, the results are the same, namely, the material must "give" in order to change the shape of the deceleration vs. time pulse delivered to the product. The nature of this deflection is controlled by a series of simple physical formulas.

The relationship of the variables involved in dynamic package response is very straightforward and once it is understood by the designer, it can be of great help in optimizing cushion systems.

FIGURE 26
INPUT AND CUSHIONED RESPONSE SHOCK PULSES



(Source: Westpak, Inc.)

It is likely that package design and testing will become more technical in the future. However, the increased sophistication will simply involve adaptations of a few basic techniques explored herein. The designer is encouraged to learn why and how cushion material do their job and to use this information to design better package cushion systems.

APPENDIX I

DEFINITIONS OF TERMS

ACCELERATION	A vector quantity describing the time rate of positive change of velocity of a body in relation to a fixed reference point. It is usually expressed in G's which are multiples of the gravitational constant. Deceleration is the time rate of negative change of velocity.
AMPLIFICATION	The ratio of the peak response acceleration to the peak input acceleration.
AMPLITUDE	The magnitude of variation in a changing body from its zero value. It may refer to displacement, velocity, or acceleration.
COMPRESSION SET	The loss of thickness of a cushion after a specified time interval following the removal of a compression load.
CREEP	The strain time response of a material to a constant stress.
CUSHION	A material used as a shock and vibration isolator.
CYCLE	A complete sequence of values of a periodic quantity occurring over a definite time period.
DAMPING	The dissipation of oscillatory or vibratory energy with motion or with time. **CRITICAL DAMPING** is the minimum viscous damping that will allow a displaced system to return to its initial position without oscillation.
DISPLACEMENT	A quantity describing the change of position of a body and usually measured from a position of rest.
DURATION	When referring to a shock pulse, duration is the time required for the acceleration of the pulse to rise from some stated fraction of the maximum amplitude and to decay to this same value. The usual practice is to use ten percent of the maximum amplitude as the fraction.
EQUIVALENT DROP HEIGHT	The height of a free fall required by a body in a vacuum to attain a particular instantaneous velocity at impact.
FRAGILITY	The ratio of the maximum acceleration that an object can safely withstand to the acceleration of gravity.
FREQUENCY	The reciprocal of the period necessary for one complete oscillation. This is often described in cycles per second or "Hertz" abbreviated Hz.
FREQUENCY, FORCING	The frequency of excitation.
FREQUENCY, NATURAL	The frequency of free oscillation of a system.

FREQUENCY, RESONANT	The frequency at which a spring-mass system displays its maximum response.
HARMONIC	A sinusoidal quantity having a frequency that is an integer multiple of a fundamental or resonant frequency.
IMPACT	A single collision of one mass with a second mass.
ISOLATOR	A device or material used to reduce the severity of applied shock and/or vibration to a packaged item.
MASS	A physical property indicating the acceleration resulting from a given force.
OSCILLATION	Variation with time of the magnitude of a quantity with respect to a specified reference.
OVERSHOOT	Excessive momentary response of a recording system to an applied signal.
PERIOD	Smallest interval of time in which a reoccurring event repeats itself.
PERIODIC VIBRATION	An oscillation whose wave form repeats at equal increments of time.
PIEZOELECTRIC	The capability of some crystalline materials to generate an electric charge when stressed.
PIEZOELECTRIC TRANSDUCER	A device which depends upon deformation of its sensitive crystalline element in order to generate an electrical charge and voltage.
PIEZORESISTIVE TRANSDUCER	A device that depends upon deformation of its sensitive element in order to change resistance of that element.
POWER SPECTRAL DENSITY	A term used to describe the intensity of random vibration in terms of mean squared acceleration per unit frequency. The units are G^2/Hz.
RESILIENCE	A material characteristic indicating an ability to withstand temporary deformation without permanent deformation or rupture.
RESONANCE	Resonance of a system in forced vibration exists when any change, however small, in the frequency of excitation causes a decrease in the response of the system. Resonance represents a maximum of response of a spring-mass system to forced vibration.
SHOCK	A sudden, severe, non-periodic excitation of an object or system.

SHOCK MACHINE	A device for subjecting a system to a controlled and reproducible mechanical shock.
SHOCK PULSE	A substantial disturbance characterized by a rise and decay of acceleration from a constant value in a short period of time. Shock pulses are normally displayed graphically as curves of acceleration as a function of time.
SHOCK SPECTRUM	A plot of the maximum response experienced by a single-degree-of-freedom system as a function of its own natural frequency in response to an applied shock input. The response may be expressed in terms of acceleration, velocity, or displacement.
SIMPLE HARMONIC MOTION	Periodic vibration that is a sinusoidal function of time.
SINGLE-DEGREE-OF-FREEDOM SYSTEM	A system consisting of a rigid mass attached to a referenced foundation by a mass-less spring that is constrained along a straight line.
STRAIN	Deformation per unit length.
STRESS	Force per unit length.
TRANSDUCER	An instrument that converts shock and vibration or other mechanical phenomena into a corresponding electrical signal.
TRANSMISSIBILITY	The dimension-less ratio of the response amplitude of a system in steady state forced vibration to the excitation amplitude. The ratio may represent acceleration, forces, displacements or velocities.
VELOCITY	A vector quantity describing the time rate of change of displacement of a body in relation to a fixed reference point.
VELOCITY CHANGE	The difference in system velocity magnitude and direction from the start to the end of a shock pulse. The magnitude may be determined from the integral of the acceleration versus time signature.
VELOCITY SHOCK	A mechanical shock resulting from a rapid net change in velocity. The velocity change is rapid if it takes place in a time that is very short compared to the natural period of the test specimen.
VIBRATION	The oscillation of an element of a mechanical system about a fixed reference point.
VIBRATION, PERIODIC	A vibration consisting of a wave form that is repeated at equal time intervals.

VIBRATION, RANDOM	An oscillation having an instantaneous frequency and amplitude that can be specified only on a probability basis.
VISCOELASTIC	An adjective indicating that a material or system has both energy storing and energy dissipating capability during deformation.