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Aim and Scope

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Minimum Sample Size Needed to Construct Cushion Curves Based on the Stress-Energy Method

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ABSTRACT: Cushion curves are graphical tools used by protective package designers to evaluate and choose foamed cushioning materials. Thousands of samples and hundreds of laboratory hours are needed to produce a full set of cushion curves according to the ASTM procedure D 1596. The stress-energy method considerably reduces the number of samples needed to construct cushion curves for closed-cell cushioning materials. Consequently the laboratory and data analysis time are reduced as well.

The stress-energy method was used to find the minimum sample size needed to construct cushion curves for closed-cell cushioning materials. A reference set of data collected for ARCEL® resin foam blocks using the stress-energy method was used. Lines fitted to this reference data set were statistically compared against lines fitted to reduced size sample sets. This comparison revealed that 15 samples (5 replicates at 3 energy levels) were sufficient to fit lines without statistical difference. The data analysis also showed a limitation of the stress-energy method associated with densities higher than 2.2 lb/ft^3 for the materials used.

Cushion curves for two densities of expanded polyethylene were successfully constructed using the reduced sample size of 15. These curves were compared to published data for EPE and were found to vary within expected lab-to-lab tolerances.

INTRODUCTION

MILLIONS of packages are transported every day in different package configurations according to their distribution environment. Some packages are palletized, some are transported within a case, and others are transported as units themselves. These different distribution situations determine different hazards that products must survive. Common hazards during transportation and distribution include shock, vibration, compression, and temperature and humidity extremes.

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Shock, vibration, and compression are the most common hazards (Schueneman & Marcondes, 2004). Shock occurs with an impact to a package system. This can happen when packages are dropped, but also from when packages impact each other or as they travel through a commercial sorting facility. For example, packages transported in the small parcel environment are subject to falling from conveyor belts into bins during the sorting process. Packages that travel by rail are subject to side impacts caused by the rail cars coupling. The severity of the impact might also have to do with the package configuration. For example, palletized loads are generally subject to shorter drop heights than individual boxes that can be manually handled.

The nature and intensity of vibration experienced by a packaged product depends on the type of transportation used. Different modes of transport will determine different vibration inputs, and packaging materials could actually magnify the inputs if the designer is not careful with material choice.

Compression may be experienced during transportation and storage. Some packaging materials are susceptible to deformation and degrading strength during storage. This might be due to the nature of the material itself, or environmental conditions such as temperature and humidity.

Shock protection is the focus of this work. Most products are engineered only to survive impacts expected during normal intended use, so it becomes necessary to protect them from distribution hazards occurring while transported from manufacturing to the customer. The goal of the package designer is to only add enough packaging so that the protection of the package and the inherent ruggedness of the product together match the severity of the hazards in the distribution environment.

To protect against shock during shipment, cushioning materials can be added to the package system to dissipate some of the energy produced by an impact before it reaches the product. There are several kinds of cushioning materials available to package designers. They include polymeric materials in the form of foam blocks and molded shapes, air bags, and bubble wrap, to name a few. Cellulosic materials are also available, such as molded pulp. Each of these cushioning options has its own shock absorbing properties.

Foams are divided into two categories with respect to their physical structure. There are closed-cell foams and open-cell foams. Common closed-cell foams used in protective packaging are expanded polystyrene, expanded polyethylene, and expanded polypropylene. There are also foams made of copolymers of these materials. Expanded polyurethane is an example of open-cell foams.

Cushion curves are one of the tools package designers use to evaluate and choose cushion materials. These curves communicate the deceleration expected to be transmitted through the cushioning material for a given drop height, static loading, and material thickness. ASTM test procedure D-1596 "Dynamic Shock Cushioning Characteristics of Packaging Materials" describes the process to collect the data to produce the curves. Thousands of drops are performed in order to collect enough information to produce a full set of cushion curves for a particular material. Foam manufacturers provide these curves as part of the technical information about their products.

In the last two decades, new ways of describing the ability of polymeric closed-cell foam cushioning materials to protect against shock have been put forth. One of the models relies on the dynamic stress-energy relationship of a cushioning material. Using this model, the shock absorbing characteristics of a material can be described by a single equation independent of drop height or material geometry. Moreover, the dynamic stress-energy relationship can be derived from far fewer drops. This dramatically reduces the cost with fewer labor hours to collect the data and less time spent on data analysis.

The objective of the work presented here was to find the minimum number of samples necessary to produce cushion curves from equations based on the dynamic stress-energy model. Traditional cushion curves are expensive to produce because of the thousands of drops and samples needed. Considerable savings can be achieved by using the stress-energy method, but so far no work has been published on minimum sample size.

REVIEW OF LITERATURE

Shock is one of the most common hazards in the transportation of goods. Isolating the packaged product from shock events that could result in damage is one of the challenges of package designers. Shock may result from a sudden acceleration or deceleration caused by events that are very common in the distribution of goods. During their distribution cycle, packages may be dropped, side kicked, or tossed (Schueneman & Marcondes, 2004). Trucks containing packages may go over pot holes, and start and stop several times during a trip. In the rail transportation environment, railcars containing packages go through the process of coupling. Since products are designed only to withstand the hazards at intensities according to their normal use, cushioning material might be added to a package system to absorb some of the energy of shipping related shock events before it reaches the packaged product.

Cushioning materials absorb energy through deformation. In other words, the energy it takes to deform or deflect the cushion during an impact is not transmitted to the product. Therefore, the ability of the material to deform is a very important factor in shock absorption (Marcondes, 2001). Not all cushioning materials are equally capable of absorbing energy.

There is a wide variety of cushioning materials used in packaging. The most common are polymeric foams in form of molded parts, sheets, planks, foam in place, and free flowing shapes. There are also other polymeric cushioning options such as bubble wrap and air pillows. Molded pulp and corrugated boards are examples of non-polymer based.

Cushioning Materials

The most important characteristics of a cushioning material that affect its compressive behavior are the material composition, density, and, in case of polymeric foams, the cell structure and size. Of the above, the most important characteristic is the material composition. Two foams with the same density, but of different material composition, will behave differently as far as deflection or deformation (Imeokparia, Suh, & Stobby, 2004). The focus of the work presented here is on closed-cell polymeric foam materials. Therefore, any future reference to cushioning materials in this text should be understood as a reference to polymeric foams.

Concepts in Closed-cell Cushioning Material Deflection

Working length of a cushioning material is defined as the maximum deflection in which the cushion will behave linearly: for a constant change in force, there is a constant change in deformation. The ratio between the change in force and the corresponding deflection of a block of foam is known as the spring constant (K). The spring constant is depend-ent on material geometry, orientation, and of course material composition.

Another related concept is the stress-strain ratio or the modulus of elasticity (Young's Modulus) of a material. Stress is defined as force per area of material and strain is the ratio of the resulting deflection and the original thickness. The modulus of elasticity is a property of the material and does not depend on cushion geometry or orientation. When a foam is said to "bottom-out", it has reached its maximum strain and, therefore, its ability to absorb energy in a shock event. Static stress is also known in packaging as the static loading. It is the ratio of the weight of the product and the area of foam which bears the product. In English units, static loading is expressed in units of lb/in^2 and is often abbreviated as psi.

Cushioning Material Classification

In terms of their elasticity, foams are classified as either elastic or nonelastic (Hatae, 1996). Elastic materials are those which don't sustain permanent deformation after deflection caused by an impact. Nonelastic materials, on the other hand, sustain permanent deformation. In packaging for distribution this classification is important, since it is necessary to consider multiple impacts as likely for most products. The permanent deformation sustained by a nonelastic material on a first impact will greatly influence its ability to deflect on subsequent impacts. According to Hatae (1996), in the package design field, for a material to be classified as elastic, it must show permanent deformation of no more than 10% after compression to a strain of 65%. Expanded polystyrene and expanded polyethylene are two common cushioning materials used in packaging. Expanded polystyrene is classified as nonelastic, whereas expanded polyethylene and expanded polyurethane are available in elastic form (Lee, Park, & Ramesh, 2007).

In terms of their structure, foams are classified as either closed-cell or open-cell foams. The nomenclature itself is descriptive of the difference. Closed cell foams are composed of individual bubbles with air trapped inside, with no air traveling from bubble to bubble or cell to cell. Open cell foams, on the other hand, are made up of interconnected bubbles where air travels from bubble to bubble. Closed-cell foams are typically more rigid than open cell foams. Expanded polystyrene, expanded polyethylene and expanded polypropylene are examples of closed cell foams. Expanded polyurethane is an example of an open cell foam. One

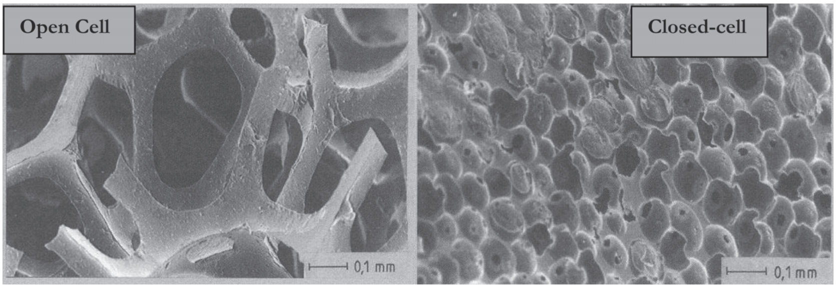


Figure 1. *Open cell and closed-cell foams. Pictures are copyright of Carl Hanser Verlag, 1992. Reprinted with permission.*

is usually able to distinguish between these two types after visually inspecting them. Figure 1 shows pictures of open cell and closed-cell foams.

Because of the difference in physical structure, open-cell and closed-cell foams have different mechanisms of shock isolation. Shock isolation by closed-cell foams is mostly a function of air compression and cell-wall flexibility, whereas in open-cell foam, air compression does not play a part, since there is no air trapped in cells (Burgess, 1993a). In open cell foams the damping is achieved by "buckling of cell filaments" with negligible pneumatic contribution (Shuttleworth, Shestopal, & Goss, 1985, p.333). Cell size and density of a closed-cell foam greatly influence the foam's ability to deflect, absorb energy, and isolate shock. However, different materials of the same density will behave very differently because, as previously stated, material composition is the most important characteristic. Expanded polystyrene, for example, is very common in package cushioning, but it is rigid and subject to permanent deformation after an impact. Expanded polystyrene is also very light weight. Expanded polyethylene is very resilient and not as susceptible to deformation after impact. It is also more expensive than expanded polystyrene. Foams made from copolymers of polystyrene and polyethylene are also available which capitalize on the advantages of foams made from both polymers.

In terms of their use in package cushioning, foams can be fabricated or molded. Molded parts are more expensive and require a high volume operation in order to make up for the cost of the mold. Fabricated parts are cut from extruded planks of the expanded foam to the desired shape and size. These fabricated parts usually have the molded surface of the planks removed.

Mechanical Shock

"A mechanical shock occurs when an object's position, velocity or acceleration suddenly changes" (Brandenburg and Lee, 1991). For example, when a package is dropped, it experiences an increase in velocity as it is falling followed by a sudden decrease when it hits the floor. Shock to the package happens when it suddenly decelerates upon hitting the floor. The duration of a shock is typically expressed in milliseconds and its magnitude in units of g (1 g = acceleration of gravity = 386.4 in/s^2). Figure 2 is a simplified representation of a shock pulse. The area under the curve is the velocity change (ΔV) which is represented by Equation 1, where V_i is impact velocity and V_r is rebound velocity. Velocity change also corresponds to the energy dissipated during that shock.

$$\Delta V = |V_i| + |V_r| \tag{1}$$

The shock pulse represented in Figure 2 is defined as a half-sine pulse, and it is the most common shock pulse experienced by packages protected with foam. The area under the curve can also be represented by Equation 2, where G_{pk} is peak deceleration and τ is duration in seconds.

$$\Delta V = \frac{2}{\pi}(G_{pk})(\tau) \tag{2}$$

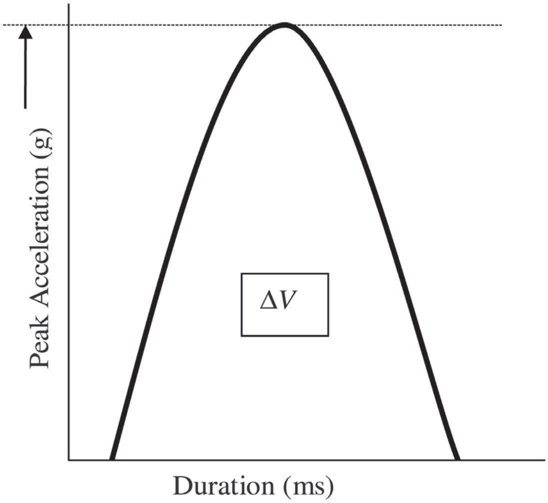


Figure 2. Simplified shock pulse. Reproduced with permission from Schueneman and Marcondes (2004).

According to Brandenburg and Lee (1991), package damage is related to the three factors that describe a mechanical shock: Peak deceleration, duration, and velocity change. When two of these are known, the third can be estimated.

When cushioning material is added to a package system, it deflects during a shock event. This increases the duration of the shock pulse, lowering the peak deceleration.

Conventional Evaluation of Cushioning Materials for Protective Applications

In 1945, Mindlin proposed that there should be a rational way to approach protective package design relying on knowledge of the distribution environment, the mechanical properties of the cushioning material, and of the product itself. According to Mindlin, these could be summarized by knowledge of the following three factors: the maximum acceleration transmitted through the cushioning material to the product, the form of the acceleration-time relationship, and the ruggedness of the structural elements of the product.

In 1956, an ASTM procedure, D-1596—"Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material," was designed to evaluate cushioning materials. The latest revision of this procedure was in 2003. The procedure evaluates the maximum deceleration transmitted through cushioning materials. The data collected is reported in the form of cushion curves. Cushion curves are pairs of plots representing data specific to a cushioning material density, thickness, and drop height. One plot in the pair shows the results for the first impact. The other plot shows the averaged results of the 2nd through 5th impacts. The plots show the maximum deceleration transmitted through the material expressed in units of G (G's are multiples of the acceleration of gravity, g, which equals 386.4 in/s^2) over a range of static loadings. Curves for different thicknesses of the material are usually shown on the same plot. Figure 3 shows an example of a pair of cushion curves. The lowest portion of the curves represents the ideal area for that particular material. In the lower static loadings, the G's are higher indicating that the cushioning material is not being sufficiently challenged, so not enough deflection is achieved. The foam is said to be underloaded in this situation. Not much of the shock is absorbed by the cushion in this case. At the opposite end, one can see a rise in G's again, where the foam is be-

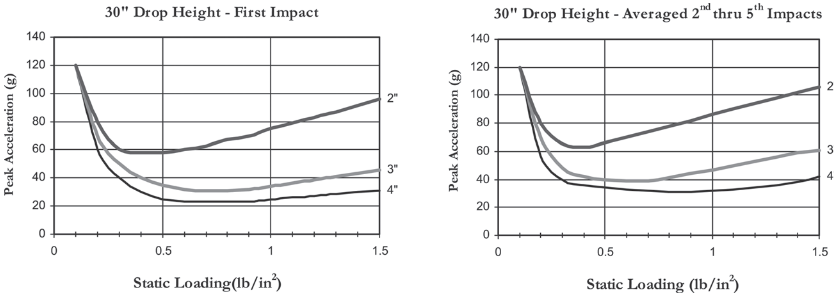


Figure 3. *Example of pair of cushion curves.*

ing overloaded and approaching maximum deflection, or bottoming out. In this case, the cushion absorbs some of the shock, but the product is subjected to higher deceleration when the cushion bottoms out.

Hundreds of hours of laboratory time and thousands of samples are required to produce a set of cushion curves for one material. In addition to laboratory time, there is also time spent in sample production and data analysis that needs to be taken into account. Besides being costly to produce, cushion curves have other limitations related to package design. First, traditional cushion curves offer information only about the variable combinations tested (drop height, static loading, and thickness) leaving the designer with the need to interpolate or extrapolate to come up with an estimate for values that were not tested. For example, if a product is known to be able to survive up to 40 G's, the package designer could look at the curve above for the first impact and see that this material could protect the product from a 30-in drop height, if it is 3 or 4 inches thick at a certain range of static loading. However, the same information is not clear for a thickness of 2.75 in. Another limitation is that the information on the curves does not lend itself well to computer aided design (Daum, 2006).

Evaluation of Cushioning Materials Using Stress-energy Relationship

In 1962, Soper and Dove published a work where, through dimensional analysis, they established that the peak response of a cushion system in a dynamic stress situation is a function of two variables: the energy absorbed per unit volume of material and the "characteristic initial strain rate" (p. 266). This indicates that early on, researchers were interested in simplifying the way that cushioning materials were evaluated, by relying on properties of the materials themselves, and not so much on specific variables such as geometric dimensions. No suggestions were made in this work on how to improve the way that the information about cushioning materials was presented, or how to simplify the data collection.

In 1990, Burgess proposed a method for consolidating the data from cushion curves into one single stress-strain curve relationship that describes the material on a continuous range of application and in a format more compatible with computer aided design. Burgess showed that even though stress is a function of strain and strain rate, the increase in drop height necessary to change the strain rate is so large that, in practice, stress can be thought of as a function of strain only. He also showed that, in performing a force and energy balance of a shock event, the energy to be absorbed per unit volume of cushioning material is equal to the area under the dynamic stress-strain curve for the material. Moreover, the energy is also a function of strain at peak compression. Burgess tested his hypothesis by taking the data from existing cushion curves of an arbitrary drop height and material thickness and deducing the dynamic stress-strain curve for that particular material. The results of this work, when compared to other drop heights and thicknesses, supported his hypothesis. Since the stress-strain relationship is a characteristic property of the material, one can predict the transmitted peak deceleration of an object dropped onto that material without restriction to the cushioning material geometry or drop height. Burgess' method proved to work well for resilient closed-cell foams. He also concluded that, if new data were to be collected for a material, far fewer drop tests would be necessary when compared to the number needed to produce the traditional cushion curves.

In 1994, Burgess proposed a third method for describing the shock absorbing ability of a cushioning material based on a single shock pulse. As was demonstrated in Burgess' previous work for consolidating cushion curves, in order to produce a dynamic stress-strain curve for a material, it is necessary to know the peak G (maximum transmitted deceleration), the energy density (energy absorbed per unit volume), and the dynamic stress (peak G multiplied by static stress). All of the quantities necessary to arrive at these parameters can be found by analyzing one instrumented shock pulse of a drop onto a test sample. The pulses are plotted showing peak deceleration along a duration measured in milliseconds. Based on the energy absorbed at each instant of the pulse, a series of energy densities corresponding to certain times were produced which could then be plotted against the dynamic stress corresponding to those times. In order to follow this procedure, data analysis equipment capable of measuring the peak deceleration at the different instants of the pulse must be used. Burgess found that the accuracy of this method was sensitive to the filtering frequency chosen to filter noise out of the pulse prior to analysis. Noise in the shock pulse is inherent to this type of test because of equipment configuration. The filter frequency which showed the best results was 330 Hz, but the recommendation was made for more work on signal conditioning. No other published materials were found that addressed this question of how best to filter the pulse when the cushion curves are not available for reference.

More recently, Burgess produced a procedure to collect data to evaluate cushioning materials using a stress-energy method (Daum, 2006). This follows the concepts that were demonstrated in Burgess' work published in 1990. Instead of relying on the stress-strain relationship, the procedure relies on the dynamic stress-energy relationship. Since the previous work had demonstrated that both stress and energy could be thought of as a function of strain, then it follows that dynamic stress and energy can be correlated. This is practical because of the variables that define each of these. Dynamic stress (Equation 3) is defined by the static loading (s) multiplied by peak deceleration (G) (Equation 3). Energy is the weight (W) multiplied by the drop height (h) divided by the volume of material, which is equal to the bearing area (A) multiplied by the thickness (t). Since static loading is equal to weight divided by bearing area, energy can be simplified to Equation 4.

$$stress = G \times s \tag{3}$$

$$energy = \frac{sh}{t} \tag{4}$$

The significance of this in practical terms is that all of these variables are the ones used in producing traditional cushion curves using the ASTM D1596 procedure. Additionally, as Burgess had concluded in the work in 1990, fewer samples are needed to produce a curve from which peak transmitted deceleration can be predicted.

A procedure designed by Burgess, based on the stress-energy relationship, was used in Daum (2006) to produce cushion curves for four different densities of a closed-cell material (ARCEL® resin). For two of the densities, molded and fabricated samples were used, and separated as distinct material sets. That was the first documented time that cushion curves were produced from experimental data relying only on the dynamic stress-energy relationship in the sampling plan and data analysis. As a conservative measure, a larger number of samples than was believed necessary was used. The experiment was designed based on five samples per energy level. The procedure prescribed ways to find the maximum and minimum energy, but did not determine how many intervals were necessary. The data collected showed very high correlation between the dynamic stress and the dynamic energy for all the data sets collected. Curves were fitted to the data with correlation coefficients above 0.9. The coefficient of correlation is a measure of how closely variables co-vary. The coefficient of correlation is a number between −1 and 0, and 0 and 1. A coefficient of −1 is a perfect negative correlation, and a coefficient of 1 is a perfect positive correlation. Therefore, coefficients above 0.9 translate to a very close positive correlation between the stress and energy measured (Ott & Longnecker, 2001). The curves fitted followed the general format of Equation 5, where y is the predicted value of peak deceleration, x is the energy level, and A and B are coefficients specific to each material.

$$y = Ae^{Bx} \tag{5}$$

Equation 5 form has been derived by Burgess (1993b) as the expected behavior of a closed cell foam whose cushion properties are dominated by the compression of air inside the cells.

The procedure included 250 drops for the three lower density material sets, and 300 drops for the three sets of material with higher densities. One of the conclusions presented in Daum's work was that, based on the results obtained by the procedure, it should be possible to achieve the same quality of predictability with fewer samples (2006).

Evaluation of Sample Statistics for Statistical Difference

Statistical procedures for testing hypothesized values of population parameters using sample statistics are well documented in statistical textbooks (Ott & Longnecker, 2001; Bhattacharyya & Johnson, 1977). Hypothesis testing is one approach where the null hypothesis (H_0) might be that the population parameter is equal to a certain value, and the alternative hypothesis (H_a) would be that it is different. An appropriate test statistic is chosen depending on whether one is testing a mean, a proportion, or the slope or intercept of a regression line. A rejection region for the sampling distribution of the test statistic is defined based on a value of α (for a confidence level of 95%, $\alpha = 0.05$). For sample sizes smaller than 100, the Student's *t*-distribution table (found in most statistics textbooks) is recommended to identify the critical *t* value of the statistic that would determine the borders of the rejection region, for the hypothesis test, based on the chosen value of α. It is also necessary to determine the degrees of freedom, or the number of observations in the sample that are free to vary, associated with the sample size. For the testing simple regression slopes or intercepts, the degrees of freedom are two less than the total sample size. The observed value of the test statistic from the sample is standardized by taking the ratio of the difference between the observed statistic and the assumed population parameter and dividing it by the standard error (or the amount of variability in the distribution of the observation) of the statistic (Equation 6).

$$t = \frac{statistic - parameter}{error} \tag{6}$$

The standardized *t*-observed is compared to the t-critical from the Student's *t*-distribution table and a decision to either reject or not reject H_0 is made depending on whether the observed value falls in the rejection region of the density curve. An assumption is made that the values for the parameter in question are normally distributed in the population. When one is interested in finding whether an observed value is statistically dif-

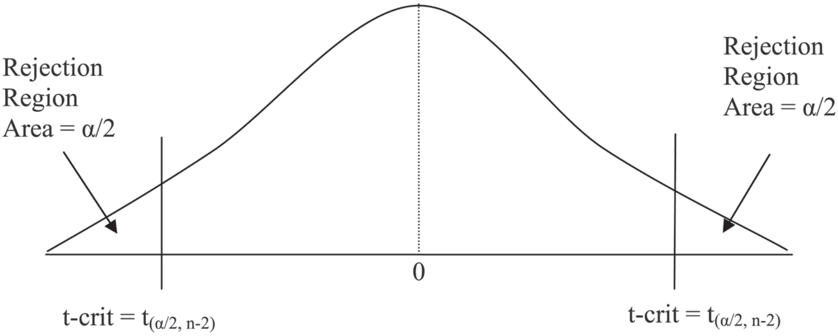


Figure 4. *Illustration of rejection region of a two-tailed hypothesis test.*

ferent from another, the hypothesis testing is set up so the null hypothesis says it is equal to a certain value, and the alternative hypothesis is that it is different. This creates a two-tailed test, where the rejection region, which is equal to α, is made up of two areas equal to half of α at each tail end of the density curve. This is illustrated in Figure 4. When the values are compared for statistical significance, they are considered to be statistically different if the *t* test statistic value falls in the rejection region of the curve.

MATERIAL AND METHODS

Test Equipment

The test equipment used was a Lansmont Cushion Tester, model 23. The platen of the cushion tester was instrumented with a PCB ICP® piezoelectric accelerometer model number 353B15, serial number 80368. The shock pulses were captured and analyzed using the GHI WinCAT® version 2.8.1 software, which plots the captured pulse as maximum deceleration in the time domain. This equipment is compliant with the requirements in ASTM D-1596 for cushion testing. Figures 5 and 6 are pictures of the actual equipment set up used to collect the data.

The equivalent freefall drop height (h_{eq}) was calculated by Lansmont Test Partner Velocity Sensor ® software version 2.0.1. This calculation is done based on the impact velocity (V_i) of the platen when it hits the sample using Equation 7, where g is the acceleration of gravity. The impact velocity is monitored by equipment:

$$h_{eq} = \frac{V_i^2}{2g} \tag{7}$$

An equivalent freefall drop height must be calculated because the platen does not fall in a true free fall on the test sample. The platen is guided by rods, as it falls, which cause some friction. So, the machine drop height is higher than the equivalent free fall drop height.

When a shock pulse is captured, it is often necessary to apply an electronic filter to remove high frequency "noise" caused by the mechanical structure of the testing equipment. Since these higher frequency events are not caused by the impact on the cushion sample, it is of no interest for measuring the transmitted shock. In fact, such events may degrade the accuracy of subsequent shock pulse measurements. Therefore, the noise

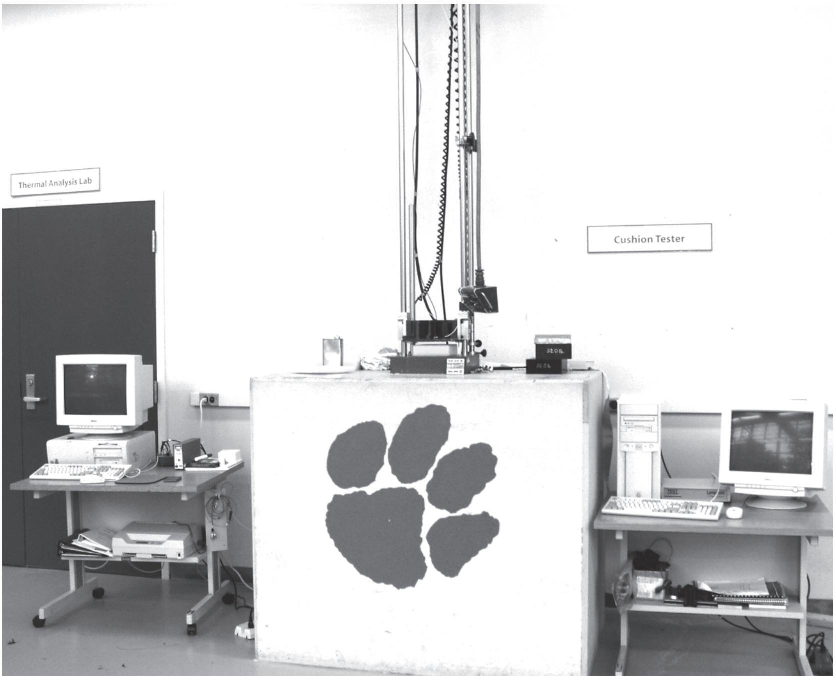


Figure 5. *Cushion testing equipment set up.*

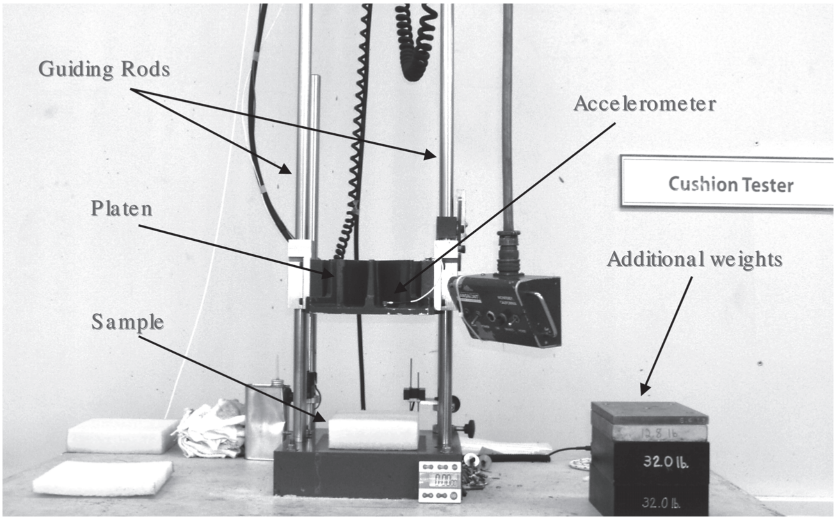


Figure 6. *Close up of the equipment.*

should be removed. Since the frequencies of the "noise" are typically much higher than the fundamental frequency of the shock pulses, this is achieved by using a low-pass electronic filter (included in GHI WinCAT® software). As prescribed in the test procedure (Daum, 2006), the filter frequency was calculated using Equation 8, where F_f is the filtering frequency and τ_{10} is the effective pulse duration in seconds.

$$F_f \geq 10\left(\frac{1}{2\tau_{10}}\right) \tag{8}$$

Equation 8 can be further simplified to Equation 9

$$F_f = \frac{5}{\tau_{10}} \tag{9}$$

These equations require that the pulse duration be determined. In practice, the effective pulse duration (duration of an equivalent "clean pulse) is different from the baseline duration. Mechanically-generated pulses are smooth curves with a rise and decay, rather than with the sharp corners shown in the idealized pulse in Figure 7. It is common practice to determine effective pulse duration as the time between the points at 10% of peak pulse amplitude on the rise and decay (Department of Defense, 2006).

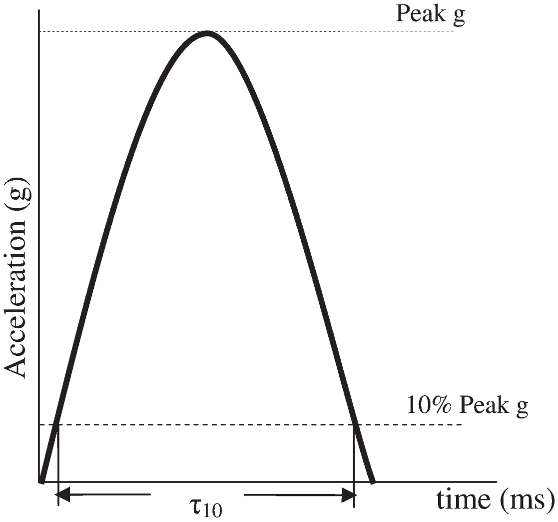


Figure 7. *Illustration of effective pulse duration.*

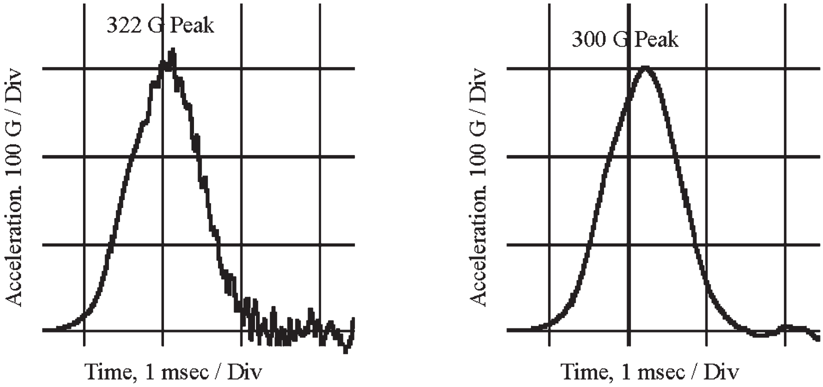


Figure 8. *Unfiltered and filtered pulses (Reprinted with permission from Kipp, 2002).*

Figure 8 shows an unfiltered pulse on the left and a filtered pulse on right of a shock pulse illustrating effective pulse duration. In reality, the beginning and the end of a pulse are not as clean; therefore, the effective pulse duration is a conservative estimate of duration, which leaves out the tails of the pulse at both the beginning and the end (Kipp, W., 2002).

The pulse acquisition software used for the tests included a function which could automatically pick the beginning and end of the shock pulse. However, the software sometimes misinterpreted the effective duration due to noise and the smooth rise and decay. For the sake of consistency, all pulses were analyzed by manually setting the boundaries of effective duration used to calculate the filtering frequency.

Testing Phases

There were four different phases of testing:

- *Phase I:* initial collection of data on ARCEL® resin foam blocks.
- *Phase II:* statistical evaluation of lines fit to reduced sets of samples against the lines fit to the full data set acquired in Phase I using the *t*-test to determine if estimates from the reduced samples were statistically different from those from the reference data set.
- *Phase III:* data collection for expanded polyethylene (EPE) using the reduced sample plan found in Phase II and comparing it to published EPE data.
- *Phase IV:* homogeneity testing of the lines for the five drops performed on each sample using the original data collected in Phase I.

Three different possibilities were considered for reducing the original sample size with the objective of finding a minimum sample size necessary to represent the larger set of data:

- Reduction of the number of energy intervals
- Reduction of the number of replicates per energy level
- Reduction of the number of drops performed on each sample

Only the options of reducing the number of energy level intervals, and reducing the number of drops on each sample were within the scope of the work presented here. Reducing the number of energy levels is presented in Phase II of this study, whereas the reduction in the number of drops is discussed in Phase IV.

Phase I—ARCEL® resin Data Collection

The materials used in Phase I were provided by Nova Chemical, Inc. in the dimensions required by the test plan (See Appendix A for details). Six sets of blocks of ARCEL® Resin foam were cut and all three dimensions were measured. ARCEL® Resin is a common closed-cell foam material used in protective packaging, and therefore a good candidate for these tests. The six sets were made up of four different densities of material (1.2 lb/ft^3, 1.7 lb/ft^3, 2.2 lb/ft^3, and 3.0 lb/ft^3). There were four sets of molded material, and two sets of fabricated blocks (1.2 lb/ft^3 and 2.2 lb/ft^3). Molded and fabricated samples differed in that the molded samples still had the outer skin on the top and bottom faces of the blocks which is characteristic of the molding process. Fabricated samples were cut down to the desired thickness by removing the skins of thicker boards. These materials were shipped to the Clemson University in corrugated boxes using a small parcel carrier. All materials were conditioned at 73°F and 50% relative humidity prior to testing. Samples were kept out of the conditioning chamber for no longer than 30 minutes before being tested.

Table 1 summarizes the number of samples used, and density of the materials tested. There were five samples per energy level. The five energy levels were achieved by different combinations of sample dimensions as well as drop height and the weight that was dropped. Appendix A shows how each of the replicates for the energy levels for one of he materials tested were produced. Five impacts were performed on each sample. The minimum energy level for each of the six material sets was 5

Table 1. *Summary of Materials Tested.*

	Energy Levels	Number of Drops Planned	Number of Drops Analyzed
1.2 (lb/ft^3) Molded	10	250	220
1.2 (lb/ft^3) Fabricated	10	250	230
1.7 (lb/ft^3) Molded	10	250	240
2.2 (lb/ft^3) Molded	12	300	275
2.2 (lb/ft^3) Fabricated	12	300	265
3.0 (lb/ft^3) Molded	12	300	265

in-lb/in^3. The maximum energy level for 1.2 lb/ft^3 molded and fabricated set and 1.7 lb/ft^3 set was 50 in-lb/in^3, and for the remaining three material sets was 80 in-lb/in^3.

There were fewer drops analyzed than planned due to equipment failure capturing either the shock pulse or the equivalent drop height in the first impact. This was due to equipment sensitivities and trigger thresholds. Trigger thresholds must be defined in the software by the operator. In some cases, the threshold was too low and the release action of the cushion tester triggered the instrumentation too soon resulting in lost data. Since cushioning materials perform differently on the first impact, it is crucial to have first impact information. Therefore, when first impact data was not captured, no further drops were performed for a particular sample.

The actual drop testing was conducted within the guidelines of ASTM D-1596. Each shock pulse was filtered, analyzed, and the peak deceleration was recorded. At least one minute was allowed between each impact on a particular sample. The peak deceleration was multiplied by the static loading resulting from the total weight used and the area of the face of the sample. The product of this multiplication is the dynamic stress to which the sample had been subjected. The dynamic stress was tabulated for each sample at each of the energy levels for each drop from 1st through 5th.

Following industry practice, the data for each material density set was divided into 1st impact data and averaged 2nd–5th impact data. Therefore, each material had a pair of plots to describe the dynamic stress-energy relationship, one for the 1st impact and the other for the averaged 2nd–5th impacts. The collected data was plotted with energy on the x-axis and dynamic stress on the y-axis.

Phase II—Statistical Evaluation of Lines Fit to Reduced Sample

The dynamic stress data was transformed with the natural logarithm to make the XY relationship linear. This transformation is a common transformation for data with an exponentially increasing relationship, which was the case of the data collected for the ARCEL® Resin samples. Linearization was applied to allow for the statistical tests planned. The plan included comparing the slope and intercept of lines fit to reduced data sets to the full data set as a reference. The transformation of Equation 5 is shown in Equation 10:

$$\ln y = \ln A + Bx \tag{10}$$

The comparison used the t-test to determine if the slope (*B*) and intercept ($\ln A$) of the line from the reduced data set were statistically different from the slope and intercept of the line fit to the full data. The statistical software package SAS® 9.1 was used to fit regression lines to each set of transformed data. The output contained the coefficient of correlation for the regression model, the slope, and the intercept of the line with their corresponding error. It also included *t*-values for each of the estimated parameters (slope and intercept).

Since the dynamic stress relationship could be described by a line, basic algebra was used as a starting point. Algebra dictates that only two points are necessary to define a line, so the starting point was to reduce the data to two energy levels. The energy levels chosen were the two extreme energy levels. Lines were fitted to the two-energy level data, and the slope and intercept estimates for the lines were compared to the corresponding estimates from the lines fitted to the total data set for that material. Statistical differences were evaluated based on t-value of the estimate using a 95% confidence level ($\alpha = 0.05$). If the value of the estimate was found to be statistically different from that of the full data set, the number of energy levels was increased until no statistical difference was evident.

Phase III—Reduced Sample Evaluation Using EPE

Once the minimum number of samples was found as outlined in Phase II, a testing plan using EPE was designed. The energy levels were determined; and drop heights, static loadings, and thicknesses were chosen to produce the planned energy levels. Cushion testing was conducted according to the stress-energy procedure, but using the reduced number of samples. This was done to compare the results obtained to existing information about EPE in order to validate the theory that with that reduced number of samples the cushioning properties of a material could be described.

Two densities of EPE were used: ETHAFOAM™ 220 (2.3 lb/ft^3), and ETHAFOAM™ Nova (1.7 lb/ft^3) (both are trademarks of Dow Chemical Company). Both are produced as extruded planks. The planks were donated by Span Packaging of Greenville, SC. Samples were cut at a Clemson University laboratory using a vertical band saw. Samples were then stored under standard conditions (73°F @ 50% relative humidity) prior to testing. Cushion testing was performed on the samples using the exact same procedure and equipment as had been used on the ARCEL® Resin samples in Phase I.

The static loadings corresponding to the lowest portion of the published cushion curves (as described in Chapter 2 of this work) for two drop heights considered typical in the industry (24 and 30 inches) were used for these predictions. The range of static loading for the Ethafoam™ Nova was between 0.5 and 1.2 lb/in^2, and the range of static loading for the Ethafoam™ 220 was between 1.0 and 2.0 lb/in^2.

Regression lines were fitted to the data collected and prediction equations were found. These equations were used to predict peak deceleration (G) for static loadings at the lower portion of the published cushion curves for two drop heights: 24 and 30 inches. The G values predicted using the equation from the regression line were compared to the ones predicted using ETHACALC™ Millennium, which is a software tool offered by Dow Chemical Company for calculating G values based on inputs such as drop height, area of foam, and weight of object.

Phase IV—Homogeneity Testing of Data for Individual Impacts

The homogeneity of the lines produced for each drop in the sequence was analyzed in order to determine if fewer than five drops could be performed on each sample, without loss of information. Line homogeneity, in this case, is defined as agreement from drop-to-drop. If the lines for drops 4 and 5 were statistically the same with respect to their slope and intercept, for example, one could say that the fifth drop was unnecessary. The data was separated into material densities as well as by drop. Five lines representing equation 10 were associated with each material, as opposed to the industry practice of two lines. Each of the five lines was compared to each other in the following sequence: the intercept and slope of the line fit to drop 1 data of a particular material density was compared to each of the subsequent drops individually for that density. Then, drop 2 was compared to each of the subsequent drops, and so on up to drop 4 being compared to drop 5. This was done for each material set.

RESULTS AND CONCLUSIONS

Phase I

Visual observation of the scatter plots for each of the material density sets, such as that in Figures 7 through 12, revealed that the dynamic stress-energy relationship could be described as increasing at an increasing rate. It was also noted that the variation within each energy level increased as the energy level increased. Furthermore, some of the peak decelerations recorded were much above the intensity one would expect any product to survive. These energy levels corresponded to combinations of static loading, drop height, and thickness that would be outside of the limits one should expect these materials to perform. Therefore, the data belonging to energy levels where recorded deceleration values were higher than 200 G's were excluded from the reference set. Figures 9 through 14 show the plots of all the data of each of the material densities tested with curves fitted and the corresponding R^2 (coefficient of correlation). The values on the y-axis have been withheld to protect the proprietary information of Nova Chemicals Inc.

Phase II

Linearization

In order to be able to easily compare the lines for statistical difference, the data was linearized by transforming dynamic stress using the natural logarithm. After the transformation was applied, the data was plotted and visually inspected. Figures 15 through 20 show the plots of the linearized data without the higher levels of energy that were eliminated from the sets as described in Phase I. The values on the y-axis have been withheld to protect the proprietary information of Nova Chemicals Inc.

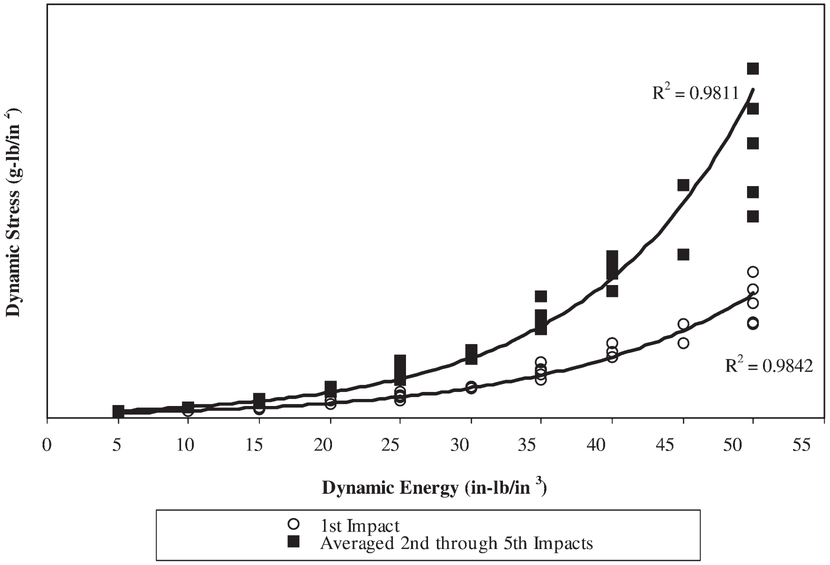


Figure 9. *Scatter plot of data for 1.2 lb/ft³ molded ARCEL® Resin blocks.*

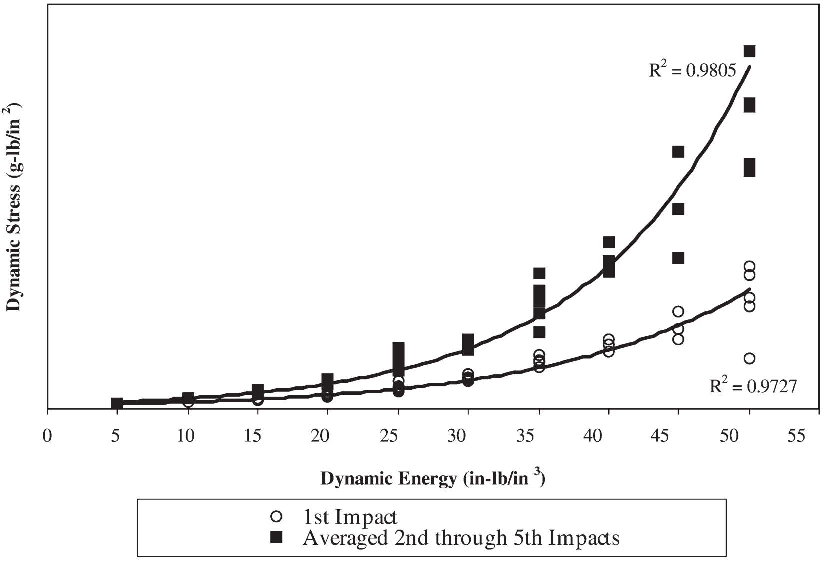


Figure 10. *Scatter plot of data for 1.2 lb/ft³ fabricated ARCEL® Resin blocks.*

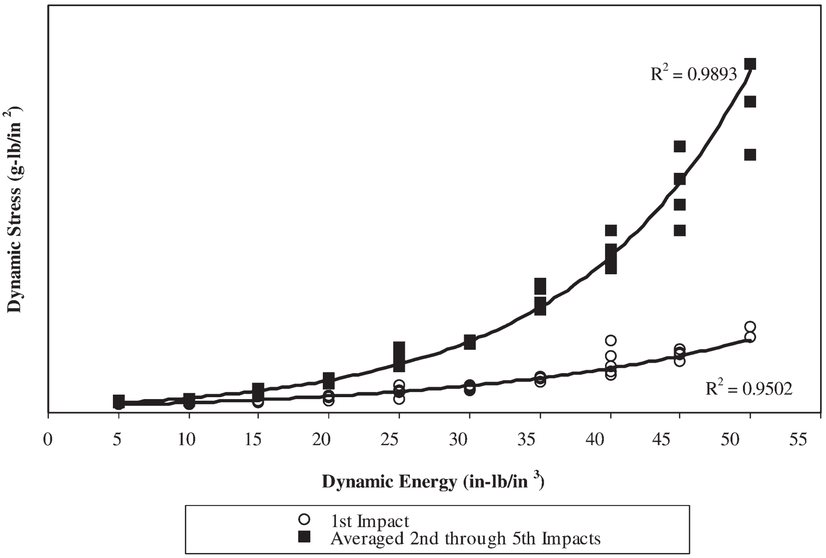


Figure 11. *Scatter plot of 1.7 lb/ft³ molded ARCEL® Resin blocks data.*

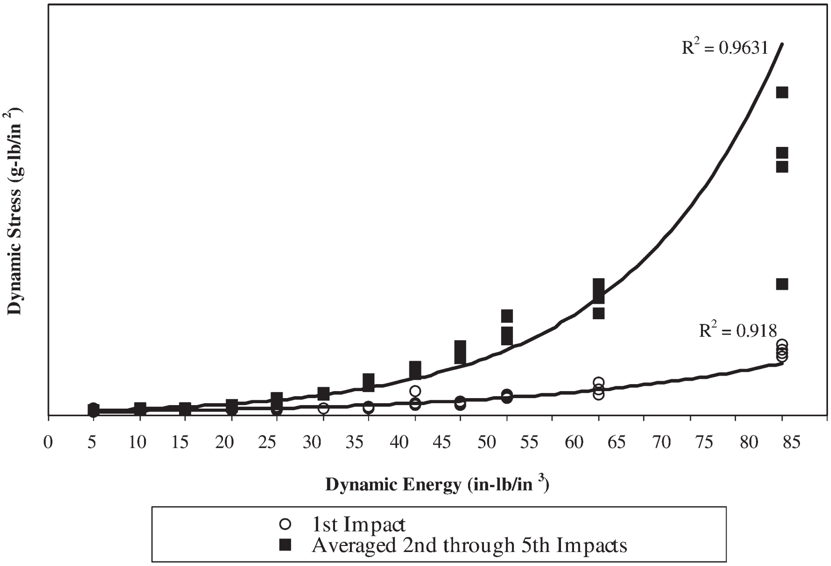


Figure 12. *Scatter plot of 2.2 lb/ft³ molded ARCEL® Resin blocks data.*

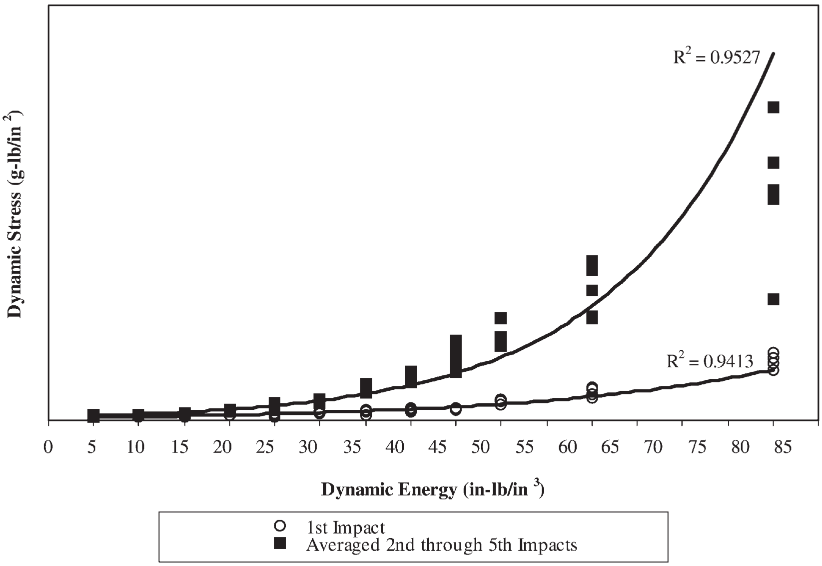


Figure 13. *Scatter plot of 2.2 lb/ft^3 fabricated ARCEL® Resin blocks data.*

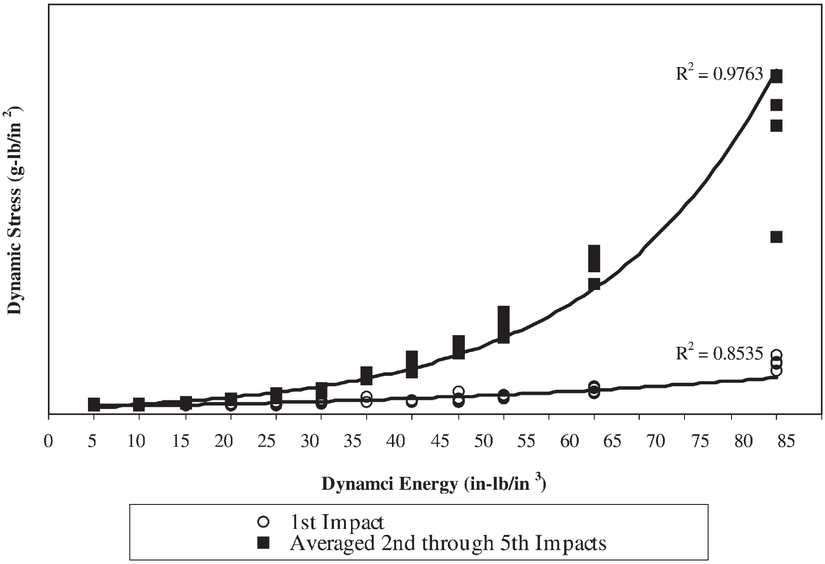


Figure 14. *Scatter plot of 3.0 lb/ft^3 molded ARCEL® Resin blocks data.*

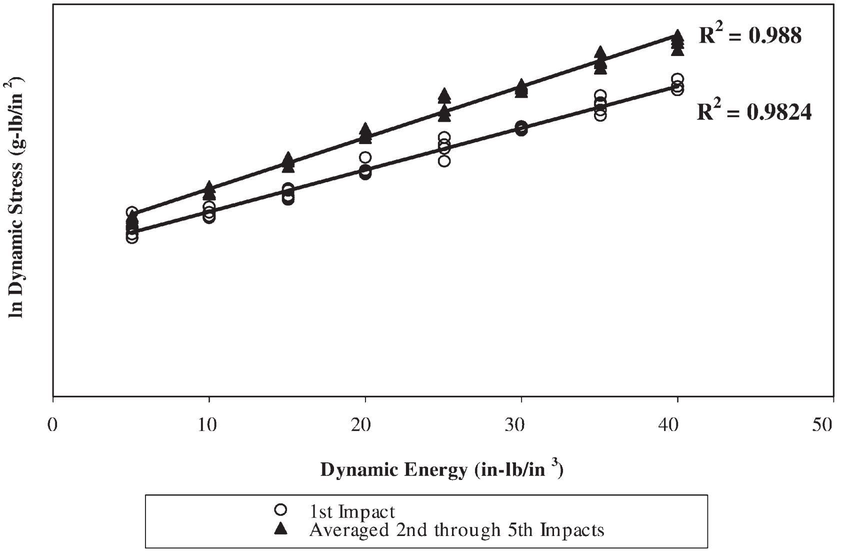


Figure 15. *Linearized data for 1.2 lb/ft³ molded ARCEL® Resin blocks.*

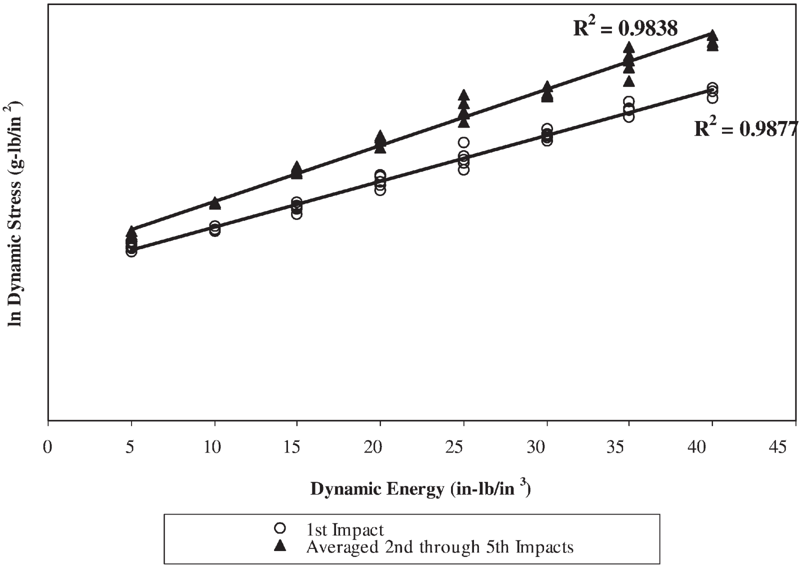


Figure 16. *Linearized data for 1.2 lb/ft³ fabricated ARCEL® Resin blocks.*

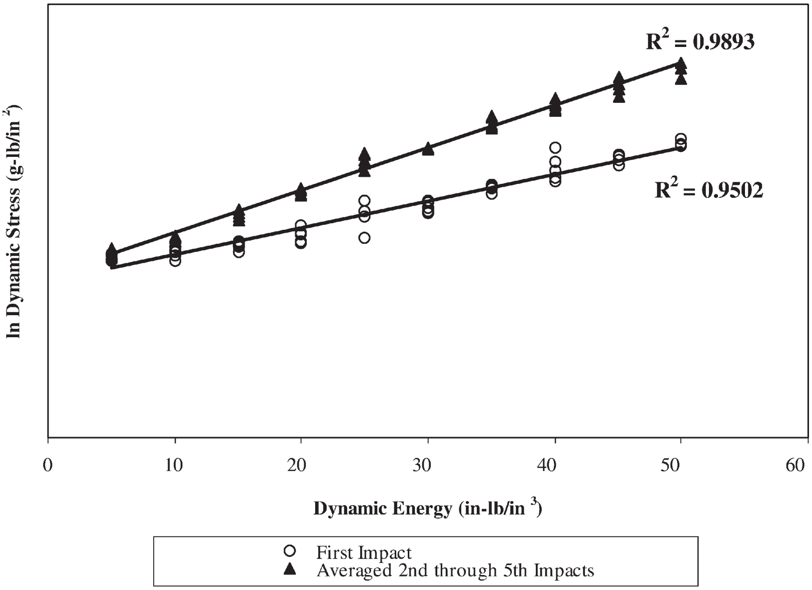


Figure 17. *Linearized data for 1.7 lb/ft^3 molded ARCEL® Resin blocks.*

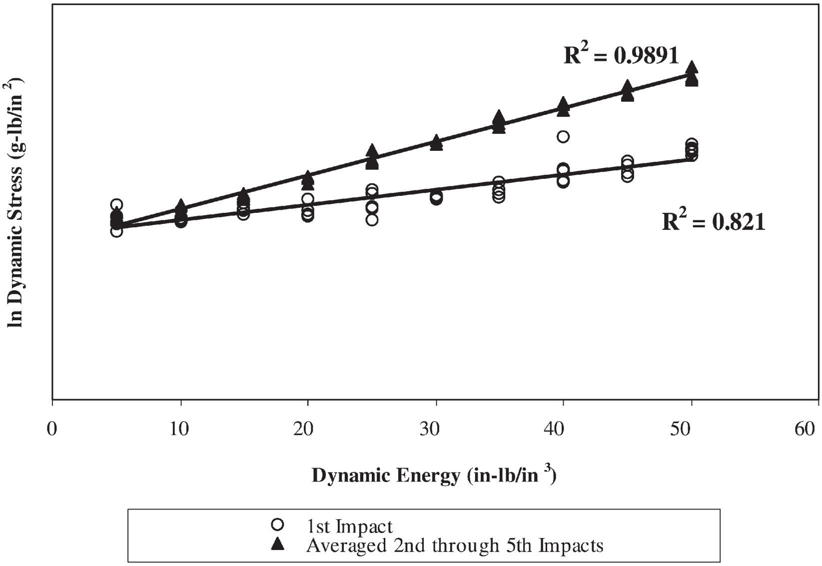


Figure 18. *Linearized data for 2.2 lb/ft^3 molded ARCEL® Resin blocks.*

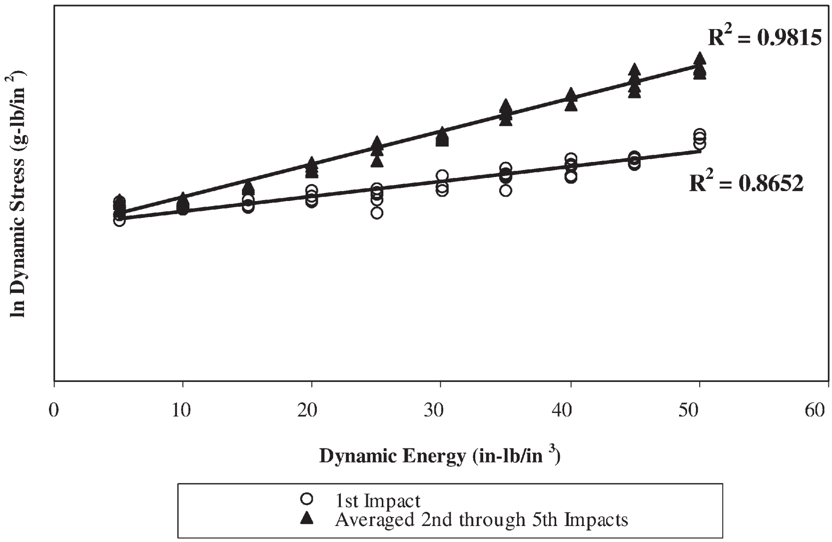


Figure 19. *Linearized data for 2.2 lb/ft^3 fabricated ARCEL® blocks.*

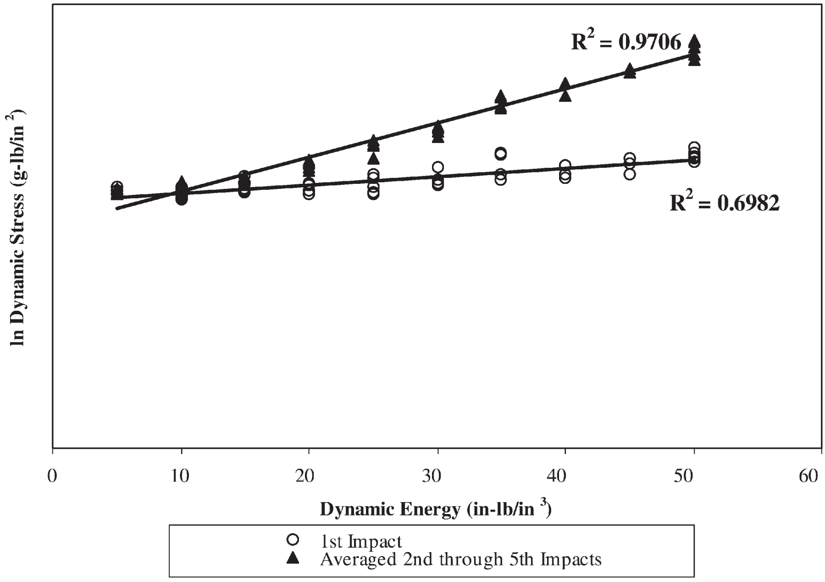


Figure 20. *Linearized data for 3.0 lb/ft^3 molded ARCEL® blocks.*

Table 2. *Summary of Reference Data.*

	Energy Levels	**Energy Range (in-lb/in^3)**
1.2 (lb/ft^3) Molded	8	5–40
1.2 (lb/ft^3) Fabricated	8	5–40
1.7 (lb/ft^3) Molded	8	5–40
2.2 (lb/ft^3) Molded	10	5–50
2.2 (lb/ft^3) Fabricated	10	5–50

As can be observed in Figure 20, the data for the 3.0 lb/ft^3 foam are not as linear after transformation. A curve was still evident in the averaged 2nd through 5th impact data, and more variation was present in the 1st impact data when compared to other densities, resulting in a lower R^2. One of the implications of this is that there may be more factors required to describe the material behavior at this density than those that exist in the dynamic stress-energy relationship. Therefore, no further analysis was performed on this data with regard to reducing the sample size.

Five data sets were ultimately analyzed after the lines were fit. Table 2 summarizes the data that was used for analysis as the reference data in seeking the minimum sample size with which one could describe the stress-energy relationship of these materials.

Two-point Reduction

The reduction to two energy levels produced lines which were statistically different for some of the material sets. Table 3 shows the summary of the results of the statistical comparison of estimates for the intercept and the slope of the lines obtained with only two energy levels. For two

Table 3. *Results of Statistical Comparison for Lines with Two Energy Levels.*

	Results of Statistical Comparison (α = 0.05)			
	1st Impact		**Averaged 2nd–5th Impacts**	
Densities	**Intercept**	**Slope**	**Intercept**	**Slope**
1.2 (lb/ft^3) Molded	No Stat. Diff.	No Stat. Diff.	No Stat. Diff.	No Stat. Diff.
1.2 (lb/ft^3) Fabricated	No Stat. Diff.	No Stat. Diff.	**Stat. Diff.**	No Stat. Diff.
1.7 (lb/ft^3) Molded	No Stat. Diff.	No Stat. Diff.	No Stat. Diff.	No Stat. Diff.
2.2 (lb/ft^3) Molded	No Stat. Diff.	No Stat. Diff.	**Stat. Diff.**	**Stat. Diff.**
2.2 (lb/ft^3) Fabricated	**Stat. Diff.**	No Stat. Diff.	**Stat. Diff.**	No Stat. Diff.

lines to be considered the same, both the intercept and the slope must be statistically the same.

The results in Table 3 indicate that the intercept seems to be a lot more sensitive to the reduction in energy levels included than is the slope. Two of the three sets that showed statistical difference were of fabricated samples. The data also show that the averaged 2nd–5th impact data is more sensitive. This could be an indication of the effect that multiple impacts have on materials that permanently deform upon stress. Air compression within the cells is primarily responsible for the shock absorption in closed-cell materials (Burgess, 1993). However, it is known that the cells may rupture due to impact, so, it may be harder to predict the behavior of these materials as multiple impacts change the shock absorbing ability.

Three-point Reduction

Since there were statistical differences found between the lines produced with two energy levels and the lines from the full set, another energy level was added to the middle of the range previously evaluated. Table 4 summarizes the results of the statistical comparison of the parameters for the 3-point lines and the lines from the full reference set.

As can be seen in Table 4, there were no statistical differences observed between the lines fitted through 3 points of energy data and the lines from the full set of data. These results suggest that the ability of these materials to absorb energy could be described with 15 samples (5 for each of three energy levels). Different combinations of three energy levels were tested. The lower densities are not sensitive to the choice of the three energy levels, but the 2.2 lb/ft^3 data sets sensitive.

Upon closer observation, the 2.2 lb/ft^3 data sets also revealed the same S-shape observed in the 3.0 lb/ft^3 data. The S-shape in the scatter plot explains why changing the 3 energy levels used changes the slope and/or intercept of the resulting lines. It is important to determine the two extremes carefully by considering minimum and maximum static loadings that would be appropriate for the density of material under evaluation. The S-shape also suggests that, even though the dynamic stress-energy model at this density can pass a statistical test, other factors may be at work as well. The cell wall rupture that occurs as these closed-cell foams are subjected to multiple impacts may shift the dependence from air compression to other mechanical properties of the foam for absorbing shock.

Table 4. *Results of Statistical Comparison for Lines with Three Energy Levels (α=0.05).*

First Impact

Density (lb/ft^3)	***t*-Slope**	**Slope Error**	***t*-Intercept**	**Intercept Error**	***t*-Critical (α/2, *n*-2)**	**Statistical Difference**
1.2 Molded (n=13)	–0.72	0.00279	1.06	0.0734	2.201	No
1.2 Fabricated (n=13)	–1.15	0.00235	1.16	0.05858	2.201	No
1.7 Molded (n=15)	1.04	0.00397	–0.23	0.10877	2.160	No
2.2 Molded (n=15)	–1.03	0.00293	1.60	0.09619	2.160	No
2.2 Fabricated (n=15)	–1.23	0.00333	1.80	0.10934	2.160	No

Averaged 2nd through 5th impacts

Density (lb/ft^3)	***t*-Slope**	**Slope Error**	***t*-Intercept**	**Intercept Error**	***t*-Critical (α/2, *n*-2)**	**Statistical Difference**
1.2 Molded (n=13)	0.15	0.00325	–0.41	0.08551	2.201	No
1.2 Fabricated (n=13)	0.47	0.00361	–0.46	0.08984	2.201	No
1.7 Molded (n=15)	–1.16	0.00224	1.80	0.06126	2.160	No
2.2 Molded (n=15)	0.77	0.00156	–0.92	0.05099	2.160	No
2.2 Fabricated (n=15)	0.82	0.00195	–0.80	0.06387	2.160	No

ARCEL® Resin materials can be affected by multiple impacts, because they are a copolymer of styrene and ethylene. Homopolymer EPS is crushable, and some copolymers of EPS exhibit the same property. The same phenomenon may not be present in more resilient closed cell cushioning materials, such as EPE (expanded polyethylene) or EPP (expanded polypropylene).

Phase III

Test of the Three-point Plan with EPE

Two different densities of EPE (expanded polyethylene) from Dow Chemical, Inc. were used to test the three-point plan. Blocks of Ethafoam™ Nova (1.7 lb/ft^3) and Ethafoam™ 220 (2.2 lb/ft^3) were cut to dimensions which, combined with drop height and weight would represent 3 energy levels. Five samples per energy level were prepared and five drops were performed on each sample. The five samples in a specified energy level were exact replicates of each other. All samples used were 2 inches thick, and the replicates within an energy level did not vary in area or static loading. This test plan differed from the test plan in Phase I, where replicates of the same energy level were not duplicates in terms of dimensions (see Appendix B for details of sample dimensions, drop heights, and static loadings). Table 5 shows the energy levels used for each of the two materials tested.

The equations corresponding to the lines fit to the results of the cushion testing of these Ethafoam™ materials were used to predict the transmitted deceleration.

The transmitted G's calculated by using the 3-point predicting equation were compared to the transmitted G's expected according to ETHACALC™. Tables 5 and 6 show the comparison for the two material densities tested at two different drop heights. The difference between the predicted G's from the data and expected G's from ETHACALC™ varies within a range similar to what ASTM D-1596 reports as between laboratories standard deviation. The ASTM reported

Table 5. *Energy Values for 3-Point Test of Ethafoam™.*

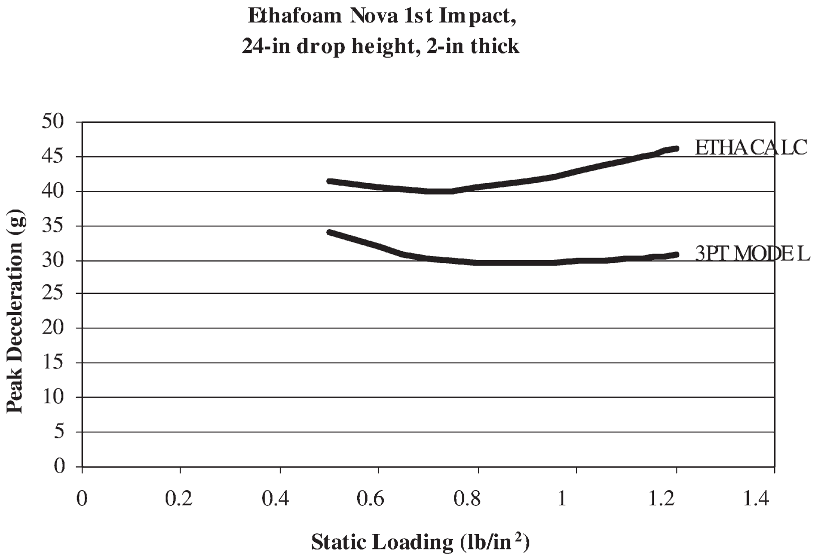
Material	Energy Values Tested
Ethafoam™ Nova (1.7 lb/ft^3)	5 in-lb/in^3, 25 in-lb/in^3, and 40 in-lb/in^3
Ethafoam™ 220 (2.2 lb/ft^3)	10 in-lb/in^3, 25 in-lb/in^3, and 50 in-lb/in^3

Table 6. *Predicted G using 3-Point Equation vs. ETHACALC® for 1st Impact on 2-in Ethafoam™.*

Material	Drop Height (in)	Static Loading (lb/in^2)	Predicted G (3pts)	Predicted G (Ethacalc)	Difference (G)	Percent Difference
Nova	24	0.5	33.97	41.43	7.46	18
	24	0.7	30.32	40.08	9.76	24
	24	0.9	29.47	41.56	12.09	29
	24	1.1	30.14	44.42	14.28	32
	24	1.2	30.88	46.15	15.27	33
	30	0.5	39.04	50.10	11.06	22
	30	0.7	36.85	51.60	14.75	29
	30	0.9	37.88	56.05	18.17	32
	30	1.1	40.95	61.82	20.87	34
	30	1.2	43.15	64.94	21.79	34
220	24	1.0	28.44	31.22	2.78	8
	24	1.2	27.84	32.37	4.53	14
	24	1.4	28.03	33.97	5.94	17
	24	1.6	28.82	35.87	7.05	20
	24	2.0	31.81	40.18	8.37	21
	30	1.0	34.78	40.92	6.14	15
	30	1.2	35.45	43.62	8.17	19
	30	1.4	37.16	46.79	9.63	21
	30	1.6	39.77	50.23	10.46	21
	30	2.0	47.58	57.48	9.90	17

Table 7. *Predicted G using 3-Point Equation vs. ETHACALC® for Averaged 2nd–5th Impacts on 2-in Ethafoam™.*

Material	Drop Height (in)	Static Loading (lb/in^2)	Predicted G (3pts)	Predicted G (Ethacalc)	Difference (G)	Percent Difference
Nova	24	0.5	38.55	46.55	8.00	17
	24	0.7	35.03	45.85	10.82	24
	24	0.9	34.66	47.99	13.33	28
	24	1.1	36.08	51.54	15.46	30
	24	1.2	37.30	53.63	16.33	30
	30	0.5	44.81	57.05	12.24	21
	30	0.7	43.25	59.54	16.29	27
	30	0.9	45.45	65.05	19.60	30
	30	1.1	50.24	72.01	21.77	30
	30	1.2	72.01	75.78	3.77	5
220	24	1.0	36.99	42.28	5.29	13
	24	1.2	37.09	44.42	7.33	17
	24	1.4	38.26	47.29	9.03	20
	24	1.6	40.28	50.62	10.34	20
	24	2.0	46.65	58.05	11.40	20
	30	1.0	46.62	56.35	9.73	17
	30	1.2	48.96	61.14	12.18	20
	30	1.4	52.89	66.64	13.75	21
	30	1.6	58.32	72.56	14.24	20
	30	2.0	74.10	84.92	10.82	13



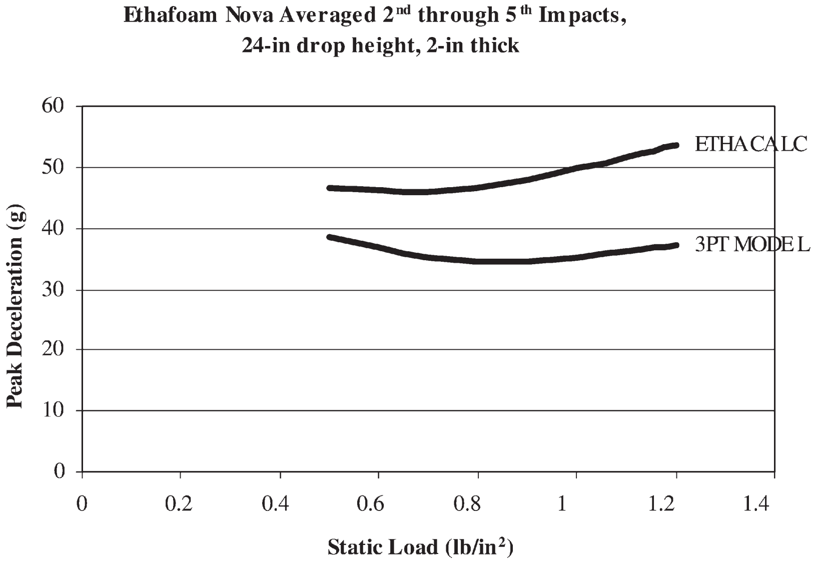


Figure 21. *Cushion curves for Ethafoam™ Nova.*

range is from 5 to 15 G's, and the ranges in Tables 5 and 6 are 7 to 22 G's for ETHAFOAM™ Nova and 2 to 14 G's for the ETHAFOAM™ 220. Differences in equipment, instrumentation, and even within the materials themselves are responsible for part of the variability in these results. The narrower range of variability in the difference in G's for the ETHAFOAM™ 220 could be due to the loading of the equipment for the tests. The higher static loadings allowed for heavier weights on the platen of the cushion tester. This decreases the effect of friction, allowing less variation on the equivalent drop height between drops.

Figure 21 shows the cushion curves corresponding to the Ethafoam™ Nova data in Tables 6 and 7.

Phase IV

Homogeneity Testing for the Individual Drops on ARCEL® Resin

Homogeneity testing was conducted for the regression lines fitted to the full set of data for each of the five drops performed on each sample. This analysis revealed that the lines fit to the data from the 2nd, 3rd, 4th, and 5th impacts individually were different the line fit to the data from the 1st impact, for the lowest density foams (1.2 lb/ft^3 molded and fabricated). This confirms a well-accepted concept in the industry. However, there was no statistical difference among those lines when they were compared to each other. This suggests that, for these two material sets, the testing of the material beyond the 2nd impact did not add any new information about this material. All the other densities showed statistical differences between the individual lines produced for each drop from two through five. This is presented in Table 8.

Table 8. *Homogeneity Testing Results of Individual Drops on ARCEL® Resin Blocks.*

	Drop Line Comparison			
Density (lb/ft^3)	**1st vs. others**	**2nd vs. 3rd,4th,5th**	**3rd vs. 4th & 5th**	**4th vs. 5th**
1.2 Molded	Different	Not Different	Not Different	Not Different
1.2 Fabricated	Different	Not Different	Not Different	Not Different
1.7 Molded	Different	Different	4th Not Different 5th Different	Not Different
2.2 Molded	Different	Different	Different	Not Different
2.2 Fabricated	Different	Different	4th Not Different 5th Different	Not Different

ARCEL® is a registered trademark of NOVA Chemicals Inc.

The same test was applied to the data collected for expanded polyethylene during Phase III of testing. No statistical difference was observed between the lines fit to the five individual drops performed on the ETHAFOAM™ Nova samples. Only the lines fit to drops four and five were different from the line fit to drop one on the ETHAFOAM™ 220. No other statistical differences were observed for the drops on the ETHAFOAM™ 220.

These results would support further investigation on whether it is appropriate to average the results for drops two through five as specified in ASTM D-1596. The more resilient materials may not exhibit much difference between drops two through five, so when that is the case then there should be no reason to perform five drops. Two drops, in some cases, may be sufficient.

In traditional cushion testing, five drops are performed on each sample. Using computers, it is simple to produce the equation for the curve of the dynamic stress-energy relationship for a material based on the data collected in cushion testing. There is no reason to average the results of the 2nd–5th impacts. Individual curves can be easily produced for the number of drops as may be appropriate for a given distribution situation.

Summary of Conclusions

The data for the higher density materials tested seemed to indicate that, while the stress-energy correlation was strong, energy is not the only predictor of dynamic stress, especially for the 3.0 lb/ft^3 material.

Three energy levels were sufficient to produce lines that were statistically the same as the line produced by the full set of data for the materials tested. However, careful consideration is needed when picking the extremes of the energy levels to be used.

The test of the three energy level model using EPE produced predicted G's 7-22 G's lower than the G's predicted using ETHACALC Millennium for the Ethafoam™ Nova, and 2-14 G's lower for the Ethafoam™ 220. These are within accepted lab to lab variations.

The homogeneity testing of the ARCEL® Resin data indicated that, for the lower density materials, performing five drops on a sample may not be necessary. However, for the 2.2 lb/ft^3 data, the five drops were statistically different when compared to each other.

RECOMMENDATIONS

The first step in setting up cushion testing based on the stress-energy relationship for a closed cell cushioning material should be to determine the lowest and the highest energy value that is practical for the material under evaluation. This would eliminate unnecessary testing. Once the two extremes are defined, a mid-point should be chosen as the third point in the reduced model proposed by this study. Further work may be needed to determine the best extremes to use.

There was no investigation on reducing the number of replicates per energy level, but it may be possible to reduce the sample size in this way. Further investigation may prove this as an alternate or incremental way to reduce the total sample size.

Further investigation is necessary to understand the limits of the stress-energy model for describing the cushioning ability of ARCEL® Resin at densities higher than 2.2 lb/ft^3. The model seemed to be sufficient to explain the behavior of the two lower densities of the materials tested, but the analysis of the data from the ARCEL® Resin 2.2 lb/ft^3 seemed to indicate that other factors need to be incorporated into the model to fully explain the behavior at this density.

Two materials were evaluated by this study, ARCEL® Resin and Ethafoam™. Only two densities of Ethafoam™ were tested. Further testing of Ethafoam™ and other closed cell materials, at higher densities, should be done to see if the stress-energy model would present the same limitation observed with ARCEL Resin® higher densities. Likwise, other closed-cell foams, such as EPP (expanded polypropylene), and EPS (expanded polystyrene) should be evaluated.

While linearizing the data using the natural logarithm worked well for this work, it may be of interest to fit the data using quadratic terms. This data-fit strategy may add ability to better describe systems such as the 3.0 lb/ft^3 ARCEL® Resin, where the logarithmic treatment did not yield good results. While the data fitting and statistical proving of such method would be more complicated, a more universally applicable system might be the result of further investigation.

Homogeneity testing of the data for other materials must be conducted to further evaluate the practice of averaging results for impacts 2 through 5. It may be possible to reduce laboratory time by reducing the number of drops conducted on each sample.

APPENDIX A

ARCEL® Resin Test Template

1.2 pcf Density—Molded Samples

Sample ID	Energy (in-lb/in^3)	Area (in^2)	Weight (lbs)	s (lb/in^2)	Drop Height (in)	t (in)
5A	5	38.4	**12.8**	0.333	**15**	1
5B	5	38.4	**19.2**	0.500	**20**	2
5C	5	38.4	**12.8**	0.333	**30**	2
5D	5	38.4	**32**	0.833	**18**	3
5E	5	38.4	**32**	0.833	**24**	4
10A	10	19.2	**12.8**	0.667	**15**	1
10B	10	19.2	**19.2**	1.000	**20**	2
10C	10	19.2	**12.8**	0.667	**30**	2
10D	10	19.2	**12.8**	0.667	**45**	3
10E	10	19.2	**32**	1.667	**24**	4
15A	15	12.8	**12.8**	1.000	**15**	1
15B	15	12.8	**19.2**	1.500	**20**	2
15C	15	12.8	**25.6**	2.000	**15**	2
15D	15	12.8	**32**	2.500	**18**	3
15E	15	19.2	**32**	1.667	**36**	4
20A	20	12.8	**12.8**	1.000	**20**	1
20B	20	19.2	**19.2**	1.000	**40**	2
20C	20	12.8	**25.6**	2.000	**20**	2
20D	20	12.8	**32**	2.500	**24**	3
20E	20	19.2	**32**	1.667	**48**	4
25A	25	12.8	**32**	2.500	**10**	1
25B	25	12.8	**32**	2.500	**20**	2
25C	25	12.8	**64**	5.000	**10**	2
25D	25	12.8	**64**	5.000	**15**	3
25E	25	19.2	**64**	3.333	**30**	4
30A	30	12.8	**12.8**	1.000	**30**	1
30B	30	12.8	**19.2**	1.500	**40**	2
30C	30	12.8	**25.6**	2.000	**30**	2
30D	30	12.8	**25.6**	2.000	**45**	3
30E	30	19.2	**64**	3.333	**36**	4
35A	35	12.8	**32**	2.500	**14**	1
35B	35	12.8	**32**	2.500	**28**	2
35C	35	12.8	**64**	5.000	**14**	2
35D	35	12.8	**64**	5.000	**21**	3
35E	35	19.2	**64**	3.333	**42**	4
40A	40	12.8	**32**	2.500	**16**	1
40B	40	12.8	**32**	2.500	**32**	2
40C	40	12.8	**64**	5.000	**16**	2
40D	40	12.8	**64**	5.000	**24**	3
40E	40	19.2	**64**	3.333	**48**	4
45A	45	12.8	**32**	2.500	**18**	1
45B	45	12.8	**32**	2.500	**36**	2
45C	45	12.8	**64**	5.000	**18**	2
45D	45	12.8	**96**	7.500	**18**	3
45E	45	19.2	**96**	5.000	**36**	0
50A	50	12.8	**32**	2.500	**20**	1
50B	50	12.8	**32**	2.500	**40**	2
50C	50	12.8	**64**	5.000	**20**	2
50D	50	12.8	**96**	7.500	**20**	3
50E	50	19.2	**96**	5.000	**40**	4

APPENDIX B

Expanded Polyethylene Test Template

Detail of sample dimensions for testing EPE using 3 energy levels.

Ethafoam Nova

Energy (in-lb/in^3)	Length (inches)	Width (inches)	Depth (inches)	Weight (lbs)
5	6.09	6.01	2.00	25.6
5	6.06	6.01	2.01	25.6
5	6.06	6.01	2.00	25.6
5	6.02	6.08	2.00	25.6
5	6.07	6.01	2.01	25.6
25	4.04	4.10	2.00	25.6
25	4.03	4.11	1.99	25.6
25	4.03	4.09	2.00	25.6
25	4.09	4.03	2.00	25.6
25	4.06	4.07	1.98	25.6
40	4.03	4.09	1.98	32
40	4.04	4.08	2.00	32
40	4.02	4.05	1.98	32
40	4.02	4.10	1.99	32
40	4.10	4.01	2.01	32

Ethafoam Nova

Energy (in-lb/in^3)	Length (inches)	Width (inches)	Depth (inches)	Weight (lbs)
10	6.10	6.01	1.99	32
10	6.01	6.08	2.00	32
10	6.10	6.00	2.00	32
10	6.04	6.05	2.00	32
10	6.02	6.06	1.98	32
25	4.10	4.05	1.94	25.6
25	4.10	4.04	1.99	25.6
25	4.11	4.05	1.99	25.6
25	4.13	4.05	1.99	25.6
25	4.11	4.03	2.00	25.6
50	4.06	4.10	1.99	44.8
50	4.11	4.04	1.99	44.8
50	4.08	4.03	2.00	44.8
50	4.09	4.06	1.99	44.8
50	4.11	4.04	1.99	44.8

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Hybrid Expert System/Analytic Hierarchy Process for Material Selection in Flexible Packaging Structures—Part 1

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ABSTRACT: An expert system has been developed to emulate product development experts in the task of materials selection in the flexible packaging industry. Databases are used for storage of deeper domain knowledge and rule bases are used to emulate the experts' thought process. Known cases from six sub-markets (dry beverages, liquid beverages, condiments, confection, dairy products in cups and snacks) were used for development of the system. This resulted in ten databases, 25 rule-bases and over 300 rules in the system. The laminated layers of the user-chosen structure are selected in a systematic order. Both the chemical nature and the quantity (in thickness or weight per area) are selected by the system.

The expert system was developed based on the rules used by a principal domain expert and tested against an expert panel of four other experts. According to these experts, it recommended valid structures for 97% of the development cases and 75% for 20 additional cases not used for development of the system The system offers higher frequency of valid responses for cases in or similar to its development domain than it does for cases dissimilar to the development cases.

INTRODUCTION

PRODUCT development of flexible packaging is often based more heavily on business issues than on matching application needs with structure/material properties. If a consumer goods company calls with a new application, it is often in the best interest of both the converter and the customer to use a product that is already made by the converter. This approach allows the converter to forego the cost of structure development and can allow his customer to enjoy cost and logistics benefits. In some cases, several materials in stock will be sent to the customer to be evaluated for the best combination of cost / benefit. This approach is not

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extremely systematic and can result in a package that works, but perhaps not optimally for the product/distribution cycle.

When the need arises to approach the problem in a more systematic manner, a competent product development scientist is quite capable of offering a “starting point” of structure and materials. The product development scientist typically uses a set of IF . . . THEN rules and “deep” knowledge of the packaged products, packaging machines and distribution cycle.

Research of this process of material selection was conducted at the Alcan Packaging plant in Shelbyville, Kentucky in conjunction with the University of Louisville. The outcome of this research was a hybrid expert system that emulates the thought process used by product development experts employed by flexible packaging converters. The expert system is also supplemented by a decision-making system where multiple structures can be compared.

PREVIOUS EXPERT SYSTEMS IN PACKAGING

There has been some previous research conducted into expert systems, as well as other artificial intelligence tools, in packaging applications. Twede et al. presented work about a broad scoped system to specify packaging [1]. They described the entire package design process as a “series of expert tasks.” The work consisted of six modules: performance requirements, packaging solutions, test specifications, test results analysis, vendor specification and procurement. Development work was done on the first three modules and a demo was prepared for all six modules using an ammunition package as a test case.

Pelli and Grosz created an expert system application that optimized (minimized) the cost incurred in making a folding box [2]. The database files utilized included the company’s business data (machinery costs, capacity, productivity, etc.) and the specific order data (folding box type, dimensions, printing information, etc.). The expert system then recommended the optimum solution, as well as the second and third options. Optimization could be selected; for example, production cost, operating cost or total cost could be chosen. This system focused only on the conversion cost of folding boxes. The package / product interaction was not considered.

Jansen and Gruender created a system called “Pack-Design” [3]. This system was purported to assist in "all processes in package planning". This system used CAD and expert systems to design folding cartons, optimize folding carton cut plans, stack pallets, etc. in the packaging of pharmaceutical goods.

At a leading flexible packaging manufacturer in the United States, an expert system was created in the early 1990's to recommend flexible packaging products from a set list of predetermined products offered by that company [4].

Shimada and Yamasaki combined software for compressive strength analysis, a distribution barcode expert system and database systems to create a "strategic information system" [5]. This system was designed to support the users in selection of type, grade, etc. of appropriate grade of corrugated, as well as the pallet-loading pattern.

Eschke reported on an effort to build a foundational "information system" [6]. This was not an expert system, but instead a series of databases with the raw information that an expert system might need. The longer-term intent was to develop an expert system that would not over-package a product (resulting in excess cost) or to under-package a product (resulting in product damage). The databases included general regulations, specific packaging data, specific goods data and goods/packaging testing methods.

Orosz utilized an artificial neural network to analyze various analytical techniques, MIR, TSC, DSC, UV-Vis and GCMS to determine the ability of the various techniques to distinguish between various packaging films [7]. This work was done to determine the possibility of using artificial intelligence to determine the interchangeability (equivalency) of polymers in drug packaging.

Several packaging industry expert systems attempt to address cube utilization, which is how to maximize the number of package units of varying sizes that can be packed in a given space. Hall et al. discussed the use of robots with expert systems [8]. Later, Hall et al. again discussed intelligent packaging and material handling [9]. Johnsson et al. described an expert system for stacking cartons on a skid [10]. Marvel created an expert system for storing cases in a warehouse [11].

Expert systems have also been used to optimize planning and operation of packaging lines. Wallin described the state of robotics in the food industry [12]. For instance, neural networks and fuzzy logic systems coupled to robotics are cited as possible solutions to problems like picking and placing irregularly shaped objects into packaging. Thomas and

Shobrys reported on an expert system for planning the blending and packaging of lubricants [13]. Goldhahn described an expert system that was developed to optimize packaging machines, specifically a bottling line [14]. Heiner cited an expert system that supported production planning of the packaging lines in a chocolate factory [15]. Clark and Warwick utilized multilayer perceptrons and an expert system to monitor packaging lines in order to predict failure of machine components and minimize unscheduled downtime [16].

Expert systems have also been applied to fields that are closely related to packaging, such as printing. Blessing reported on an expert system that printing companies could use via a modem to get help with printing issues [17]. Ueda presented an expert system for trouble-shooting quality problems at a package printing operation [18]. Rothbarth utilized expert systems for reducing the number of solvents used for printing [19]. Almutawa and Alhaji presented an overview for introducing expert systems to printers [20].

SYSTEM DEVELOPMENT

Expert system development usually entails the steps of knowledge acquisition, selection of chaining strategy, programming tool selection, coding and testing [21].

During knowledge acquisition, the system developer attempts to document how the domain expert approaches the problem, as well as recording the rules that the experts use [21]. In this case, multiple domain experts were consulted and the resultant process used for the expert system was an amalgamation of the best practices of the domain experts.

The general strategy represented by the system was to select a packaged product, the amount packaged (fill weight) and generic structure. An example of a generic structure is “Film/Adhesive/Film”. The intended user of the system is someone who has at least some knowledge of flexible packaging. Many people in the industry who are not domain experts are quite aware of plant capabilities at this level of abstraction. Multiple generic structures can also be selected and compared using the system.

The experience of the domain experts fell into the marketing areas listed in Table 1. While a long way from being exhaustive, these markets represent hundreds of millions of dollars in sales of flexible packaging.

During the knowledge acquisition phase, two forms of knowledge

Table 1. *Domain of the System.*

Category	Example of a Flexible Package
Condiment	Fast food ketchup pouch
Confection	Candy bar wrapper
Dairy products	Cream cheese cup lidding
Dry beverage	Coffee brick pack
Liquid beverage	Stand up pouch children's beverage
Snack food	Chip pouch

were identified. In some cases, the experts used a mental "table" of information. This is what expert system developers often call "deep knowledge" [22]. For instance, if the packaged product were "ketchup," the domain expert immediately recognizes that the packaged product is a reasonably viscous blend of liquid with solid particles that is somewhat acidic. This type of knowledge is difficult to code into expert system rules but lends itself well to representation using computer databases. Databases were also used to house and store data that the system uses and generates.

The other type of knowledge identified was the procedural processing of "rules-of-thumb". In this case, the product developer executes mental "if . . . then" statements. A simplified example rule might be: "If the product is a liquid and the fill weight is less than 1/2 ounce, then the sealant thickness should be 1.0 mil." These "rules-of-thumb", utilized in many types of diagnostic and configuration problem solving, are the type of knowledge that expert systems were originally developed to emulate [22].

Selection of the chaining strategy is an important step in expert system development. Typically open-ended configuration expert systems lend themselves to forward chaining and more closed-ended diagnostic systems lend themselves to backward chaining [22], Depending on perspective, the material selection of flexible packaging materials can be viewed as configuration or diagnostic. However, the act of selecting what material to use for any given layer is typically a diagnostic problem, so backward chaining was selected. This was tested on a prototype for sealant material selection and was found to work well.

After study of the process of material selection and selection of a chaining algorithm, an expert system development tool was selected. The problem at hand required a system that allowed for knowledge to be accessed from both databases and rule-bases, and also allowed for control of the user interface. Many commercial systems were reviewed and the expert system tool adopted was Knowledge Pro for Windows®.

Once the general strategy of addressing the problem and the system tool were selected, the "coding" of the knowledge was begun. For this phase of the project, the knowledge of one domain expert, dubbed the "key expert" was used. This was done to prevent any confusion of multiple experts who might make different choices from affecting the expert system, which is a common problem in expert system development [21].

The programming and testing of expert systems is an iterative process [23]. With every rule change made to improve the outcome of one case, the other test cases may need to be re-evaluated to assure that the rule change did not inadvertently affect the outcome of other cases. To make this manageable, the scope of the project was narrowed to cover 100 test cases in the markets listed in Table 1. These 100 test cases were selected to assure a diverse set of flexible packaging problems within the domain of flexible packaging laminations, as shown in Table 2. The test base required the system to make recommendations for 367 layers and to recommend a thickness for each layer. An additional 20 problems were selected that fell out of this scope in order to test the system's ability to "go beyond" the design base. Coextrusions, mono-layer materials and non-sealing flexible packaging structures were not a part of the project scope. Table 3 shows an excerpt of the test cases.

The expert system is designed to select layers from the inside (product contact) and to work toward the outside. Some experts in the expert panel followed this approach and others did not. This approach was utilized because very thick sealants can affect the material selected for the outer layer of a package. Layer "chemistry" was selected first for each layer and then layer thickness for each layer was selected. No trade names were used in the system.

Table 2. *Test Base Diversity.*

Category	Example
Inherent product differences	Watery liquids, viscous liquids, blends, chips, granules, powders, etc.
Same product, different fill weight	1.5 ounce and 2 ounce salad dressing
Similar, but different product	Unflavored tortilla chips vs. flavored tortilla chips
Same product, same weight, different package	Yogurt in PS vs. PP cups
Generic structure	Salad dressing in foil or non-foil pouches

Table 3. *Excerpt of Test Applications Table.*

Problem	Group	Generic Product	Package Type	Opening	Cup	Structure	Fill Weight, ounces	Length, inches	Opened Width, inches	Repeat Tolerance	Print Quality
1	Condiment	Honey mustard	Roll fed lidding	Peelable lid	PVC	Fi/Adh/Fi/HSC	1.00	2-1/4	1-11/16	1/64	Low Res
3	Condiment	Honey mustard	Roll fed lidding	Peelable lid	PVC	Fo/Ext/Fi/HSC	1.00	2-1/4	1-11/16	1/64	Low Res
4	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Adh/Fi	0.50	2-13/16	3	1/32	Med. Res
5	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Adh/Fo/Ext	0.50	2-13/16	3	1/32	Med. Res
6	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Adh/Fo/Ext/Fi	0.50	2-13/16	3	1/32	Med. Res
7	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Ext/Fi	0.50	2-13/16	3	1/32	Med. Res
8	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Ext/Fo/Adh/Fi	0.50	2-13/16	3	1/32	Med. Res
9	Condiment	Ketchup	4 Seal flat pouch	Tear	n/a	Fi/Ext/Fo/Ext	0.50	2-13/16	3	1/32	Med. Res
24	Confection	Chocolate bar	Sealable tube wrapper	Peel	n/a	Fi/Adh/Fi/CS	0.50	3	5	1/32	Med. Res
25	Confection	Chocolate bar	Sealable tube wrapper	Peel	n/a	Fi/Adh/Fi/CS	1.00	5-3/4	4-3/8	1/32	Med. Res
45	Dairy	Cream cheese	4 Seal flat pouch	Tear	n/a	Fi/Ext/Fo/Adh/Fi	1.00	5-1/2	4	1/32	Low Res
46	Dairy	Cream cheese	Die cut lidding	Peelable lid	PP	Fi/Adh/Fo/Ext	8.00	4-3/4	4-1/16	1/64	Low Res
47	Dairy	Cream cheese	Roll fed lidding	Peelable lid	PP	Fi/Adh/Fo/Ext	8.00	4-3/4	4-1/16	1/64	Low Res
51	Dairy	Yogurt 6 pack	Roll fed lidding	Peelable lid	PS	Fi/Adh/Fo/HSC	4.00	7-5/16	4-7/8	1/64	High Res
52	Dairy	Yogurt 6 pack	Roll fed lidding	Peelable lid	PS	Pa/Adh/Fi/Pri/HSC	4.00	7-5/16	4-7/8	1/64	High Res
55	Dry beverage	Coffee ground	3 Seal flat pouch	Tear	n/a	Fi/Adh/Fi	1.50	5	11	1/32	Med. Res
60	Dry beverage	Coffee in tea bag	4 Seal flat pouch	Pull open	n/a	Fi/Ext/Fo/Ext	0.15	3-1/4	8-1/4	1/32	High Res
61	Dry beverage	Fruit drink mix	3 Seal flat pouch	Tear	n/a	Pa/Ext/Fo/Ext	0.25	3-1/4	9	1/32	High Res
66	Dry beverage	Tea bag	3 Seal flat pouch	Tear	n/a	Pa/Ext/Fo/Ext	0.15	2-14/25	6	1/32	Low Res
70	Liquid beverage	Fruit drink	Die cut lidding	Peelable lid	PS	Fo/HSC	10.00	4-1/8	3-1/2	1/64	High Res
71	Liquid beverage	Fruit drink	Stand up pouch	Straw	n/a	Fi/Adh/Fo/Adh/Fi	6.00	3-15/16	13.8976	1/64	High Res
75	Liquid beverage	Orange juice	Die cut lidding	Peelable lid	PS	Fo/HSC	10.00	4-1/8	3-1/2	1/64	High Res
79	Snack	Corn chips	3 Seal tube fin pouch	Peel	n/a	Fi/Ext/Fi	4.50	10	13	1/32	Med. Res
84	Snack	Corn chips flavored	3 Seal tube fin pouch	Peel	n/a	Fi/Ext/Fi	10.00	14-1/2	20	1/32	Low Res
85	Snack	Potato chips	3 Seal tube fin pouch	Peel	n/a	Fi/Ext/Fi	2.13	10	13	1/32	Med. Res
89	Snack	Potato chips flavored	3 Seal tube fin pouch	Peel	n/a	Fi/Ext/Fi	5.50	14	16-3/4	1/32	Med. Res
90	Snack	Potato chips kettle	3 Seal tube fin pouch	Peel	n/a	Fi/Ext/Fi	12.00	14-1/2	20	1/32	High Res

EVALUATION OF THE SYSTEM

The system as written consists of 10 databases, 25 rule bases and over 300 rules. Testing of such a system can be conducted in a number of ways. First of all, a significant amount of testing occurs during the programming stage of expert systems. As stated above, the addition or modification of a rule to improve the system behavior on one case may cause the system to change its selection on another case. As a result, much testing is done during the programming stage.

After the programming stage, testing of expert systems is an important step. A fundamental concept for testing of "intelligent" computer applications is the "Turing test", where a human and computer, which are isolated from each other respond to an interrogator, who compares the responses [24]. However, there are many cases in which more than one answer may be correct. For this kind of case, consideration of the validity of the answer is often used [21]. Both of these types of evaluation were used for the expert system developed.

This system was evaluated in the following ways:

1. Agreement on the 100 test cases with an expert panel of 4 domain experts (other than the key expert).
2. Validity of the system's recommendations for the 100 test cases according to the expert panel.
3. Validity according to the expert panel on 20 additional test cases outside of the 10 case the scope (some within the same domain, others in completely different domains).

RESULTS

First, the system's agreement with expert panel members was tested. This was done with the 100 cases described above. If an expert panel member was not experienced in a given area, the panel member was instructed not to provide an answer. No member of the expert panel felt fully qualified for all of the cases. Experts 1 and 2 answered a variety of questions, while experts 3 and 4 limited their answers to snack food packages. There were four methods used to assess agreement:

1. How often does the system exactly match the experts? (100 opportunities)

2. For each layer in each structure, how often do the system and the expert disagree on the chemistry (e.g. LDPE vs. LLDPE is a disagreement) (367 opportunities)
3. For each layer in each structure, how often do the system and the expert disagree on the material thickness? (367 opportunities)
4. What was the total agreement of all layers and thicknesses? (734 possibilities).

Table 4 is an excerpt of the table showing answers provided by the expert system and the experts. Areas where the experts disagreed with the system are highlighted. The measures of agreement, shown in Table 5, ranged between 5 and 98 % depending on the expert and on the measure. Exact structure matches, which is the most conservative measure, is of course significantly lower than the others. As can be seen, material selected and thickness both contribute to the lack of agreement with the exception of expert 4, who matched the system in 98% of the cases for materials and only 5 % of the thicknesses. During further investigation, it was learned that there was a bias in the answers provided by Expert 4 toward thinner materials.

The data in Table 5 are essentially a measure of the agreement between the key expert and other experts, since the expert system exactly matches the key expert on this test set. Of course, this led to the evaluation of expert-to-expert agreement, presented in Table 6. Expert-to expert agreement was generally low. In fact, the experts on the expert panel agreed with the system recommendations more often than they agreed with each other. While these levels of agreement are disappointing, they are not unique. Similar levels of agreement between expert systems and experts, as well as between experts, have been reported in fields where there can be more than one valid answer [25,26].

Although exact agreement with experts on the test base was low, the system could still be giving valid answers. To investigate this, each member of the expert panel was asked to answer the following questions on the material selections made by the system for all 100 cases.

1. Where there is a lack of agreement, did the system make a valid recommendation?
2. After seeing the system's recommendation, did the expert feel that the system made an equally valid or better recommendation?

Table 4. *Materials Specified by System Expert Panel.*

Expert	Problem	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
2	1	48 ga PET	1.5# MPU	48 ga PET	4# EVA Based HSC	
system		48 ga PET	1.5# MPU	48 ga PET	4# EVA Based HSC	
2	2	28.5 ga 1235 Foil	1.5# MPU	48 ga PET	4# EVA Based HSC	
system		28.5 ga 1235 Foil	1.5# MPU	48 ga PET	4# EVA Based HSC	
2	3	28.5 ga 1235 Foil	7# EAA-LDPE coex	48 ga PET	4# EVA Based HSC	
system		28.5 ga 1235 Foil	7# EAA-LDPE coex	48 ga PET	4# EVA Based HSC	
1	4	**48 ga MPET**	1.5# MPU	**150 ga LDPE**		
2	4	**70 ga Opp Print Grade**	1.5# MPU	**200 ga LLDPE**		
system		75 ga metOPP	1.5# MPU	200 ga LLDPE		
1	5	**48 ga PET**	1.5# MPU	28.5 ga 1235 Foil	14# EAA-LDPE coex	
2	5	**60 ga Opp Print Grade**	1.5# MPU	28.5 ga 1235 Foil	14# EAA-LDPE coex	
system		75 ga Print Grade BOPP	1.5# MPU	28.5 ga 1235 Foil	14# EAA-LDPE coex	
1	6	**48 ga PET**	1.5# MPU	28.5 ga 1235 Foil	7# EAA-LDPE coex	**50 ga LLDPE**
2	6	**60 ga Opp Print Grade**	1.5# MPU	28.5 ga 1235 Foil	7# EAA-LDPE coex	**150 ga LLDPE**
system		75 ga Print Grade BOPP	1.5# MPU	28.5 ga 1235 Foil	7# EAA-LDPE coex	100 ga LLDPE
1	7	**48 ga MPET**	7# EAA-LDPE coex	**100 ga LDPE**		
2	7	**70 ga OPP Print Grade**	7# LDPE	**200 ga LLDPE**		
system		75 ga metOPP	7# LDPE	150 ga LLDPE		
1	8	**48 ga PET**	7# EAA-LDPE coex	28.5 ga 1235 Foil	1.5# MPU	**50 ga LLDPE**
2	8	**60 ga Opp Pring Grade**	7# LDPE	28.5 ga 1235 Foil	1.5# MPU	**200 ga LLDPE**
system		75 ga Print Grade BOPP	7# EAA-LDPE coex	28.5 ga 1235 Foil	1.5# MPU	100 ga LLDPE
1	9	**48 ga PET**	7# EAA-LDPE coex	28.5 ga 1235 Foil	14# EAA-LDPE coex	
2	9	**60 ga Opp Print Grade**	7# LDPE	28.5 ga 1235 Foil	14# EAA-LDPE coex	
system		75 ga Print Grade BOPP	7# EAA-LDPE coex	28.5 ga 1235 Foil	14# EAA-LDPE coex	
1	10	**48 ga PET**	1.5# MPU	150 ga LDPE		
2	10	**70 ga Opp Print Grade**	1.5# MPU	**200 ga LLDPE**		
system		75 ga Print Grade BOPP	1.5# MPU	150 ga LDPE		
1	11	**48 ga MPET**	1.5# MPU	150 ga LDPE		
2	11	**70 ga MetOpp**	1.5# MPU	**200 ga LLDPE**		
system		75 ga met OPP	1.5# MPU	150 ga LDPE		

Table 5. *Summary Comparison of Expert Panel vs. Expert System.*

	Expert			
	1	**2**	**3**	**4**
# Structures specified	53	63	21	21
# Layers specified	188	246	63	63
# Thickness specified	188	246	63	63
Total selections	376	492	126	126
Structure differences	37	38	8	20
Percentage agreement structure (%)	**30**	**40**	**62**	**5**
Thickness differences	54	61	10	39
Percentage agreement thickness (%)	**71**	**75**	**84**	**38**
Material differences	41	33	10	1
Percentage agreement materials(%)	**78**	**87**	**84**	**98**
Total materials and thickness differences	95	94	20	40
Percentage agreement materials (%)	**75**	**81**	**84**	**68**

These data are presented in Table 7. As can be seen, the expert panel members felt that the system recommended valid structures in at least 94% of the cases. The experts felt that the system made equally good or better recommendations in at least 86% of the cases. The discussions that ensued during this part of the evaluation revealed that each member of the expert panel had some sort of bias that affected his answers. The key expert was also found to have bias that was programmed into the expert system. The result of this discovery was that one rule containing bias was modified, thus increasing the system's validity rating with Expert 1 up to 97%.

Table 6. *Summary Comparison of Agreement between Experts.*

	Expert 1 vs. Expert 2	**Expert 3 vs. Expert 4**
# Structures specified	36	21
# Layers specified	142	63
# Thickness specified	142	63
Total selections	284	126
Structure differences	30	19
Percentage agreement structure (%)	**16.7**	**9.5**
Thickness differences	48	40
Percentage agreement thickness (%)	**66.2**	**36.5**
Material differences	52	4
Percentage agreement materials(%)	**63.4**	**93.7**
Total materials and thickness differences	100	44
Percentage agreement materials (%)	**65**	**65**

Table 7. *Validity of Expert System Recommendations.*

	Expert			
	1	**2**	**3**	**4**
# Structures specified	53	63	21	21
# Layers specified	188	246	63	63
# Thickness specified	188	246	63	63
Structure differences	37	38	8	20
If different, system recommendation is valid	34	38	8	20
System recommendation technically equivalent	21	23	6	12
System recommendation technically superior	9	9	2	6
Expert recommendation technically superior	7	6	0	1
Total valid recommendations for system, %	**94.3**	**100.0**	**100.0**	**100.0**
System recommendations equal or better than expert, %	**86.8**	**90.5**	**100.0**	**90.5**

The expert system was also tested by comparing its performance on 20 cases that were in various ways outside of the scope of the original 100 test cases. Some of these cases were within the market areas outlined in Table 1 and others were not. There were also combinations of packaged product type, weight and package type that are not available on the market (these were classified as "imaginary" applications. Prior to running this test base, the expert panel projected the "expected success" of the system to select materials for the application as good, fair or poor, given the test base used to program the system.

After the system was used to make selections for these 20 cases, the expert panel was asked to evaluate the following questions:

1. Is the recommended structure a valid one?
2. Is it the optimum structure?
3. Did the system perform in a satisfactory manner?

The results of system performance on this "unknown test base" are presented in Table 8. As can be seen in the table, the expert panel felt that the system generates valid structures 88% of the time, optimum structures 72% of the time and performed satisfactorily 75% of the time. As expected, the system has more difficulty with applications that are significantly different (Expected Success Poor) from the original 100 case test base. The system recommended structures that the experts considered valid for 8 of the 9 "imaginary" applications. There were two cases where the system was unable to make any recommendation.

Table 8. *Analysis of System Performance on Unknowns.*

Problem	Expected Success	Structure Valid?	Structure Optimum?	System Performance OK?	Imaginary Applications
1	G	Y	Y	Y	
2	G	Y	Y	Y	Y
3	G	Y	Y	Y	
4	G	N	N	N	
5	G	Y	Y	Y	
6	G	Y	N	N	
7	G	Y	Y	Y	Y
8	G	Y	Y	Y	Y
9	G	Y	Y	Y	Y
10	G	Y	Y	Y	Y
11	F	Y	Y	Y	
12	F	Y	Y	Y	Y
13	F	Y	Y	Y	Y
14	F	Y	Y	Y	Y
15	P	Y	Y	Y	
16	P	N/A	N/A	N	
17	P	N/A	N/A	Y	Y
18	P	Y	N	Y	
19	P	N	N	N	
20	P	Y	N	N	
	Yes	**16**	**13**	**15**	**9**
	No	**2**	**5**	**5**	**0**
	Yes Percentage	**88.9**	**72.2**	**75.0**	**100.0**
	No Percentage	**11.1**	**27.8**	**25.0**	**0.0**

CONCLUSIONS

An expert system was constructed to select materials for flexible packaging structures. It was evaluated against a panel of expert product developers in the flexible packaging industry. Based on the experts' assessment of the system's performance, the system is able to recommend valid materials and thicknesses in over 90% of the cases for existing or new applications within the market areas in Table 1. The system could recommend as well or better than the experts in over 85% of the cases. The system also appears to typically recommend valid structures for cases that were within the market areas in Table 1, but beyond the original scope of design. However, for cases outside of the market areas in Table 1, the system should not be used for material selection.

As stated earlier, multiple generic structures can be selected using the system. This feature can be selected by changing the system mode. In the multiple structure mode, the structures can be compared using decision theory, specifically the analytic hierarchy process. That part of the research will be discussed in a separate paper.

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Effect of Unitization and Product Types on Readability of Tagged Packages of Consumer Goods

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ABSTRACT: Proper implementation of radio frequency identification (RFID) has the potential to revolutionize supply chain management. This technology provides simultaneous indirect scanning of multiple packages and palletized loads equipped with a RFID tag, transmitting substantially more information than a bar code. Also, stored information on the tag can be updated according to inventory status, thus, eliminating key limitations of barcode technology. This study was designed to address some of the currently known shortcomings of the RFID technology. One of the commonly occurring drawbacks is transmitted signal from RFID antennae is reflected from metal objects or absorbed by water contained in a product. These limitation of effective reads can be easily shown using EPC Hotspot, which is capable of creating a profile map for product cases based on the correct reads of RFID tags. This study included three types of packaged products that were palletized. These were filled beverage in metal cans, filled water in plastic bottles and plastic wrapped paper towels. The objective of the study was to assess overall tag readability of three newly developed Gen 2 RFID tags as a function of tag location and orientation, product composition, case location on a pallet load and speed of material handling equipment. The results indicated that overall readability was highest for 'paper towels' followed by 'water filled bottles' and 'soda filled cans' across all RFID tags. Also, it was established that normal forklift speeds barely affect overall tag readability with the exception of very poor tag "visibility" for filled beverage in metal cans. In summary a better understanding of tag placement on products at the case level was achieved at the completion of this study along with effective speeds of material handling equipment that allow for high read rates.

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1.0 INTRODUCTION

NUMEROUS studies have shown varying conclusions with regards to RFID readability. The following is a summary of findings from previous research involving industry testing. It has been assumed that a warehouse shipping mixed loads of RFID-tagged shipping containers, could automatically verify the order accuracy and update inventory status by driving each pallet load through a portal equipped with readers. This was made possible by connecting readers to the transaction and warehouse information systems. All the packages simultaneously transmitted embedded information on the tags to the host computer. Similarly, these tags could be re-programmed with new information to reflect the inventory status change. Such systems can increase transparency in manufacturing and retail supply chain system. RFID tags on each consumer package could offer other potential benefits. For instance, reductions in grocery check-out lanes to a doorway. In the presence of such RFID technology it is not far when a refrigerator can identify products within its storage area or provides instructions to a microwave to cook a meal. Similarly, a patient can be reminded to take his prescription medication at a specified time. There are many possible applications for this seemingly magical new packaging technology in the future. However, the potential of RFID can be truly exploited if RFID tags are consistently and reliably read. Unfortunately past research is indicating that the reliability of such technologies and tag read rates is dramatically less than what the leading proponents claim.

One of the key research studies published in 2006 by Clarke et-al [1], showed major limitations with read capability of RFID tags. Among the key findings the study concluded that only 25% of the tags on shipping containers containing water-filled bottles could be read. Rice filled jars (dry products) had a 74–79% read rate. Furthermore, even empty boxes did not provide a 100% read rate. However this study was done when both the type of tags used (Gen 1) and portal designs were still in infancy. In the past year tag design and portals have been improved and the industry has shifted to a Gen 2 tag.

Additional research and testing has been presented on readability of tagged packages of apparel, produce and consumer goods by Singh et-al [2] and on packages of water bottles by Brofman and Agular [3]. In the water bottle study only 25% of the tagged packages could be effectively read. Singh et-al presented various factors that influence readability and provided effective tag location that could permit better read rates. These studies showed the initial limitations of Gen 1 tags on readability through products containing water and packages having a metal component in the read field.

Currently one of the debatable concerns in the RFID industry is the relative orientation of a tag's antenna and those of the interrogator. Most manufacturers say that tag orientation has little effect on read range and tag readability. As the white paper produced by one supplier, Intermec [4] explains:

> "Because no line of sight is required, RFID-tagged objects can be read in different orientations at very high speeds. Orientation sensitivity depends on the antenna design and the amount of interference that is present. In some environments tags may be read in any orientation. This gives product and package designers' tremendous flexibility in tag placement options, and eliminates the need for human intervention to scan labels or to ensure items are placed properly for reading in conveyor belt or retail applications."

One of the few published studies is by a manufacturer/supplier of RFID equipment, Alien Technologies, who evaluated readability for a variety of possible conditions, including location of tagged cases, antenna type and position, tag orientation, proximity of the tag to the reader, relative orientation of the antennae, number of tags in field, movement speed through portal, product variables and interference [1]. The results were optimistic, with a high percentage of tags read in spite of of the variables. The study concluded that the tag and case orientations had very modest effect on readability. Liquid and metal products had some effect when tags faced away from the antenna but 'could be worked around' [1]. The Alien Technology research and Intermec claims, however, may be biased since the number of tests for each variable was not completely disclosed, and so their significance is uncertain. The testing was done on Alien Technology's products using hardware that was a prototype. The test was set up to give constructive results, with no tags embedded at the centre of problematic materials. Intermec's implication, that there are also some environments where orientation does matter, has not been developed. At least one research centre has found problems with tags in some orientations. A study performed by Clarke et al. showed that the read rates are indeed affected by tag orientation [1].

This paper is a continuation of a recently concluded research which evaluated the variables affecting RFID tag readability in a conveyer belt environment [5]. The research presented in this paper accounts for effects of tag orientation, product and package type as well as using new Gen 2 RFID tags and readers.

2.0 MATERIALS AND METHOD

2.1 Test Materials and Description

2.1.1 Pallets

A total of three palletized loads using Grocery Manufacturers' Association recommended wood pallets measuring 1.02 m × 1.22 m (40″ × 48″) were used for this study.

2.1.2 Product

Cases of products used and their pallet configurations for the study were:

- Carbonated beverage in metal cans—144 cases per pallet, 18 per tier (Figure 1)
- Drinking water in plastic bottles—35 cases per pallet, 7 per tier (Figure 1)
- Plastic wrapped paper towels—24 cases per pallet, 6 per tier (Figure 1)

In order to cover the variables of the packaging and product type that in the past have been an issue for effective readability of RFID tags, the palletized configuration of packaged products were selected and are shown in Figure 2.

Paper Towel **Bottled Water** **Carbonated Beverage**

Figure 1. *Cases of Product used in the Study.*

Paper Towel **Bottled Water** **Carbonated Beverage**

Figure 2. *Pallet Patterns used in the Study.*

2.1.3 RFID Hardware

Alien Technology Corporation's (Morgan Hill, CA, USA) ALR 9780 RFID reader and ALR-9610 circular polarized antennae were used for this study. The ALR-9780 provides both EPC Class 1 Gen 1 and Gen 2 support and was connected to a computer using RS-232 computer interconnection. It provides up to four ultrahigh frequency (UHF) antennae. Alien Gateway V2.15.08 middleware was used to collect all data. Four ALR-9610 circular polarized antennae were used, since they were less sensitive to the tag orientation and sufficed the read distance requirements for this project.

2.1.4 RFID Tags

Three types of Class 1—Gen 2 tags used (Figure 3):

- Raflatac G2 Short Dipole (UPM Raflatac, Fletcher, NC, USA)
- Avery AD-222 (Avery Dennison RFID, Clinton, SC, USA)
- Alien "Higgs" (Alien Technology Corporation, Morgan Hill, CA, USA)

They all measured approximately 10.16 cm × 1.27 cm (4 in × 1/2 in)

Tag #1 - Raflatac G2 Short Dipole Inlay **Tag #2 - Avery AD-222 Inlay**

Tag #3 - Alien "Higgs" Inlay

Figure 3. *RFID Tags used for Study.*

and were mounted with the horizontal tag orientations after experimentation was conducted using the EPC Hotspot Software.

2.1.5 Portal and Fork Lift Truck

A counterbalanced fork truck was used to carry and transfer the above palletized loads of product through a portal at three different speeds to simulate various driving conditions. These were 2.4 kph (1.5 mph), 8.1 kph (5.0 mph), and 16.1 kph (10.0 mph). A standard portal was used as described and shown with in Figure 4.

2.1.6 Instant EPC Hotspot v2.5 software

Instant EPC Hotspot software (Integral RFID, Richland, WA, USA) contains several tools to map out the RF-performance around a case of packaged-product [6]. The software was used for this research to conduct an in-depth analysis at every 2.54 cm (1 in) of the three product-package combinations. Easy to comprehend visual results were created to instantly identify the best location for tag placement and tag orientation on cases of each of the three products studied.

This, the first stage of testing, was done using one Alien ALR-9780 circular polarized antenna mounted on a stand, 91.44 cm (36 in) from the center of the antenna to the floor. Each of the products tested was placed on top of a 76.2 cm (30 in) high plastic stand located at 90 degrees and

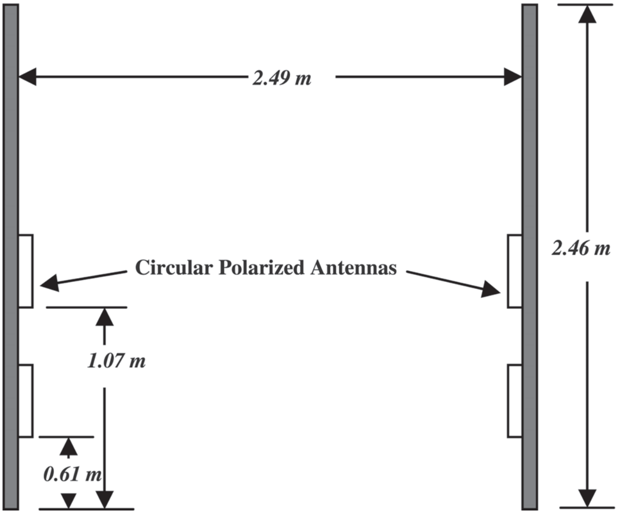


Figure 4. *Portal Setup.*

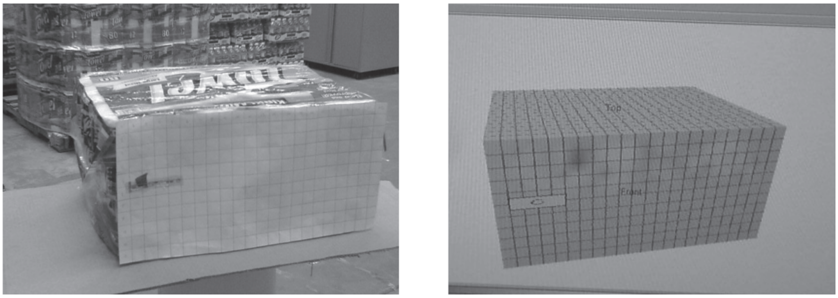
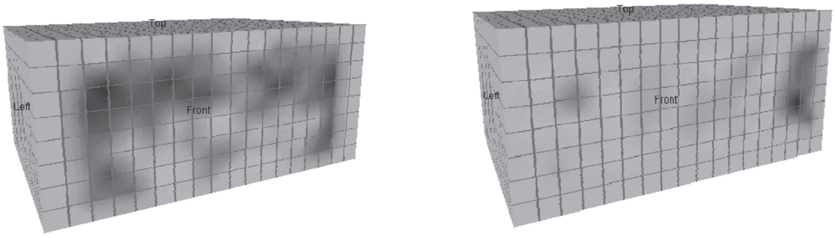


Figure 5. *Test Setup for Optimum Tag Location Testing in the Horizontal Orientation.*

91.44 cm away from the antenna. With each product tested, the face of the case and the front of the antenna were kept 91.44 cm apart. For each product, two sides of the case were selected to determine an optimal tag location, the front face and back face with respect to the antenna [7].

Each face to be tested was equipped with a 2.54 cm × 2.54 cm (1 in × 1 in) grid drawn on a piece of paper that was taped to the face of the case to be tested. The center of the tag was placed at the intersection of each horizontal and vertical line. The tag was moved from intersection to intersection for each read. Once the case and antenna were set up, the dimensions of the case were entered in the software's Case Setup page [6]. The Hotspot test option, which brings up a 3-dimensional version of the product, was selected. The software creates a 2.54 cm × 2.54 cm grid on each face of the case. The face representing the face of the case to be tested and the closest size tag were selected from the on screen options. On the 3-dimensional on-screen image, an intersection was selected that allowed the tag to fit completely on the case without overhang, and the actual tag was placed in the same location on the product to be tested (Figure 5).

The tag was placed on the front of the package, the antenna activated, and results were recorded at each grid intersection. When each intersection had been tested, a still image of the face tested was saved, and the tag was moved to the back of the package, and the test was repeated. Again, once all intersections had been tested on the back side of the package, a still image of the face tested was saved. Once both sides had been completed with the tag in the vertical orientation, the tag was repositioned horizontally on the case, and both the front and back side of the case were tested again. This testing procedure was done for all four tags on all three packages.

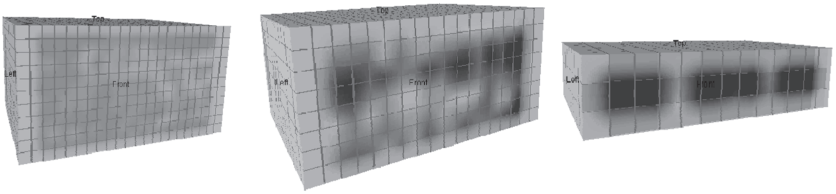


Horizontal **Vertical**

Figure 6. *RF Performance Comparison of Alien "Higgs" Tags Placed on Bottled Water Cases.*

Figure 6 shows a comparison of the RF performance of the Alien "Higgs" tag placed on bottled water cases in horizontal and vertical orientations. Figure 7 shows a comparison of the RF performance map for the same tag used horizontally on the three cases of products used for the study.

Using the RF performance maps for the three product cases and the three tags used, an optimal tag location and orientation was selected for all combinations. For the case with beverage metal cans, the ideal tag location was on the widest side, centered 2 inches from the bottom of the case. The bottled water and wrapped paper towel cases benefited from tag placement on the narrow end centered 4 inches from the bottom of the case. The main reason for these placements was due to case configuration and positioning on the pallet. In an attempt to promote tags towards the outer edges of the pallet, exterior sides were chosen to increase readability. Once tag location and case location were chosen, HotSpot was configured to "know" where each case is on a pallet. This was done by programming each tag with a number, and corresponding that with a specific location on the pallet for each case. As the palletized loads



Paper Towels **Water Bottles** **Carbonated Beverage**

Figure 7. *RF Performance Comparison of Alien "Higgs" Tags Placed Horizontally for Products.*

Table 1. *Results for Carbonated Beverage in Metal Cans.*

Tag	Fork Lift Speed (kph)	Number of Tags Read per Trial (Total = 144) 1	2	3	4	5	Average	Readability
Raflatac G2 Short Dipole	2.41	68	68	68	67	68	68	47.22%
	8.05	66	64	64	65	66	65	45.14%
	16.09	54	54	54	55	56	55	38.19%
Avery AD-222	2.41	67	68	68	67	67	67	46.53%
	8.05	66	66	67	67	65	66	45.83%
	16.09	56	54	55	54	54	55	38.19%
Alien “Higgs”	2.41	60	60	61	62	60	61	42.36%
	8.05	54	54	55	56	55	55	38.19%
	16.09	54	54	54	54	54	54	37.50%

passed through the portal, HotSpot software identified each accurate tag read (3 or more reads) to a specific pallet location. Any tags not read were displayed and noted.

3.0 DATA AND RESULTS

The results for all tests conducted are represented in Tables 1–3.

The following are the key findings from this study:

- Of the three types of palletized products, paper towels performed the best, followed by water in plastic bottles and then metal cans

Table 2. *Results for Drinking Water in Plastic Bottles.*

Tag	Fork Lift Speed (kph)	Number of Tags Read per Trial (Total = 35) 1	2	3	4	5	Average	Readability
Raflatac G2 Short Dipole	2.41	35	35	35	35	35	35	100%
	8.05	35	35	35	35	35	35	100%
	16.09	35	33	35	35	35	35	100%
Avery AD-222	2.41	35	35	35	35	35	35	100%
	8.05	35	35	35	35	35	35	100%
	16.09	34	34	35	35	34	34	97%
Alien “Higgs”	2.41	35	35	35	35	35	35	100%
	8.05	35	35	35	35	35	35	100%
	16.09	35	34	35	35	35	35	100%

Table 3. *Results for Paper Towels in Plastic Wraps.*

Tag	**Fork Lift Speed (kph)**	**Number of Tags Read per Trial (Total = 24)**						
		1	**2**	**3**	**4**	**5**	**Average**	**Readability**
Raflatac G2 Short Dipole	2.41	24	24	24	24	24	24	100%
	8.05	24	24	24	24	24	24	100%
	16.09	24	24	24	24	24	24	100%
Avery AD-222	2.41	24	24	24	24	24	24	100%
	8.05	24	24	24	24	24	24	100%
	16.09	24	24	24	24	24	24	100%
Alien “Higgs”	2.41	24	24	24	24	24	24	100%
	8.05	24	24	24	24	24	24	100%
	16.09	24	24	24	24	24	24	100%

- Drinking Water in Plastic Bottles:
  - —Pallet patterns greatly effect read rates. There were no center cases on the pallet. All cases touched the outer edges of the pallet and were tagged accordingly.
  - —As all tags were exposed directly to the antenna, read rates were extremely consistent (Tables 2).
  - —All three tags performed well and average reads were nearly 100%.
  - —Speed of the fork lift truck had negligible effect on the read rates
- Carbonated Beverage in Metal Cans:
  - —The overall read rate for metal cans for all speeds and tag types was a little over 42%.
  - —Tag type 1 and 2 (44 %) performed better than tag type 3 (39 %) for readability with metal cans.
  - —Speed of the fork lift truck had an inverse effect on the read rates for all tag types. The average read rate for 2.41 kph was the highest (45.37%) followed by that for 8.05 kph (43.06%) and 16.09 kph (37.96%)

4.0 CONCLUSIONS

In conclusion, three products were used to determine effect of pallet speeds through a portal on read rates using three different types of Gen 2 tags. After analyzing the data from this study the following conclusions were reached:

1. Fork truck operating speeds have very little effect on read rates.

Higher speeds over 15 kph reduced tag read rates by about 10% as compared to slower speeds around 2 kph.

2. The read rates for Gen 2 tags are significantly better for all package types as compared to previously reported data and findings for Class 1 Gen 1 tags.
3. Presence of air gaps created in secondary packaging (trays and shippers) configurations between the locations and positioning of RFID tags and primary packages or products (bottles and cans) allows RFID readers to get more effective reads and reduce interferences and reflectance or blockage by water and metal as previously reported.
4. All three types of Gen 2 tags studied showed similar performance in terms of read rates.
5. The type of pallet pattern (presence of air gaps) affects the read rates of packages lying within the palletized structure.

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Table 5. Comparison of state-of-the-art matrix resins with VPSP/BMI copolymers.

Resin System	Core Temp. (DSC peak)	Char Yield, %
Epoxy (MY720)	235	30
C379: H795 = 1.4	285	53

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