A Comparison of Requirements and Test Methodologies for a Variety of Impact Absorbing Materials

Floyd P. Henry, General Plastics Mfg. Co.
Robert A. Johnson, Packaging Technology, Inc.
Peter Shih, Transnuclear, Inc.
Theodore Hile, General Plastics Mfg. Co.

Introduction

Several years ago I was hiking on Mt. Rainier. I had just crossed a rock field where I had previously stowed my ice axe and gloves in my pack when I came to a nice smooth snow field. I noticed the snow field was fairly steep and also that there was a tree line about 150 yards down slope. However, I was relieved to be getting to smoother hiking and stepped right out. The first step was just fine and then suddenly my world changed. My foot slipped, twisting me around and depositing me on my back. I found myself hurtling toward the tree line head first and accelerating rapidly. At that point I realized that Abraham Maslow had it all wrong. My most basic need wasn't my next breath, in fact, I don't think I was breathing at all. The only thing on my mind was deceleration! Or at the least, some way to LIMIT an IMPACT with a tree trunk.

As luck would have it, I managed to flip over and dig into the snow with my feet, knees, elbows and fingers and come to a safe albeit bloody stop.

The point of this story is that stopping a rapidly moving object can be a life or death matter. All too often, the question of how to stop an object safely is given little attention until late in the design phase of many projects. For example, how often does a guy showing off his new car point out the brakes? Fortunately for me in my hiking experience I had practiced arresting a fall. While I had always practiced arrests with an ice axe, at least I had discussed what to do if I lost the axe. I am still alive today only because my coach and I anticipated the possibility of an accidental fall.

For most of us safe stops are routine. We all experience them hundreds of times each day whether we are in a car stopping for a red light, descending in an elevator, or just walking from one place to another. Sometimes we can't rely on the normal methods of stopping a moving object. The risk of harm to ourselves, to others or to the environment is such that special measures must be employed. We are familiar with many examples, from automobile bumpers and air bags to safety nets under trapeze artists at the circus. We like to have these things, even though we hope they are never used. An impact limiter for a nuclear material shipping container is another good example of a special measure that we all hope will never have to be used.

The primary requirement of an impact limiter is that it be a passive system that can always be counted on to work in an instant. This often means that sacrifices must be made, trading off the ideal form of deceleration for a robust system that cannot be defeated by failure of a power supply or some other mechanism.

You might ask: what would constitute ideal deceleration and why not insist on the best for our impact limiters? Simply stated, an ideal impact limiter would decelerate the payload uniformly throughout the available distance. For example, when high speed elevators come to a stop they start slowing down at a predetermined distance prior to the desired floor, decelerating at a uniform rate all the while.

The stress / strain curve for the "Ideal Impact Limiter" would have the following shape.

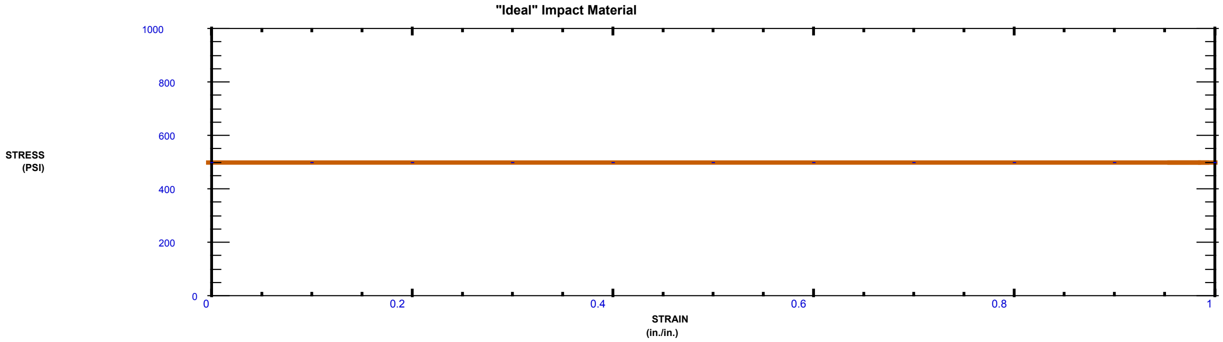


Chart 1 “Ideal Impact” stress/strain

From Chart 1 above we can see the “Ideal Impact Limiter” would have constant stress, no rebound, and employ all available distance. Unfortunately, it would have to be tuned for each specific impact.

Impact absorbing material characteristics

Obviously greater flexibility is needed for a reasonable design for our impact limiter. Since we need a passive system, some form of cushion is the obvious choice. Next we have to determine what to fill the cushion with. Typical materials include:

Foams
Woods
Honeycombs
Metal structures

Each of these materials has characteristic crush properties that have to be considered by the designer of the impact limiter. Within a particular material class, properties can vary from lot to lot as well. Most scientific literature and material properties tables are of minimal value to designers of impact limiters since they define the compressive strength of a particular material as the elastic limit or the point at which plastic failure begins. Once plastic failure begins the material absorbs energy while it is being permanently deformed. In the case of an impact limiter, the most desirable condition is a very short elastic range and plastic deformation throughout most of the material thickness. By minimizing elastic deformation rebound is also minimized.

Among foams the most commonly used is closed-cell rigid polyurethane. Phenolic foams have been used in the past but have fallen out of favor due to problems with water absorption because of the open cell characteristic of the foam (for example, florist foam is phenolic). Among woods, balsa and redwood are typically the choice of nuclear package designers. Other woods and wood products used include maple, oak, and cellulose fiber board. Honeycombs can be manufactured from a variety of materials and are used for impact absorbing applications in fields other than nuclear packaging. A survey of currently licensed packages found aluminum and stainless steel honeycombs. Other metal structures, including a large hollow steel torus and a series of seamless steel tubes have also been used as impact absorbers. Combinations of these materials can be effective with examples including a foam filled stainless steel torus and foam filled honeycombs. On one occasion the author observed a deformed impact limiter at a bridge abutment. Upon closer inspection the impact limiter was found to consist of a series of polyethylene or polypropylene containers full of polyurethane filled paper honeycomb.

The choice of impact absorbing material hinges on a variety of factors including; cost, performance, availability, fire protection and familiarity.

Note: Many package Safety Analysis Reports (SARs) were used in the research for this paper as well as actual laboratory crush tests of balsa, redwood, honeycomb and foam. Since the only information desired was that pertaining to impact limiters. SAR requests were limited to specific sections. Considerable variation was observed among different test reports involving arguably the same material (particularly balsa). No inference should be drawn as to the effectiveness of any impact limiter in service, regardless of the material used. The performance of an impact limiter depends on the design and construction of the entire structure and not solely on the specific properties of one material. Furthermore, the performance of all of the devices were proven by large scale tests.

The following examples illustrate the Crush strength curves typical of the materials reviewed in this paper.

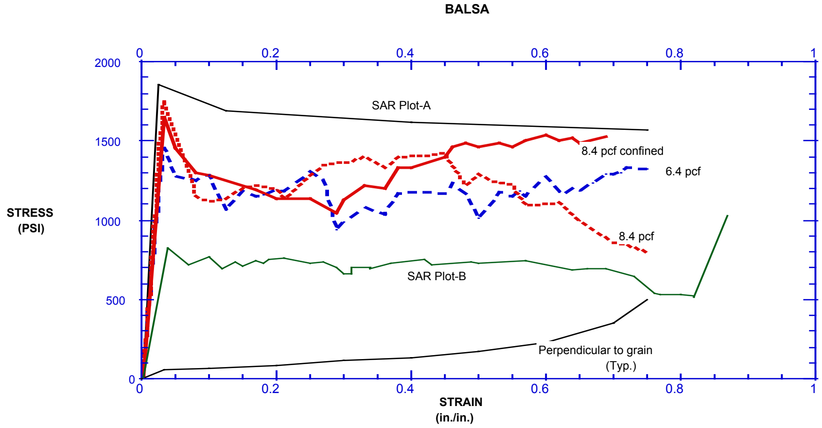


Chart 2, Balsa stress/strain

In Chart 2 above, parallel-to-grain examples of balsa wood performance were taken from two SAR plots. The remaining plots were the result of crush tests using an MTS Alliance model R/F-150 universal test machine. Balsa specimens were obtained from local commercial sources. The tested specimens exhibited a much greater initial peak relative to the SAR plots. This may have been a result of the specimen size (1 inch cubes). The lower SAR plot specimen was a 2 inch diameter by 2 inch tall cylinder. No dimensional data was found for the upper SAR plot. Discontinuities observed in the tested plot coincided with observed splitting of the sample while it was being crushed. We believe test specimen splitting would account for the markedly lower stress values at higher strains. One specimen was tested by confining the wood in a square steel tube, the test results show generally increasing stress with increasing strain following the initial peak stress. The upper SAR plot is believed to be the result of averaging stress at various strains.

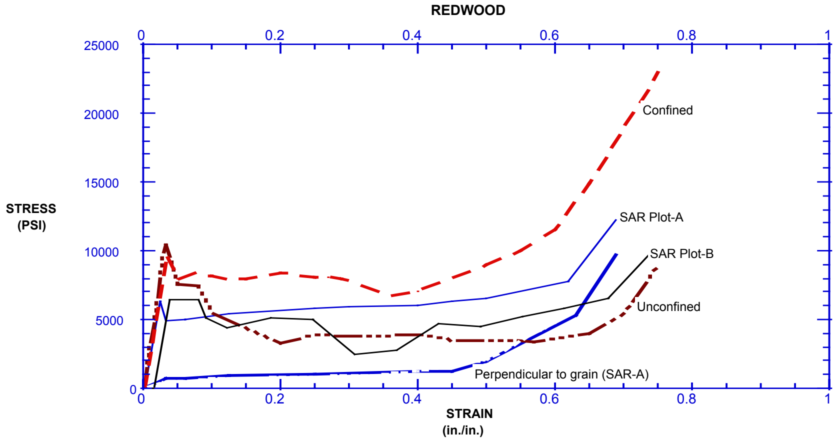


Chart 3, Redwood stress/strain

Chart 3 above, showing redwood performance was developed along the same lines as the balsa analysis. The test specimens of the redwood were obtained from a piece of retired lawn furniture. The wood was in good condition indicating that it had been under cover and did not show signs of sun and rain damage. Two observations are worthy of note. The effect of confining the test specimen is greater with redwood than with balsa. Secondly, the anisotropic character of woods is obvious from both plots. Directions provided for the installation of woods in impact limiters are very specific as to the grain orientation.

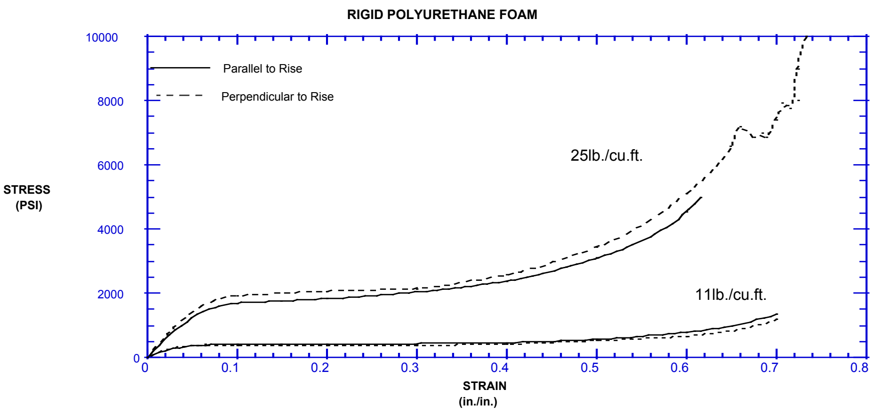


Chart 4, rigid polyurethane foam stress/strain

Both rigid and flexible polyurethane foams have been used for impact limiters in nuclear shipping containers for over a quarter century. The public is often surprised to find that a rigid material is the choice for protection from the largest impacts.

All of us are familiar with flexible polyurethane foam. We routinely sit or lounge on it in the form of seat cushions and pillows. As a result, there is a tendency to regard flexible foams as superior cushions. However, all flexible foams are nothing more than variously damped springs. Small amounts of flexible foam serve well for normal handling protection of fragile objects. However, since flexible foams (springs) store energy, they can cause significant rebound making them poor impact limiters for large impacts. One way of looking at the choice is whether the task is to protect the egg from the world or the world from the egg. Rigid foams are the material of choice for the latter.

One of the greatest attractions of rigid polyurethane foams is their nearly perfect isotropic crush properties. On the other hand, all woods and honeycombs are highly anisotropic. The difference arises from the symmetrical cell shape of foams. Woods and honeycombs consist of aligned tubular cells, similar to a series of soda straws. Consequently the cell resists buckling in the direction parallel to the cells' long axis and is significantly weaker in the perpendicular direction. The orientation of the fibers combined with the close packing of the cells provides some resistance to buckling and gives woods and honeycombs the advantage of greater energy absorption than foams in the parallel orientation when compared at the same density.

Rigid foam density can be varied uniformly from 4 to 40 lbs./ cu. ft. This allows the designer freedom to choose the best energy absorber for a given application rather than create a composite of two or more densities. Also, foam can be formed in-situ in the impact limiter, eliminating significant labor, and creating a unified object locking all components in place. Moreover, specially formulated rigid polyurethane foams can be made to create an intumescent char that, in the event of a fire, will prevent smoldering of the foam inside the overpack and provide a high level of thermal protection.

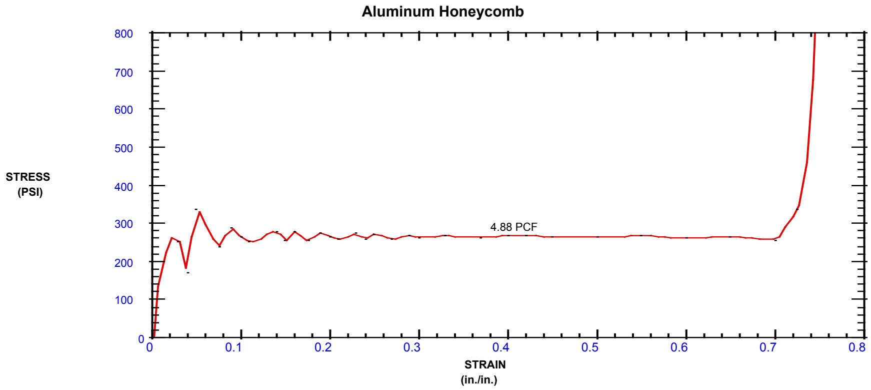


Chart 5, honeycomb stress/strain

As an engineered product honeycombs are available in many different crush strength ranges. One advantage they have over rigid polyurethane foams is the ability to achieve higher energy absorption at a given density, as with woods. Two characteristics of honeycombs must be considered by the impact limiter designer. The first is the presence of a relatively high initial stress peak often giving rise to peak g-loads regardless of the severity of the impact. This peak is often mitigated by pre-crushing the honeycomb. Crushing occurs by folding the individual cells in an accordion like manner. By purposely creating the first accordion fold the initial peak can be eliminated. The second honeycomb characteristic is unforgiving if not taken into account. This is the severe lockup condition that occurs when the folds all meet when crushed to high strain levels. This lockup condition can be seen at the right side of Chart 5. At that point the stress levels can increase dramatically to potentially destructive levels if sufficient kinetic energy remains. In contrast, woods and foams lock up more gradually during crushing due to the more random distribution of cell sizes and the capability of the material to extrude or be squeezed to the side under lower forces than metals. Another advantage of metal honeycombs is that they are generally less affected by temperature and strain rate effects than woods or foams. However, the adhesives used to form bonds at the honeycomb nodes have been observed to become very weak at temperatures over 200°F, allowing a sharp drop off in crush strength.

Other materials have been used for impact limiters but to a lesser extent than the materials noted previously. Of those materials, the most important are various metal structures. For many of these structures enough is known about the failure mechanism of steel that the design performance can be accurately predicted from classic physics and the help of finite element analysis. A torus shape has been used in at least two different large impact limiters, one of which was also filled with rigid polyurethane foam. Another interesting application employed by one of the authors of this paper was a series of steel tubes. The structure ultimately imitated that of a macro-celled honeycomb. In order to ensure that crushing occurred as desired, the tubes were crimped so as to force buckling in a three-lobe form.

To summarize the differences between the various common impact limiting materials:

- Woods and honeycombs exhibit an initial force spike.
- Woods may require confinement when crushing parallel to the grain for accurate test results.
- Woods and honeycombs are very anisotropic (honeycombs are typically not even measured perpendicular to the cell orientation.)
- Woods and Honeycombs are capable of absorbing more energy at a given density than polyurethane foams.

- Polyurethane foam is nearly perfectly isotropic, eliminating concerns with oblique impacts and the necessity of orienting the material within the impact limiter.
- Honeycombs crush in a stepwise fashion, the cells fold up like an accordion.
- Honeycombs are the most efficient energy absorbers with a characteristic flat curve until crush is complete (lockup).
- Honeycombs lock up with a very sharp increase in force.
- Woods and Polyurethane foam approach lockup much more gradually than honeycombs.
- Honeycombs provide no thermal protection from a fire though they can be effective conductors of decay heat.
- Polyurethane foam can provide superior thermal protection by developing an intumescing char, this char provides a protective cocoon around the payload.

Along with the differences in energy absorbing capability the designer must also contend with a variety of other factors when choosing an impact absorbing material including: cost, availability, temperature extremes, fire resistance, long term life, not to mention prejudice for or against a particular type of material.

For many impact limiters fire resistance is not a factor. In the case of overpacks such as the TRUPACT II, the impact absorbing material must also provide protection from an engulfing fire or be combined with other materials that provide such protection. At one time it was thought that redwood was inherently fire resistant in metal containers. One of the SARs includes the following statement “The outer assembly is made of select, kiln dried redwood to take advantage of redwood’s high specific energy and fire resistant characteristics.” This statement is true only if oxygen can be excluded or limited to low levels in the package. If the package is punctured in such a way as to allow hot gasses to escape while also admitting air, the wood can smolder and burn inside the package.

Quality Assurance requirements

From reviewing numerous SARs spanning many years, two trends appear to have developed. Compressive strength performance verification of the engineered materials (honeycomb and foam) is accomplished by testing the material and meeting tolerance bands placed about the nominal crush strength curve and density for a given product. In one case the SAR states, ”The manufacturer of the honeycomb has guaranteed the crush strength to be within ± 12.5% of the nominal value over the temperature range of –20°F to 200°F.” Another SAR states “The crush strength of the material is 750 psi ± 10%. The manufacturer’s force-displacement plots for honeycomb samples are presented….” For rigid polyurethane foams similar requirements are found in two of the referenced SARs including this, “…the average parallel–to-rise compressive stress for a foamed component shall be the nominal compressive stress ± 15% at strains of 10%, 40% and 70%.” And this “The applicable stress-strain curves (at room temperature approximately 70-75°F) for polyurethane foam of about 12.5 pounds per cubic foot (pcf, lb/ft^3) are presented in figure 2.3-2. The nominal, room temperature stress-strain curve is bounded by ± 15% on crush stress…“

A second trend exists with respect to the verification requirements for the properties of woods. For woods, the strength requirement is correlated to density during the design phase and tolerance bands are placed about the wood density. For example, “License drawings and the supporting analysis specify the crush strengths of the redwood and balsa wood to be 6240 psi ± 620 psi and 1550 psi ± 150 psi respectively. For manufacturing purposes, verification of the impact limiter material is accomplished by verifying the densities of the wood. Three samples from each redwood board are to be tested for density, and the average density of the samples shall be 23.5 ± 3.5 pounds/cubic foot." In addition, moisture content was specified from 5% to 15%, while no density requirement could be found for the balsa. Another example from an impact limiter drawing: "Redwood: Density – 19.00-27.00 lb/ft^3, average segment density 21.8 – 24.2 lb/ft^3, moisture content – 15% max, crush stress, prl to grain 5750-7000psi (based on segment averages)" It is not clear if the drawing requires actual crush strength tests; however, no other references to required tests were found in the SAR.

The disparity in the two methods of confirming the crush strengths of the various materials used to fabricate impact limiters is troubling, especially what appears to be an assumption that maintaining a ± 15% tolerance for wood density equates to achieving a ± 10% tolerance for compressive strength. Why should manufacturers of honeycombs and foams be held to a higher standard of proof than fabricators of wood products? Considering the range of variation in density and crush strength found in this short exercise it would seem prudent to require even greater scrutiny of the wood products than the engineered materials.

Those of us familiar with the performance of impact limiters to the hypothetical accident conditions will not doubt the effectiveness of any of the devices reviewed for this paper. However, the general public has not had the benefit of long experience and observation of large scale tests. Furthermore they have shown a tendency to distrust much of the handling of nuclear materials. Therefore, it would seem that **an opportunity exists to enhance public confidence in nuclear material packages** by improving the verification of these materials (woods) by requiring actual crush tests as is the case with honeycombs and foams.

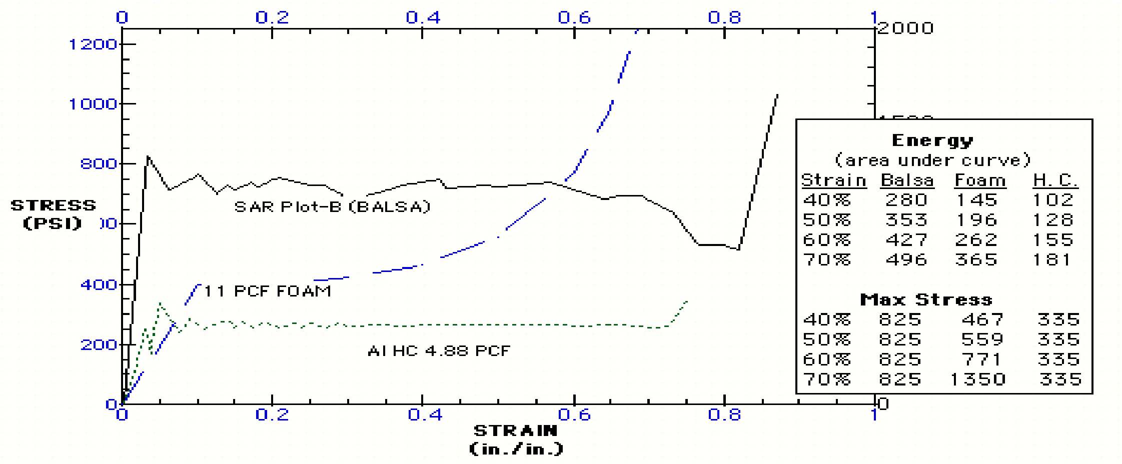
Proposal

It is proposed that new package designs incorporate changes to the verification tests of impact absorbing materials that would show the material is capable of safely absorbing the kinetic energy of the required hypothetical accident impact. In addition, testing could also supply verification of the safety margins that would exist under the specified conditions. For the most part this data already exists and all that would be required is additional data reduction that can easily be accomplished with a variety of computer programs in wide use.

Simply stated, designers should eliminate requirements for average stress values and tolerances. Instead **establish requirements for minimum energy absorption capability coupled with maximum allowable crush stress levels.** In both cases safety margins can be stated both in the design requirements and in the actual results achieved. The analysis will still have to account for factors such as temperature and strain rate effects. However, these allowances will in no way impair the validity and strength of this proposed method. It will be important to recognize the potential for misleading test results arising out of splitting and fracturing test specimens and steps should be taken to minimize this.

The area under the stress/strain curve of any crush test specimen represents the energy absorbed by that specimen during the test. This area is a partially dimensioned value (stress times strain) that when multiplied by the volume of impact absorbing material crushed, will provide the impact absorbing capability for the material tested. A simple example is presented to illustrate.

A boiling water reactor power plant is being dismantled. One of the items to be removed is a contaminated pump assembly. The pump has been sealed and disconnected from all other equipment. It sits on a 3 ft. by 5 ft. base. The entire assembly weighs 10 tons. Moving the pump assembly to the shipping cask requires a 30 ft. lift. The engineer has information available on three candidate materials for an impact limiting pad to be attached to the base of the pump assembly. Those materials are the Balsa wood from SAR-B, 11 pcf rigid polyurethane foam and 4.88 pcf honeycomb (see Charts 2, 4, and 5). All three curves are repeated below. Energy densities are presented for crush to 40%, 50%, 60% and 70%for each of the materials as well as the maximum stress at the same strain levels.



Energy
(area under curve)

Strain	Balsa	Foam	H. C.
40%	280	145	102
50%	353	196	128
60%	427	262	155
70%	496	365	181

Max Stress

40%	825	467	335
50%	825	559	335
60%	825	771	335
70%	825	1350	335

The kinetic energy (KE)to be absorbed is 10*2000*30 ft. = 600,000 ft. lb.
The impact area (IA) =5'*3'*144 sq.in./sq.ft. = 2160 sq. in.
The area under the curve (energy area, EA) consists of the stress (σ) in psi multiplied by the dimensionless value of strain. If the area under the curve is multiplied by the impact area and the thickness of the crushable pad, the energy absorbing capability of the pad can be determined. Since we need to determine how thick the impact pad need be, it is a simple matter to arrange the terms to solve for T. It is decided to use the results at 60% strain for a starting point. The engineers' reasoning goes like this. He is a bit distrustful of the balsa curve beyond 60% because the stress shouldn't be declining at that point. The foam is beginning to lock up and shouldn't be pushed beyond 60%. Finally, the consequences of lockup with the honeycomb are too serious to risk going over 60%.

The equation becomes: $T = \frac{KE}{EA*IA} = \frac{600{,}000 * 12}{EA * 2160} = \frac{3{,}333.3}{EA}$

The maximum acceleration of the pump assembly can be calculated by multiplying the impact area by maximum stress and dividing by the weight (mass) of the assembly. $g = \frac{IA*\sigma}{W}$

Solving for thickness and g for each material at 60% strain yields:

Balsa	$T_b = 7.8$ in.	g = 89
Foam	$T_f = 12.72$ in.	g = 83
Honey comb	$T_{hc} = 21.5$ in.	g = 36

Now the engineer has the basis for a sound decision, weighing the importance of several factors including; cost, available space, fragility of the payload, availability of material, etc. Of course, it should come as no surprise that the lowest g comes with the thickest cushion (ultimately, only distance can mitigate impact). If the engineer would substitute the foam energy area at 40% strain he would find the task could be accomplished with a 23 in. thick pad with maximum g of 50, and very likely at a considerable cost savings.

Acknowledgments:
Thanks to: the NRC Public Documents Room and especially Donna McCulloch for locating the many SARs researched for this paper; Wayne McMurtry for background information on redwood by telephone; Charles Williamson V. P. Quality Assurance, General Plastics for establishing a first rate testing laboratory and allowing his staff to assist the author; and not least, Robert Sevasin for cheerfully testing numerous wood specimens.

References:

The following Safety Analysis Reports were researched in preparation for this paper (listed by Docket No.)

1) 71-0361
2) 71-9150
3) 71-9200
4) 71-9202
5) 71-9218
6) 71-9226
7) 71-9228
8) 71-9235
9) 71-9261
10) 71-9293

Other references:

A) *Iimpact Limiter Tests of Four Commonly Used Materials and Establishment of an Impact Limiter Data Base;* W. M Mcmurtry, G. F. Hohnstreiter, Sandia National Laboratories, PATRAM 95
B) *CSB Impact Absorber Analysis Report ED-037;* P. W. Noss, June 1999, PACTEC Document E D-037, REV. 0
C) *TSB 122 Design Data for the Preliminary Selection of Honeycomb Energy Absorption Systems;* Hexel Corp. 10/91
D) *General Plastics Test Report* #S-00810-01 for ALCORE Inc., Aug. 10, 2000
E) *General Plastics LAST-A-FOAM FR-3700 for Crash and Fire Protection of Nuclear Material Shipping Containers*, F. P. Henry, General Plastics Mfg. Co. 11th printing
F) All charts and area under the curve energy calculations were performed with: *Kaleidagraph,* Version 3.51 Dec. 14, 2000, Senergy Software