Impact-Limiting Materials Characterization*

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INTRODUCTION

Packagings for the shipment of radioactive materials are required to survive a sequence of hypothetical accident conditions. Regulatory requirements for Type B packages are specified in the United States Code of Federal Regulations (10 CFR 71, "Packaging and Transportation of Radioactive Materials"). The regulatory sequence consists of a free drop onto an unyielding target followed by a puncture and then a fire. Impact limiters are often used in packages designed to survive this hypothetical accident sequence.

The primary goal in the design of an impact limiter is to minimize the deceleration loads that the package and contents experience during the drop. Minimizing the decelerations enhances packaging performance by reducing loads in critical areas such as the closures, containment boundaries, and shielding. A secondary goal for impact limiter design is to reduce the thermal assault on the package due to the regulatory thermal event. A final objective in impact limiter design is to minimize the weight or size of the impact limiter consistent with the other design constraints. This requires materials, such as foams and honeycombs, which have a high energy absorption per unit weight or per unit volume. Characterization of the responses of the impact-limiting materials to the impact and fire events provides the design parameters required for selection of materials for the impact limiter.

Historically, there have been substantial efforts in identifying materials for use in impact limiters for specific packaging designs. These efforts include screening processes (Hill and Joseph, 1974), evaluation of materials for specific accident-resistant containers (Hill and Joseph, 1974), static and dynamic tests of foams (Berry et al., 1975) and modeling of cellular products (Neilsen et al., 1989). These references provide a basis of data and test methods. However, testing of the materials has been done for a variety of specific applications. In particular, much of the data in these references are for low-density crushable materials with structural testing performed at design-specific strain rates and with no corresponding thermal response.

Sandia National Laboratories (SNL) is developing inexpensive methods for selecting impact-limiting materials for use in radioactive materials packagings for the United States Department of Energy (DOE). Figures of merit have been developed for screening both structural and thermal response. These methods have been applied to two types of impact-limiting materials: aluminum honeycombs and polyurethane foams.

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The development of the figures of merit examined the response of the materials to the impact event with the intent of maximizing the energy absorption of the materials with respect to either the volume or mass of the materials. Three figures of merit will be presented for the structural response. The figure of merit for the thermal event is based on minimizing the heat flux due to the regulatory thermal event into the containment boundary.

STRUCTURAL TESTS

The structural tests were designed to simulate the conditions enveloped by the hypothetical free drop accident. The 9-m drop determines the initial impact velocity and, hence, for a given material thickness determines the initial crush rate. For example, the velocity at impact is 13.3 m/s. For an initial thickness of impact-limiting material of 0.3 m, the initial strain rate is $44\ s^{-1}$. To determine the effects of this strain rate, testing was performed at quasi-static ($<10^{-2}\ s^{-1}$) and dynamic ($>10^{1}\ s^{-1}$) initial strain rates. Since the length of the impact-limiting sample was fixed, the impact velocity was selected to obtain the desired initial strain rate. The dynamic testing was done with an instrumented drop weight machine. The static load tests were accomplished with a screw driven quasi-static test machine.

Figure 1 shows an idealized load-deflection curve for crushable materials. The test was designed to ensure that the materials were taken to lock-up. This required that the product of the drop height and drop weight was greater than or equal to the area under the load-deflection curve to the lock-up deflection. For the static tests, displacements exceeded those associated with lock-up.

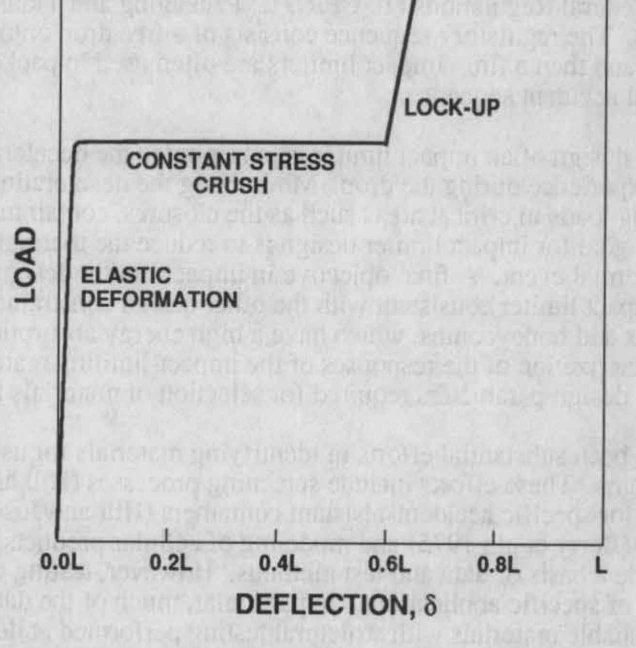

Figure 1. Idealized Crush Load-Deflection Curve

The test also simulated the lateral confinement experienced by impact-limiting materials during impact due to either the impact limiter skin or the surrounding impact-limiting materials. The lateral confinement was simulated by placing the 7.5-cm-long by 9.82-cm-diameter impact-limiting material samples in a 10-cm inside diameter steel pipe. The outside of the pipe was instrumented with strain gages to determine whether significant hoop or axial stresses were generated during the impact. No significant strains were measured.

STRUCTURAL TEST RESULTS

A series of seventeen structural tests was performed for SNL by General Research Corporation (McConnell et al., 1986). The results indicate the effects of initial strain rate and density for each of the materials. The materials tested were corrosion resistant aluminum honeycombs, supplied by HEXCEL, with nominal densities of 91 kg/m^3 and 147 kg/m^3 and char forming polyurethane foams, supplied by General Plastics (FR9900 series), with densities of 168 kg/m^3 and 288 kg/m^3. The complete results are contained in Reference (Duffey, 1992).

The data are presented in terms of the engineering stress-strain curves. Engineering stress is defined as the measured load divided by the initial cross-sectional area. Engineering strain is defined by the measured deflection divided by the initial length of the specimen. The energy dissipated by an impact-limiting material is equal to the area under the load-deflection curve and hence is proportional to the area under the stress-strain curve. For this discussion, lock-up is defined as 125% of crush strength where the crush strength is defined as the engineering stress at 0.3 strain.

The aluminum honeycomb composite results are shown in Figure 2. These curves have an initial linear portion representing the elastic deformation. As the load increases, the peak or buckling strength of the honeycomb is reached. The peak occurs at small deformation and hence represents limited energy dissipation. The peak stress is followed by a reduction in stress to a constant stress plateau representing the crush strength of the material. This plateau lasts until lock-up is initiated at 70 to 80% strain. During this crush to lock-up, most of the energy is dissipated. Past lock-up energy dissipation results in significantly larger and increasing stresses.

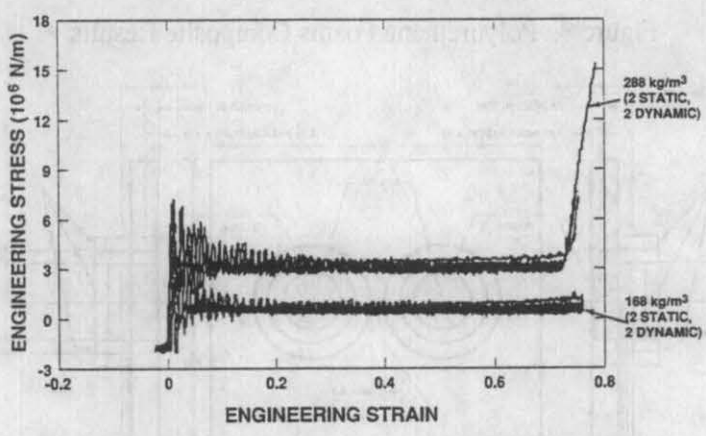

Figure 2. Aluminum Honeycomb Composite Results

The polyurethane foam results are shown in Figure 3. These curves show an initial low energy dissipation elastic response which transitions into a plateau region representing the crush of the foam. As the foam crushes, it hardens as represented by the upward slope of the plateau. Unlike the honeycomb, there is no sharp transition at lock-up. Instead, the slope of the curve continues to increase resulting in a smooth transition to the higher decelerations resulting from increasing stress. Another foam characteristic is the significant increase in strength at dynamic versus quasi-static load rates. In particular, the low-density foams experienced an approximately 40% increase in crush strength at dynamic rates and the high-density foams experienced an approximately 50% increase in dynamic crush strength.

THERMAL TESTS

The thermal tests subjected the materials to a 30-min exposure to a radiant heat environment. The radiating surface was controlled to 800°C (+30°C/-0°C) with an emissivity greater than 0.9. The intent of the thermal tests was to provide a comparison of the ability of the materials to limit the heat flux into the packaging.

The samples consisted of cylinders of crushable material that were 12.7 cm in diameter and 7.6 cm thick. Thermocouples were placed in the samples as shown in Figure 4. Data were acquired every 10 s during the heating and every minute for 90 min during cool-down. The circumference of each sample was wrapped with a ceramic fiber insulation to provide a radial adiabatic boundary. The back face of each sample was also insulated with a 5-cm-thick section of insulation. Two samples were tested simultaneously as shown in Figure 4.

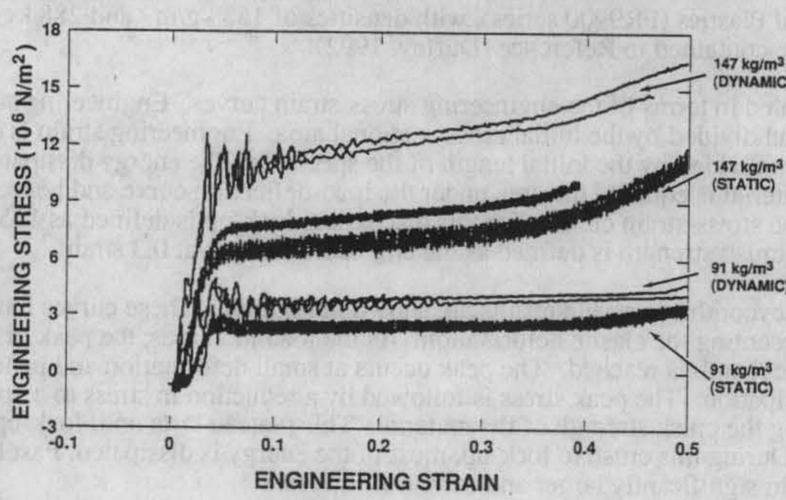

Figure 3. Polyurethane Foams Composite Results

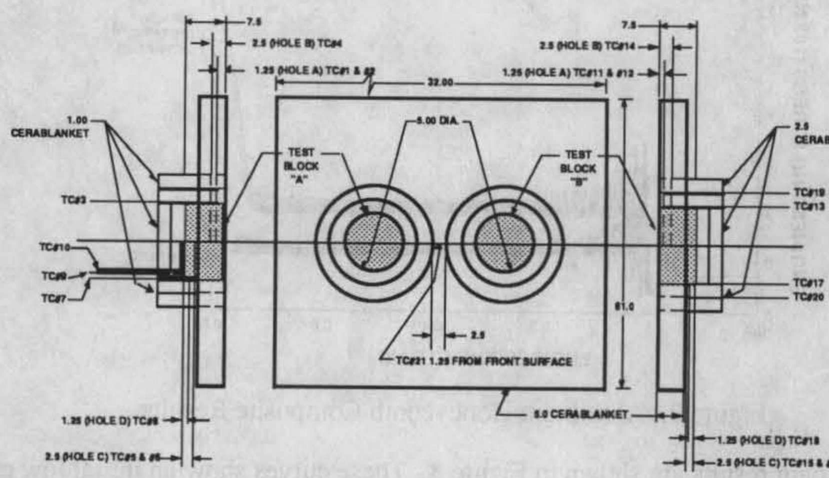

Figure 4. Thermal Test Setup

Two independent tests of each of the four different materials were performed. Each test consisted of two identical samples. The responses of 16 samples were recorded. The data are in the form of temperature histories at each location.

THERMAL TEST RESULTS

The radial data for a given axial location were used to demonstrate that the heat transfer was essentially one-dimensional. This section will discuss the results of the axial temperature distributions.

The axial temperature distribution for a low-density aluminum honeycomb is shown in Figure 5. This figure is representative of both honeycomb densities. The axial gradients through the honeycombs are small. These results indicate that the open-celled honeycomb provides minimal thermal protection.

The low-density polyurethane foam material samples experienced substantial burning during radiant heat testing. Representative data for the behavior of this material are given in Figure 6. These data indicate that once the foam was ignited, the burning and associated charring continued until the back-face temperatures were as great as that of the incident radiant environment. This was supported by the posttest material that showed the sample had been reduced to a small amount of residual char.

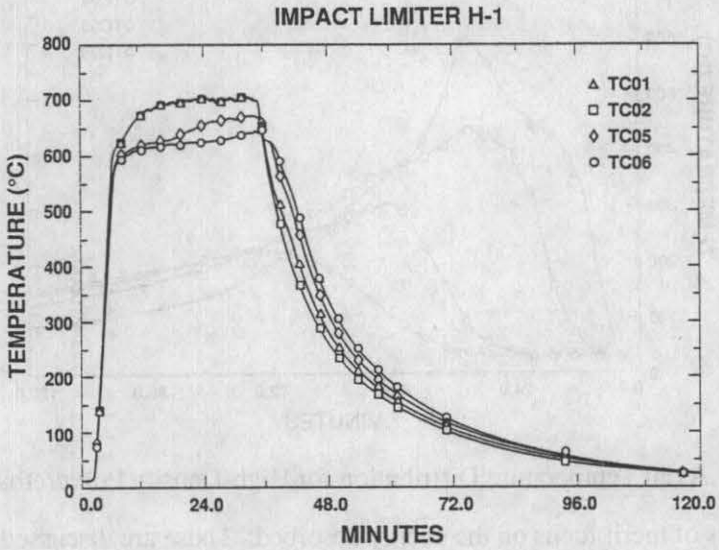

Figure 5. Axial Temperature Distribution for Aluminum Honeycomb

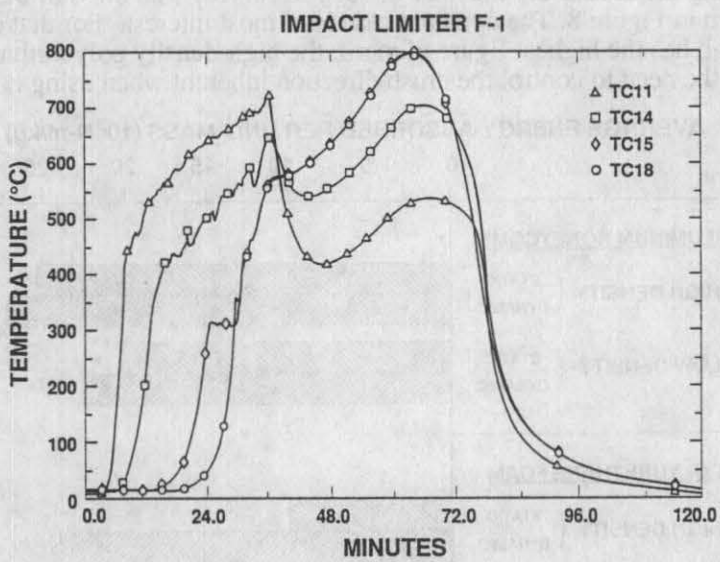

Figure 6. Axial Temperature Distribution for Low-Density Polyurethane Foam

The data for the high-density foam illustrated significantly different results as shown in Figure 7. These curves indicate good insulating capability. The back face temperature is less than 260°C. The posttest examination showed charring only of the front half of the materials, indicating that a self-sustaining charring front could not form as it did in the low-density material. These results indicate that the high-density foam can provide a good thermal resistance even in the presence of air.

FIGURES OF MERIT

In order to select materials for use in impact limiters, simple methods for screening those materials are needed. Three methods for evaluating structural response and one method for evaluating thermal response were used.

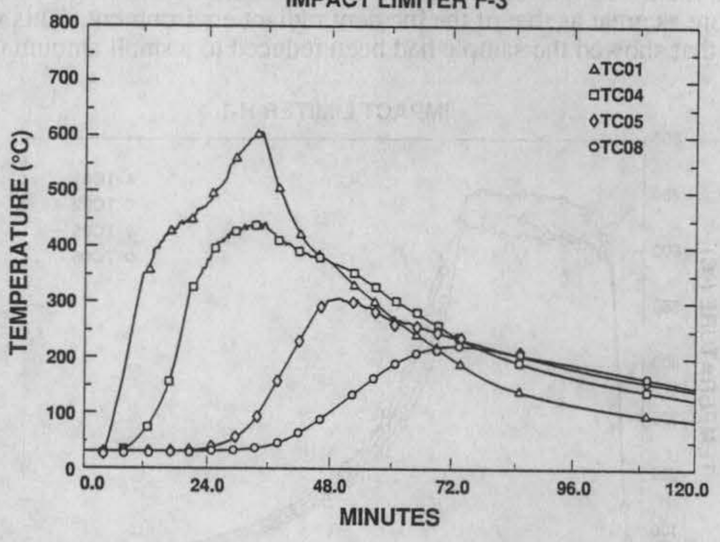

Figure 7. Axial Temperature Distribution for High-Density Polyurethane Foam

The structural figures of merit focus on the energy absorbed. These are discussed in detail in Duffey et al., 1992. The first structural figure of merit is the energy absorbed per unit mass of sample. This figure of merit should be used where weight of the packaging is a critical parameter. The energy is obtained by integrating the area under the load-deflection curves. The mass of the sample is known. The results are shown in Figure 8. The dynamic case is of most interest. For that case, while the aluminum honeycomb has the highest figure of merit, the high-density polyurethane foam is comparable without the need to control the crush direction inherent when using honeycomb.

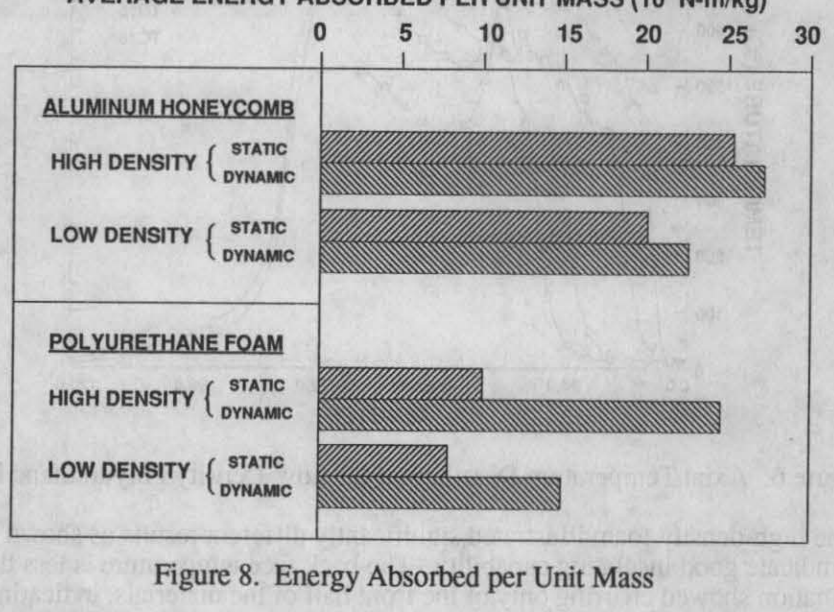

Figure 8. Energy Absorbed per Unit Mass

The second structural figure of merit is the energy absorbed per unit volume of sample. This figure of merit should be used where the size of the impact limiter is the controlling parameter. In this case, shown in Figure 9, the high-density polyurethane foam under dynamic loading is clearly the preferred material. This indicates that for a volumetrically constrained design, the polyurethane foam would be selected.

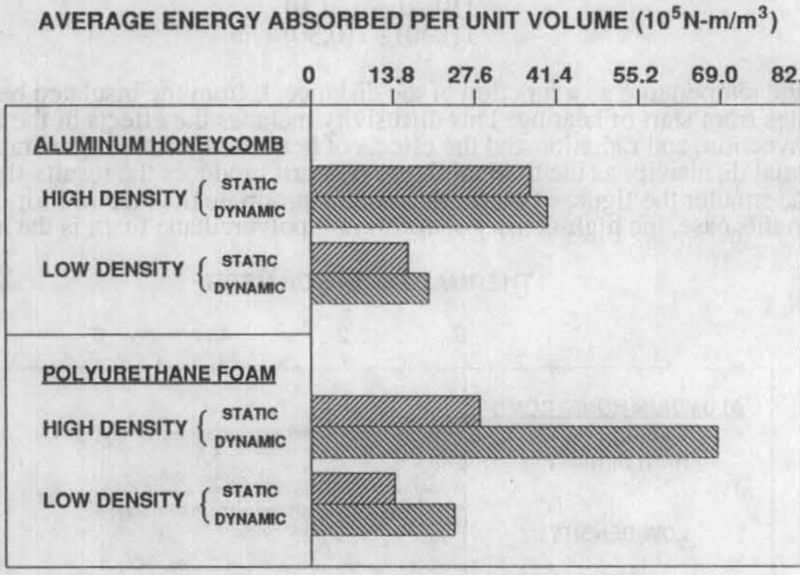

Figure 9. Energy Absorbed per Unit Volume

A third structural figure of merit uses the Janssen factor to determine the optimal strain. The optimal strain is then used to determine the energy absorbed per unit volume. The Janssen factor can be defined as the ratio of the peak acceleration observed with the sample to that which would be produced by an ideal material (one which is capable of crushing at constant crush stress to zero volume). To use this method, the optimal strain is determined from the stress-strain curve. The optimal strain occurs where a line from the origin is tangent to the stress-strain curve (see Duffey et al., 1992 for detailed discussion). The energy absorbed is determined by integrating the area under the curve to that optimal strain. The energy absorbed per unit volume is then plotted as in Figure 10. This procedure, while providing similar results for these materials as for the energy absorbed per unit volume based on lock-up, provides a more rigorous method of obtaining the maximum strain instead of relying upon an arbitrary selection of the lock-up point.

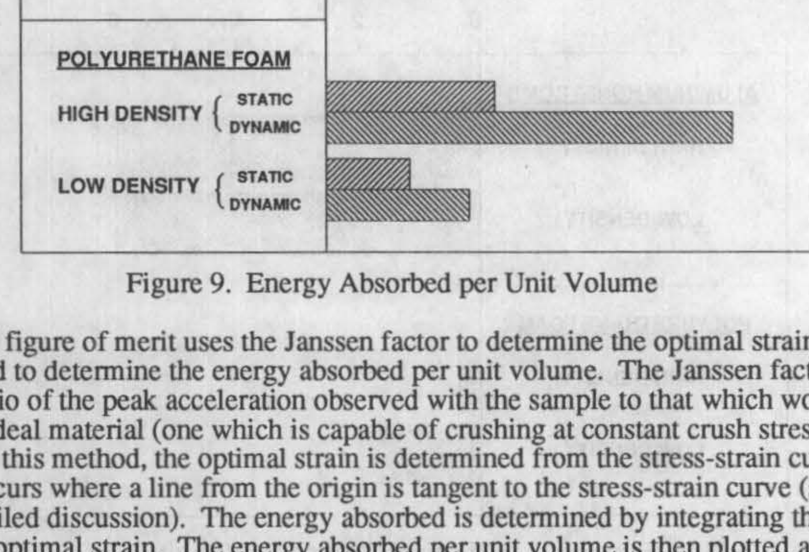

Figure 10. Energy Absorbed per Unit Volume Using Janssen Factor

The thermal figure of merit is based on treating the heat transfer through the impact-limiting material as a transient heat conduction problem. This simplification of the heat transfer phenomenon allows comparison of an "effective" thermal diffusivity. This "effective" thermal diffusivity is approximated by:

$$\frac{T(0,30) - T(0,0)}{T(l,30) - T(0,30)}$$

where T(l,t) is the temperature as a function of the distance, l, from the insulated back-face and the time, t, in minutes from start of heating. This diffusivity includes the effects of the heat transfer by conduction, convection, and radiation and the effects of heat storage and/or generation. Using this "effective" thermal diffusivity as the thermal figure of merit produces the results shown in Figure 11. In this graph, the smaller the figure of merit, the more appropriate the material for limiting the thermal flux. In this case, the high-density char forming polyurethane foam is the most appropriate material.

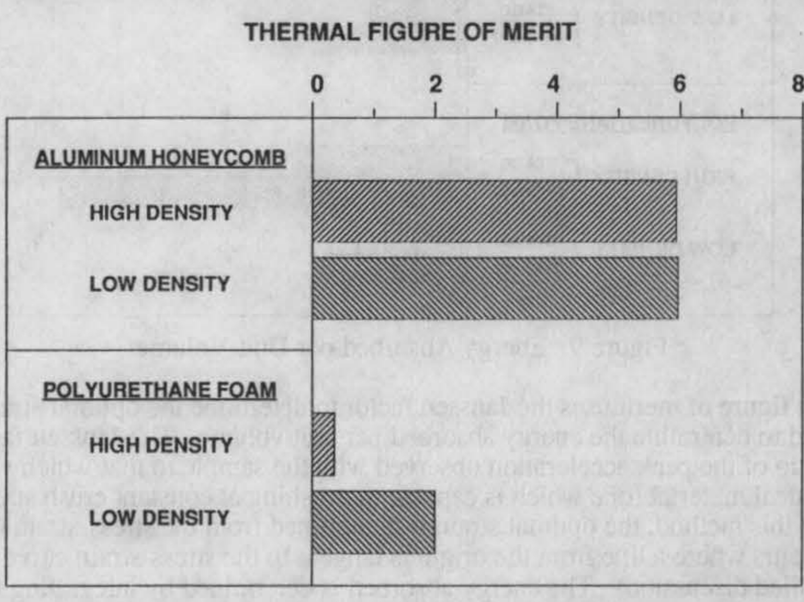

Figure 11. "Effective" Thermal Diffusivity

CONCLUSIONS

In this paper we have presented methods for characterizing impact-limiting materials, representative data obtained in materials characterization and figures of merit which can be used for selection among available materials. The figures of merit have been developed to address specific needs of the packaging design community such as minimizing the weight of the impact limiter for a given weight of packaging and protecting against the fire environment.

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