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PRACTICAL LIMITS FOR BALSA IMPACT LIMITERS

by Don Bresie

Manned Spacecraft Center
Houston, Texas

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ABSTRACT

The maximum impact velocity criterion is developed for the spherical, hard-landing payload of a planetary probe which uses a balsa impact limiter. The equations presented represent refinements to previous work of various authors. The curves allow conceptual designers to define reasonable values of allowable impact velocity for a given weight and volume of the total package.

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SUMMARY

Analytical equations are presented for the design of spherical balsa impact limiters. These limiters surround spherical hard-landed experimental packages. The purpose of the study was to determine the practical impact velocity limits for such packages in terms of reasonable size and weight allowances. Only balsa limiters were considered. The ultimate velocity limit for balsa limiters was shown to be about 530 ft/sec.

The equations presented, a refinement of previous work, are useful to about 300 ft/sec impact velocity. The lack of experimental data about the properties of balsa prevents further refinement. It is shown in the study, however, that balsa limiters become less useful with impact velocities above 300 ft/sec.

INTRODUCTION

Hard-landed experimental packages have been suggested as an economical and practical method of gathering information from a lunar or planetary surface. A package is said to be hard-landed if it is landed on the surface of an astronomical body without benefit of terminal guidance. These packages are usually spherical because of their random orientation at impact. The spheres are covered with a shell of soft material, called limiter, which attenuates impact shock. This paper deals with the design of the limiter.

The design of impact limiters has been studied under several NASA-sponsored contracts. One of the first of these studies was carried out under the Ranger program. A payload was designed to be hard-landed on the lunar surface for the purpose of making closeup pictures. A second study was made to determine the feasibility of landing a similar payload on the lunar surface by using a delivery system launched from lunar orbit. For each study balsa was used for the impact limiter material because of its high energy absorption per unit weight and the ease with which it can be shaped. Other limiter materials, such as fiber glass, aluminum honeycomb, steel honeycomb, or foam plastic have been suggested (ref. 1). However, the work presented herein considers balsa only.

Past studies have been limited to the design of limiters for specific payloads and specific impact velocities. The analysis presented in this paper covers a broad range of impact velocities and payload weights and sizes. The purpose of this analysis is to determine the practical impact velocity limits for balsa impact limiters in terms of package size and weight. These impact velocity limits may be used in the design of a delivery system for these payloads.

In addition to covering a wider range of variables, this analysis is an improvement over previous work in that fewer simplifying assumptions are made. The closed-form equations are easier to handle than previously used trial and error techniques of limiter design.

SYMBOLS

A	cross-sectional area of the payload, in.^{2}
C	crushing fraction (see eq. (8))
F	force, lb
g_0	constant = 32.2 lbm ft/lbf sec^2
K_v	energy absorbing capacity, ft-lb/ft^3
n	acceleration, earth g
R	balsa outer radius, in.
r	balsa inner radius or payload outer radius, in.
t	skin thickness, in.
V_{cb}	crushed balsa volume, ft^3
V_i	impact velocity, ft/sec
ΔV	elemental volume, in.^{3}
V_{tb}	total balsa volume, ft^3
W_b	balsa weight, lb
W_{pl}	payload weight, lb
W_s	skin weight, lb
W_t	total package weight, lb

X	vertical axis
ϵ_1	energy absorption efficiency of homogeneous balsa, natural state, a function of the crushing angle with the grain
η	total efficiency of an impact limiter
Θ	half cone angle of crushed balsa, radians
θ	arbitrary half cone angle, radians
ρ_b	balsa density, lbm/ft^3
ρ_s	skin density, lbm/in.^{3}
σ_c	crushing stress of the balsa, 153 ρ_b, psi
σ_s	working stress of the outer skin, psi
ϕ	normalized radius, outer balsa radius/inner balsa radius
ω	normalized weight, total weight/payload weight

ANALYSIS

The concept which will be treated in this paper is similar to those considered by the Jet Propulsion Laboratory for use in a lunar hard landing. The basic configuration is shown in figure 1. The payload is contained in a rigid spherical shell which serves as the primary structure. Surrounding this sphere is a shell of balsa cut in such a manner as to orient the wood fiber in a near radial direction. An outer shell of thin metal serves to keep the balsa from breaking apart upon impact. After impact, the outer shell and the balsa are blown away with an explosive charge, exposing the payload.

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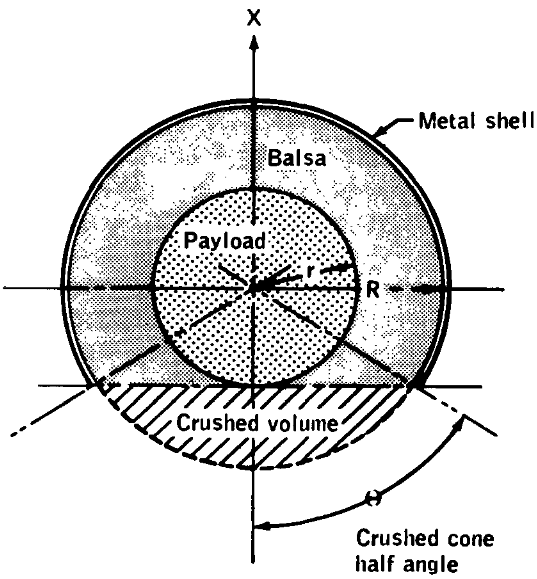


Figure 1. - Impact limiter configuration.

This analysis considers the following: (1) the variation in balsa efficiency with respect to the amount of balsa crushed; (2) the fraction of the total balsa crushed as a function of the relative dimensions of the package; and (3) the variation in skin thickness. These effects are all combined in a method which requires no trial and error solutions. There are, however, some effects that were neglected. For example, there was no consideration made for the effective change in mass of the total package as the crushed portions of the balsa come to rest. Also, the change in balsa absorption capacity as a function of impact velocity was neglected. Instead, the lower value of absorption capacity, observed at high velocity, was used in all cases. The high crushing stress was maintained, however, to prevent excessive g loading. In both cases, these effects are small, and the work presented here represents conservative amounts of balsa.

Balsa Characteristics

Balsa has been chosen as the impact limiter material because of its ability to absorb much energy per unit weight and because of the ease of its fabrication. The energy absorption capacity of various materials is shown in table I (ref. 2). Balsa is found in various densities ranging from

TABLE I. - PROPERTIES OF CRUSHABLE MATERIALS

[From refs. 1 and 2]

Material	Density, ρ_b, lbm/ft^3	Energy absorbed, ft-lbf/lbm
Styrofoam T-22	1.5	2 500
Styrofoam T-33	1.85	1 800
Styrofoam HD-1	3.0	2 000
Styrofoam HD-2	4.5	4 000
Eccofoam S	10.0	2 120
Epoxy foam	4.0	1 825
Epoxy foam with dowel pins	6.8	3 900
Aluminum honeycomb	8.0	11 000
Balsa	6-14	24 000
Steel honeycomb	- -	27 000

6 lb/ft^3 to 14 lb/ft^3. Its capability to absorb energy per unit volume is approximately proportional to its density according to the equation (ref. 2)

$$K_v = 24\ 000\ \rho_b \qquad (1)$$

where ρ_b = the balsa density in lbm/ft^3. This capability to absorb energy is reduced when the wood is crushed at some angle other than along the grain. The absorption efficiency ϵ is shown in figure 2 (ref. 2).

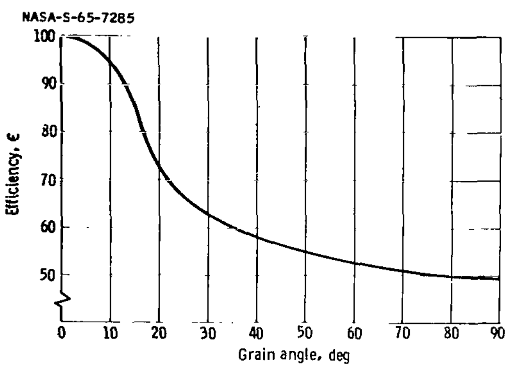


Figure 2. - Balsa absorption efficiency.

The Jet Propulsion Laboratory found experimentally that the crushing stress of the balsa is maximum in a direction parallel to the wood grain and is proportional to its density by the approximate relationship (ref. 2):

$$\sigma_c = 153\ \rho_b \qquad (2)$$

This stress is independent of strain until the wood is compressed to 20 percent of its original volume. At this point, "bottoming" occurs, and further strain produces a sharp increase in stress.

Balsa Efficiency

When the shape of the balsa package is spherical, the geometry of the balsa plays an important role in the overall efficiency of the crushed volume. For small values of Θ, shown in figure 1, most of the crushed balsa fibers lie approximately in the direction of crushing. However, for larger angles, much of the balsa grain lies at an angle with the crushing direction, thus decreasing the overall efficiency. In order to determine the overall efficiency as a function of the angle Θ a differential averaging technique was used.

A differential volume was chosen such that the fibers of that volume lie at a constant angle with the crushing direction X. This volume, shown in figure 3, is a shell of a conical frustrum with its axis of symmetry along the X-axis. The volume of this differential element was found to be

$$\Delta V = \frac{\pi R}{3}\left(\cos\theta - \cos\Theta\right)\left(R^2 + rR - r^2\right)\sin 2\theta\Delta\theta \qquad (3)$$

The average efficiency is found by the equation

$$\eta = \frac{\sum_{j=0}^{n} \epsilon_j \, \Delta V_j}{\sum_{j=0}^{n} \Delta V_j} \tag{4}$$

The results of equation (4) are shown in figure 4. This curve considers only the directional effects of crushing the balsa spnere.

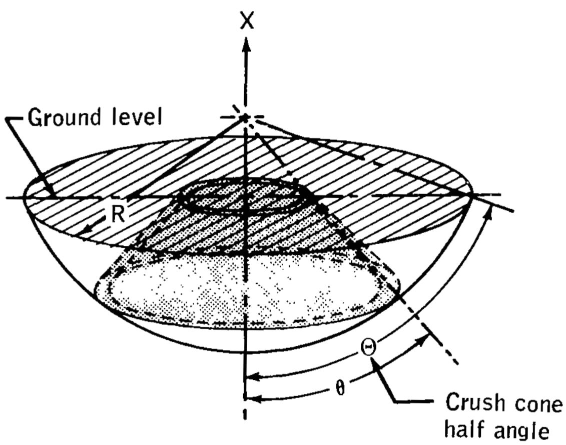


Figure 3. - Incremental crushed volume.

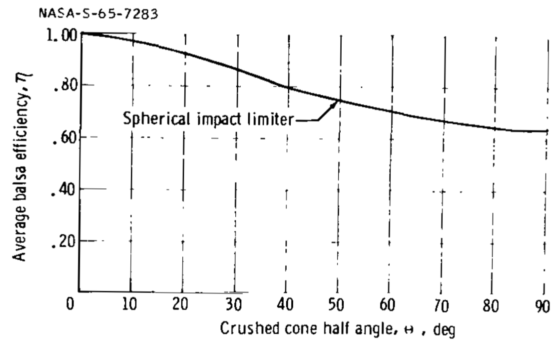


Figure 4. - Average balsa efficiency.

Balsa Crushing Fraction

The crushing fraction is defined as the ratio of the crushed balsa volume to the total balsa volume. For thin balsa shells, the lens-shaped volume crushed is a very small part of the total balsa volume. For such a shape, the crushing fraction is small. The maximum fraction possible is 0.50 for the limiting case in which r is small with respect to R and Θ is 90°. The volume of the crushed lens is expressed by

$$V_{cb} = \frac{3}{2}\pi\left(R^3 - \frac{3}{2}R^2 r + \frac{1}{2}r^3\right) \tag{5}$$

The total volume is

$$V_{tb} = \frac{4}{3}\pi\left(R^3 - r^3\right) \tag{6}$$

The crushing fraction is the ratio of these two volumes

$$C = \frac{V_{cb}}{V_{tb}} = \frac{\frac{3}{2}\pi\left(R^3 - \frac{3}{2}R^2 r + \frac{1}{2}r^3\right)}{\frac{4}{3}\pi\left(R^3 - r^3\right)} \tag{7}$$

If the ratio of the radii is defined as

$$\frac{R}{r} = \phi$$

then the crushing fraction can be expressed as

$$C = \frac{\phi^2 - \frac{1}{2}\phi - \frac{1}{2}}{2\left(\phi^2 + \phi + 1\right)} \tag{8}$$

Note that $\phi = \sec\Theta$

Therefore equation (8) can be expressed as

$$C = \frac{\sec^2\Theta - \frac{1}{2}\sec\Theta - \frac{1}{2}}{2\left(\sec^2\Theta + \sec\Theta + 1\right)} \tag{9}$$

This equation is plotted in figure 5.

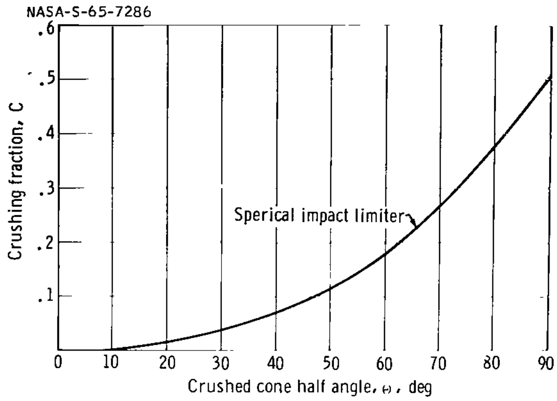


Figure 5. - Crushing fraction relationship.

In an actual design, the total lens shown cannot be crushed because of the bottoming effect. Since the bottoming effect is constant, it will be compensated for in later calculations.

Shock Loading

The highest possible shock loading on the payload occurs when the entire lower one-half of the payload sphere is subjected to the balsa crushing stress, assuming no bottoming occurs. In this case, the force on the sphere is

$$F = W_{pl} n = \sigma_c A \tag{10}$$

Equation (10) can be combined with equation (2) to derive

$$r^2 = \frac{W_{pl} n}{153 \rho_b \pi} \tag{11}$$

A range of radii is available by using various balsa densities. If a radius is needed smaller than those on the range, a density of 14 lb/ft^3 is used.

Skin Weight

An aluminum skin is used to keep the balsa from breaking up. Aluminum was selected because of its high strength-to-weight ratio and its good fabrication qualities. Good quality, high-strength aluminum has a strength-to-weight ratio of about 600 000 $psi/lb/in.^3$ This value was used in the analysis. This aluminum skin reacts to cancel the tensile tangential stress in the balsa and prevents splitting along the grain. It is assumed that only the uncrushed portion of the lower half of the skin is stressed. It must react to the force caused by the compressive, crushing stress on the lower half of the payload sphere. The force is

$$F = \text{stress} \times \text{area}$$

$$F = \sigma_c \frac{\pi r^2}{2} \tag{12}$$

The reactive force is equal to the maximum tensile stress in the aluminum skin times the cross-sectional area of the lower half of the skin.

$$F = \sigma_s \pi R \left[1 - \frac{2}{\pi} \cos^{-1}\left(\frac{r}{R}\right)\right] \tag{13}$$

By equating these two forces and rearranging the terms, the required skin thickness can be determined.

$$t = \frac{\sigma_c r^2}{\sigma_s 2 R \left[1 - \frac{2}{\pi} \cos^{-1}\left(\frac{r}{R}\right)\right]} \tag{14}$$

The skin weight is

$$W_s = \text{Surface area} \times \text{Thickness} \times \text{Density}$$

or

$$W_s = 4\pi R^2 t \rho_s \tag{15}$$

If equation (15) is combined with equation (11), the following expression is obtained

$$W_s = \frac{2\rho_s nRW_{pl}}{\sigma_s\left(1 - \frac{2\Theta}{\pi}\right)\Theta} \tag{16}$$

Balsa Volume

The volume of balsa which must be crushed in order to absorb the impact is described by the equation

$$V_{cb} = \frac{\text{Kinetic energy}}{K_v} \times \frac{\text{Factor of safety}}{\eta} \tag{17}$$

Kinetic energy is $\frac{1}{2}W_t \frac{V_i^2}{g_0}$ in ft-lb.

The factor of safety compensates for three effects. A factor of 1.25 is allowed for the bottoming effect. A factor of 1.2 is allowed to compensate for glued joints in the balsa, and 1.18 is allowed for reduced balsa efficiency at high impact velocities (ref. 2). The total factor of safety is 1.77. The total balsa weight is

$$W_b = \frac{V_{cb}\rho_b}{C}$$

$$= 3.69 \times 10^{-5} W_t \frac{V_i^2}{g_0 \eta C} \tag{18}$$

The payload weight is

$$W_{pl} = W_t - W_b - W_s$$

$$W_{pl} = \left[1 - \frac{3.69 \times 10^{-5}\ V_i^2}{g_0 \eta C}\right] W_t - \frac{2\rho_s\ nR\ W_{pl}}{\sigma_s\left(1 - \frac{2\Theta}{\pi}\right)} \tag{19}$$

$$\frac{W_t}{W_{pl}} = \frac{1 + \dfrac{2\rho_s nR}{\sigma_s\left(1 - 2\frac{\Theta}{\pi}\right)}}{1 - \dfrac{3.69 \times 10^{-5} V_i^2}{g_0 \eta C}} \tag{20}$$

The total weight divided by the payload weight, or normalized weight, obtained from equation (20), is shown in figure 6(a). By combining equation (20) with equation (17), the balsa volume is obtained.

$$V_{cb} = \frac{\left[1 + \dfrac{2\rho_s nR}{\sigma_s\left(1 - \frac{2\Theta}{\pi}\right)}\right]}{\left[1 - \dfrac{3.69 \times 10^{-5} V_i^2}{g_0 \eta C}\right]} \times \frac{153\pi r^2 \times 1.77 \times \frac{1}{2} V_i^2}{g_0 \eta \times 24\ 000 n} \tag{21}$$

By rearrangement, equation (21) can be rewritten in cubic feet as

$$V_{cb} = \frac{\left[1 + \dfrac{2\rho_s nR}{\sigma_s\left(1 - \dfrac{2\Theta}{\pi}\right)}\right] \times 0.551 \times 10^{-3} r^2}{\left[\dfrac{1}{V_i^{-2}} - \dfrac{1.145 \times 10^{-6}}{C\eta}\right] n\eta} \tag{22}$$

or, in cubic inches, as

$$V_{cb} = \frac{\left[1 + \dfrac{2\rho_s nR}{\sigma_s\left(1 - \dfrac{2\Theta}{\pi}\right)}\right] \times 0.952 r^2}{\left[\dfrac{1}{V_i^{-2}} - \dfrac{1.145 \times 10^{-6}}{C\eta}\right] n\eta} \tag{23}$$

This volume can also be expressed geometrically

$$V_{cb} = \frac{4}{3}\pi\left(R^3 - r^3\right)C \tag{24}$$

$$V_{cb} = \frac{4}{3}\pi\left(\phi^3 - 1\right)Cr^3 \tag{25}$$

By combining equations (23) and (25) the following expression can be obtained

$$\frac{1}{V_i^2} = \frac{1}{C}\left\{\frac{1.145 \times 10^{-6}}{\eta} + \frac{\dfrac{0.2272}{n}\left[1 + \dfrac{2\rho_s nR}{\sigma_s\left(1 - \dfrac{2\Theta}{\pi}\right)}\right]}{r\left(\phi^3 - 1\right)}\right\} \tag{26}$$

If equation (8) is substituted into this expression the following equation is obtained

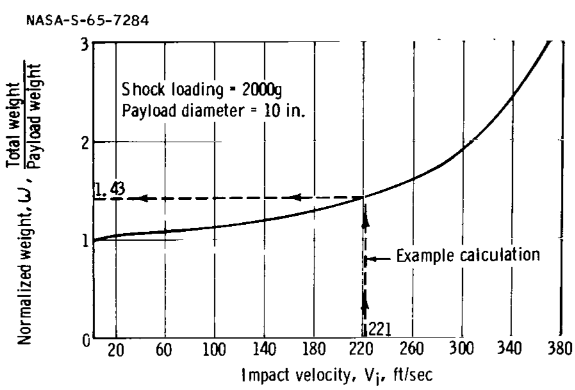
$$\frac{1}{V_i^2} = \frac{1}{\frac{1}{2}\left(\phi^3 - \frac{3}{2}\phi^2 + \frac{1}{2}\right)\eta}\left\{1.145 \times 10^{-6}\left(\phi^3 - 1\right) + 0.2272\left[\frac{1}{nr} + \frac{2\rho_s n\phi}{\sigma_s\left(1 - \frac{2\Theta}{\pi}\right)}\right]\right\} \tag{27}$$

or

$$V_i = \sqrt{\frac{\left(\phi^3 - \frac{3}{2}\phi^2 + \frac{1}{2}\right)\eta}{0.4544\left[\frac{1}{nr} + \frac{2\rho_s\phi}{\sigma_s\left(1 - \frac{2\Theta}{\pi}\right)}\right] + 2.290 \times 10^{-6}\left(\phi^3 - 1\right)}} \tag{28}$$

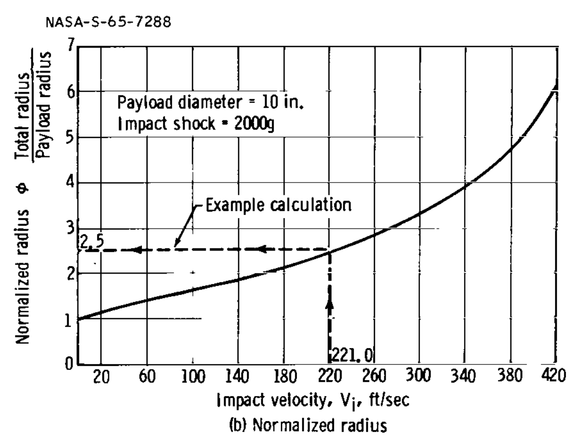
The results of equation (28) are plotted in figure 6(b).

These two example curves in figure 6(a) and 6(b) assume a maximum impact shock loading of 2000g and a payload diameter of 10 inches.



(a) Normalized weight

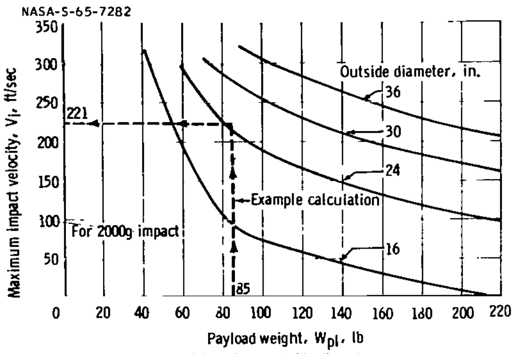
Figure 6. - Balsa requirement.



(b) Normalized radius

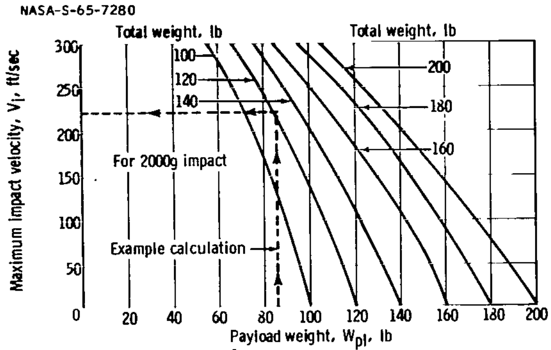
Figure 6. - Concluded.

If the most compact package is assumed, that is, with a balsa density of 14 lb/ft^3, then equations (20) and (28) can be combined with equation (11) to obtain the relationship shown in figures 7(a) and 7(b).



(a) Various outside diameters.

Figure 7. - Impact limit velocity restrictions.



(b) Various total weights

Figure 7. - Concluded.

RESULTS AND DISCUSSION

The curves resulting from the foregoing analysis are an aid in the design of impact limiters. They are also useful in determining the range of velocities which are compatible with balsa impact limiters.

A noticeable aspect of the curves is the sharp increase in balsa weight and diameter requirements at higher velocities (figs. 6(a) and 6(b)). The maximum allowable impact velocity of 530 ft/sec, represented by the asymtote of curves in figures 6(a) and 6(b), occurs when the kinetic energy of the total package before impact is equal to the total energy which the balsa can absorb.

Above this velocity a balsa impact limiter will not absorb all of the impact energy regardless of the amount of balsa used. There is a practical limit to velocity, however, much less than the maximum. This practical limit is determined by reasonable values of weight or diameter.

Examples of curves representing some of these restrictions are shown in figures 7(a) and 7(b). With the aid of these curves, a conceptual designer may specify reasonable values of impact velocity. This maximum velocity may then be used to design a delivery system. Figure 7(a) assumes a balsa density of 14 lb/ft^3 which gives the smallest size package. An example calculation is given below:

A payload is designed which weighs 85 pounds and can withstand 2000g. A total diameter of 25 inches is available. The maximum impact velocity is desired.

The most compact payload is obtained with a balsa density of 14 lb/ft^3. The required payload diameter obtained from equation (10) (fig. 8) is 10 inches. Figure 6(b) (eq. (28)) gives the maximum velocity of 221 ft/sec.

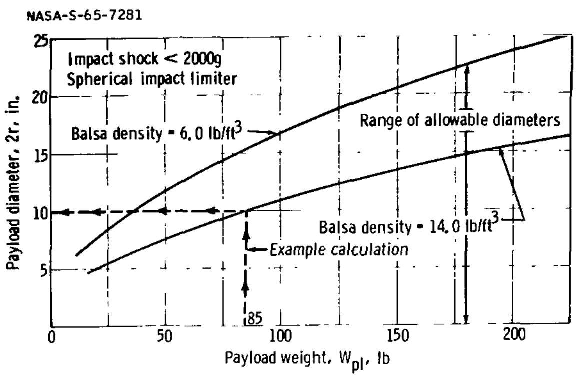


Figure 8. - Payload diameter restrictions.

Figure 6(a) (eq. (22)) shows that the total package weight will be 1.43 times the payload weight or 122 pounds. The same information can be obtained in more convenient form from figures 7(a) and 7(b). By entering figure 7(a) at 85 pounds and moving to the constant diameter line of 25 inches (interpolate), a maximum velocity of 221 ft/sec is obtained. From Figure 7(b) a payload weight of 85 pounds and a maximum velocity of 221 feet intersect at a total payload weight of 122 pounds.

It is thought that the curves and equations presented in this paper are accurate to a velocity of about 300 ft/sec. They are limited by the lack of experimental data describing the properties of balsa at higher velocities. Refinement of these equations for high velocities is possible should more data become available. However, it appears from this analysis that at these higher velocities, the practicality of balsa impact limiters is questionable.

CONCLUDING REMARKS

Some very strong restrictions are imposed on the designer of spherical impact limiters for hard-landed experimental packages. The most serious of these is the maximum allowable impact velocity inherent in the limiter material. This limiting condition occurs when the kinetic impact energy of the limiter and its energy absorption capability are equal. For spherical balsa limiters the limiting velocity is about 530 ft/sec. However, there are practical considerations which limit impact velocity before this ultimate is reached. Two of these considerations are limiter weight and volume. For example, it is not practical to design an experimental package for hard landing in which the limiter weighs many times more than the useful payload. This is shown by the increasing slope at higher velocities of the balsa requirement curves.

The designer of packages to be hard-landed must consider, in addition to velocity restrictions, limitations on the size of the useful payload. The package should be as compact as possible to prevent excessive shock loading on its internal components. This restriction is caused by the minimum available impact limiter crushing strength. This minimum crushing strength dictates the minimum useful payload density allowed.

The analysis presented in this paper is one step further toward the complete solution of spherical impact limiters. Previous analysis was adequate for low impact velocities. The analysis presented herein is useful for intermediate velocities. Further refinement could extend the usefulness of the equations to the upper limit. These refinements would include consideration of the stopped-mass effect and better experimental data on the impact limiter material. As shown by the analysis presented, however, balsa impact limiters become so impractical at velocities near the limit that it is doubtful that further refinement would be of value. More valuable advance in impact limiter technology will be the development of better limiter materials.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, September 28, 1965

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