

## A COMPARISON OF REGULATORY IMPACTS TO REAL TARGET IMPACTS

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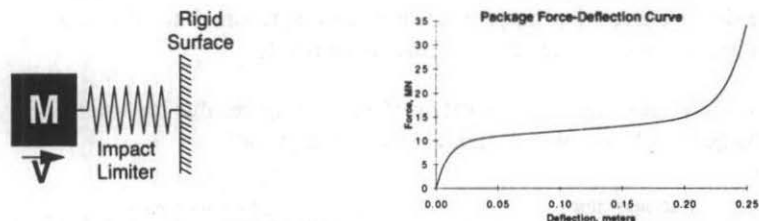
### INTRODUCTION

The purpose of this paper is to discuss the relative severity of regulatory impacts onto an essentially rigid target to impacts at higher velocities onto real targets. For impacts onto the essentially rigid target all of the kinetic energy of the package is absorbed by deformation of the package. For impacts onto real targets the kinetic energy is absorbed by deformation of the target as well as by deformation of the package. The amount of kinetic energy absorbed by the target does not increase the severity of the impact.

### METHOD

The method used for this comparison has been discussed in previous papers by the author (Ammerman 1992a, 1992b). The work in these previous papers was aimed at surface transport packages, and therefore the velocity used for impacts onto an essentially rigid target was the impact velocity for a Type B package, 13.4 m/s. For Type C packages the IAEA proposed impact velocity is 90 m/s. For the analyses in this paper it will be assumed that the design philosophy for Type C packages is the same as that for Type B packages, where the containment boundary remains essentially elastic, and absorbs very little of the impact energy. It will be assumed therefore, that all of the impact energy absorbed by the package is absorbed by the impact limiter, and the containment boundary will be treated as rigid.

With this assumption, the collision onto the rigid target can be conceptualized as a single degree of freedom spring-mass model. The energy absorbed by the impact limiter is equal to the integral of the force-deflection curve for the impact limiter. Figure 1 shows a schematic view of this type of system and the associated force-deflection curve for a hypothetical Type C package. The mass in the figure is the total mass of the containment vessel plus impact limiter.



**Figure 1:** Simplified spring-mass model for impacts onto rigid targets and associated force-deflection curve for a hypothetical Type C package.

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When the impact is onto a real target, part of the impact energy is absorbed by deformation of the target. The energy absorbed by the target is equal to the integral of the force-deflection curve for the target. At all times the force acting on the impact limiter is equal in magnitude to the force acting on the target. This situation can be conceptualized as spring-mass system with two springs in sequence. The first spring represents the target and the second spring represents the impact limiter. Figure 2 shows a schematic view of this system and the associated force-deflection curves for a hypothetical package and a hypothetical target.

The principle of conservation of energy can be applied to both of these two systems to determine the amount of strain energy in the springs. Immediately before the impact the energy of the package and target is equal to the kinetic energy of the package. At the point of maximum deformation of the package and the target the velocity is zero, so all of the energy in the system is strain energy. For impacts onto a rigid target the strain energy of the system is all in the package. During an impact with a real target the strain energy of the system is in both the package and the target.

The strain energy in each of the springs for a given displacement is equal to the area under the force-deflection curve up to that displacement. For a linear spring this results in the familiar equation  $E = 1/2K\delta^2$ , where  $E$  is the strain energy in the spring,  $K$  is the linear spring constant, and  $\delta$  is the displacement of the spring. For a non-linear spring with a force-deflection relationship defined by  $F(x)$ , equation 1 shows the mathematical expression for the strain energy:

$$E = \int_0^{\delta} F(x) dx \quad (\text{EQ 1})$$

Where:

$E$  = The strain energy in the spring.

$F(x)$  = The force in the spring as a function of displacement.

$x$  = The displacement of the spring.

$\delta$  = The displacement of the spring at the force level of interest.

If the force-deflection relationships are not defined by equations, but rather as a series of points, the integration in equation 1 can be performed numerically.

For impacts onto rigid targets, conservation of energy requires that the strain energy absorbed by the package must be equal to the initial kinetic energy, or:

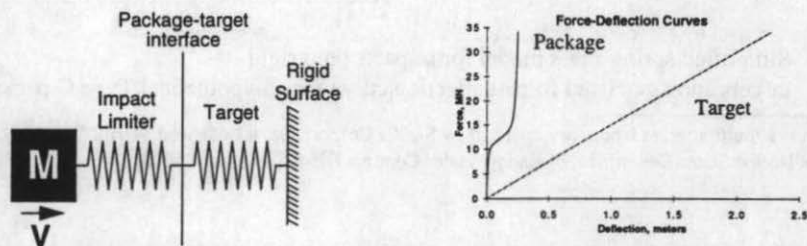


Figure 2: Simplified spring-mass model for impacts onto real targets and associated force-deflection curves for hypothetical package and target.

$$E_p = \frac{1}{2}MV_R^2 \quad (\text{EQ 2})$$

Where:

$E_p$  = The strain energy in the package.

$M$  = The total mass of the package.

$V_R$  = The impact velocity onto the rigid target (90 m/s for Type C packages).

When the impact takes place onto a yielding target the total kinetic energy must equal the strain energy absorbed by the package plus the strain energy absorbed by the target, or:

$$E_p + E_t = \frac{1}{2}MV_y^2 \quad (\text{EQ 3})$$

Where:

$E_t$  = The strain energy in the target.

$V_y$  = The impact velocity onto the yielding target.

Solving these two equations for  $V_y$  gives:

$$V_y = \sqrt{V_R^2 + \frac{2E_t}{M}} \quad (\text{EQ 4})$$

From equation 4 it can be seen the velocity for an impact onto an yielding target that causes the same level of damage to the package as an impact onto the rigid target increases when the amount of energy absorbed by the target increases, which is intuitive.

### EXAMPLE PROBLEM

To illustrate how this method can be used to generate velocities for impacts onto real targets that result in the same level of damage to the package as the regulatory velocity onto a rigid target the following example will be used. The impact of a 500 kg hypothetical Type C package onto a rigid target at 90 m/s has a kinetic energy of 2.025 MJ. The hypothetical package being considered has the force-deflection curve given in Figure 1. Integrating this curve with respect to displacement results in the energy absorbed up to a given displacement. This energy-displacement curve is shown in Figure 3, from which it can be seen the displacement corresponding to 2.025 MJ is about 0.18 meters. Combining the data from this curve with that from Figure 1 results in a relationship between the energy absorbed by a package and the force acting on the package. This curve is shown in Figure 4. For an impact target with the force-deflection characteristics shown in Figure 2 a similar procedure can be followed and the resulting energy-force curves for the package, the target, and the total system can be plotted as shown in Figure 5. At the kinetic energy level for the regulatory impact (2.025 MJ) it can be seen from Figure 5 that the force at the package target interface is about 14 MN. At this level of force the target absorbs 6.4 MJ of energy, for a total system energy absorption of 8.4 MJ. The impact velocity required to give this level of kinetic energy is 183 m/s, or slightly more than double the regulatory velocity. Examining the force-deflection curve for the target in Figure 2 shows the amount of target deformation is about 0.93 meters. This is consistent with the penetration distance observed from high-speed impacts onto hard prairie soil by packages of

about this size (Bonzon and Schamaun 1976). In summary, a package system impacting hard prairie soil at a velocity of 183 m/s yields the same force on the containment boundary as if the package had impacted an unyielding target at a velocity of 90 m/s.

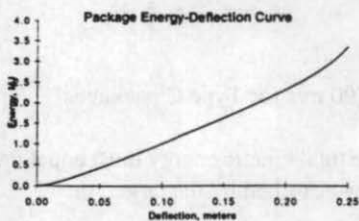


Figure 3: Strain energy absorbed by the package as a function of impact limiter crush distance.

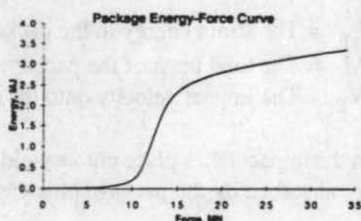


Figure 4: Strain energy absorbed by the package as a function of target contact force.

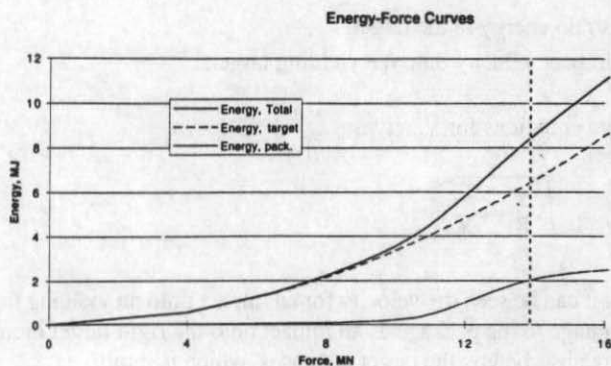
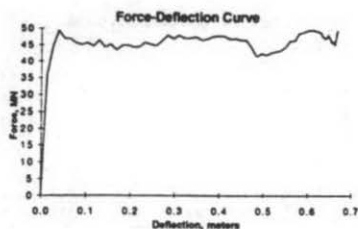


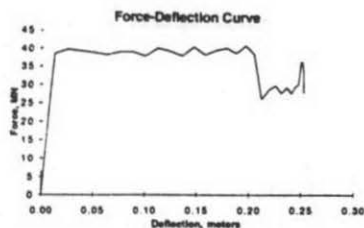
Figure 5: Energy-force curves for example package/target system for impacts onto a non-rigid target.

## REAL PACKAGES

Several radioactive material transportation packages have been designed to withstand the forces generated by high-speed impacts, such as those that would result from an airplane crash. In the United States packages for the air transport of plutonium are designed to withstand impacts of 129 m/s onto an essentially rigid target as specified in 10CFR71 (U.S. NRC 1996). Currently there are only two packages that meet this requirement, the PAT-1 and PAT-2. However, there are several packages in development that are designed to survive this impact (Pierce 1994). Figure 6 shows force-deflection curves for two of these packages that were derived from finite element analysis of end-on impacts at 129 m/s onto rigid targets. The package with the wire mesh impact limiting material has a total package mass of 2816 kg and a 1.8 m diameter. The package with the perforated aluminum sheet impact limiting material has a total package mass of 842 kg and a 0.7 m diameter. Both of these packages have a constant-force crush region of about 43 MN. This value is well above the force for the example package from Figure 1. Integrating the force-deflection curves of Figure 6 and combining the resulting energy-deflection relationship with the original force-deflection curves gives the energy-force curves shown in Figure 7. For a 90 m/s impact onto an unyielding target the amount of energy that must be absorbed by the package with wire mesh impact limiting material is 11.4 MJ. For the package

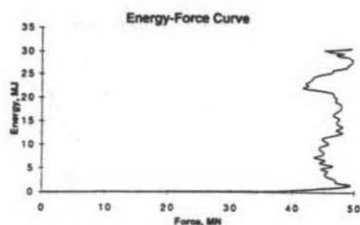


Package with wire mesh impact limiting material.

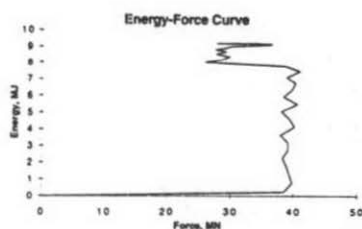


Package with perforated aluminum plate impact limiting material.

**Figure 6:** Force-deflection curves for air transport packages currently being developed. These curves were derived from finite element analysis of impacts at 129 m/s onto a rigid target.



Package with wire mesh impact limiting material.

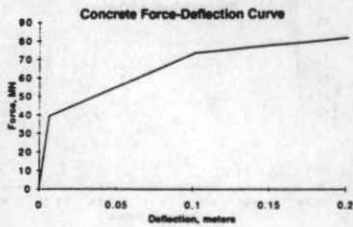


Package with perforated aluminum plate impact limiting material.

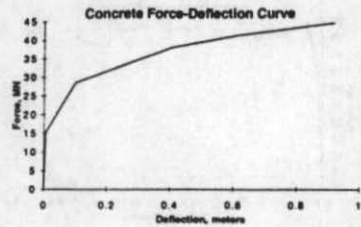
**Figure 7:** Energy-force curves for air transport packages currently being developed. These curves were derived from finite element analysis of impacts at 129 m/s onto a rigid target.

with perforated aluminum plate impact limiting material the amount of energy is 3.4 MJ. For both of these packages the 90 m/s impact take them into the constant force region of the force-deflection curve, or a force of about 47 MN for the wire mesh package and 39 MN for the perforated aluminum plate package. If these packages impact onto a real target, such as a concrete runway, the target will also absorb some of the energy. Because the two packages have different diameters the force-deflection curves for the concrete runway target will be different for the two cases. Figure 8 shows force-deflection curves for concrete runways that were derived from impact tests performed at Sandia (Gonzales 1987) for these two package diameters. These force-deflection curves yield the energy-force curves shown in Figure 9.

For the force levels listed above, it can be seen from Figure 9 that the target will absorb about 1.35 MJ for the wire mesh package impact and about 14.6 MJ for the perforated aluminum plate package impact. Adding the target deformation energy to the energy absorbed by the package and calculating the velocity required to generate this amount of kinetic energy results in an impact velocity onto a concrete runway of 95.2 m/s for the wire mesh package and 207 m/s for the perforated aluminum plate package to produce similar damage to the package as the 90 m/s impact onto a rigid target.

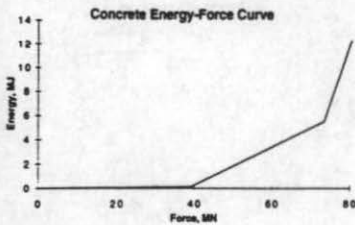


Concrete force-deflection curve for the wire mesh package (1.8 m diameter).

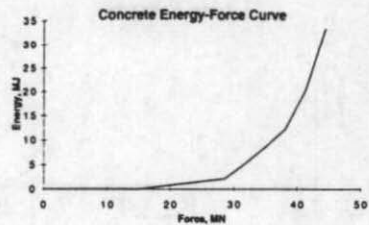


Concrete force-deflection curve for the perforated aluminum plate package (0.7 m diameter).

**Figure 8:** Force-deflection curves for concrete runways when impacted by a Type C radioactive material transportation package.



Concrete energy-force curve for the wire mesh package (1.8 m diameter).



Concrete energy-force curve for the perforated aluminum plate package (0.7 m diameter).

**Figure 9:** Energy-force curves for concrete runways when impacted by a Type C radioactive material transportation package.

Using a similar procedure for a hard prairie soil target gives equivalent impact velocities of 179 m/s for the wire mesh package and 400 m/s for the perforated aluminum plate package. The results from these analyses are summarized in Table 1. From this table it can be seen that package stiffness plays an important role in determining the velocity for impacts onto real targets that result in the same damage to the package as the regulatory impact onto the unyielding target. For both targets the impact velocity to produce equivalent damage for the perforated aluminum plate package is much greater than that for the wire mesh package.

The concrete runway target used in this example is more rigid than most real targets, and for the wire mesh package behaves nearly the same as a rigid target. The hard prairie soil target absorbs much more energy than the package for the same force level, and the resulting equivalent damage impact velocity is much higher than the regulatory 90 m/s impact velocity.

## COMPARISON WITH FLIGHT RECORDER IMPACT TESTS

Flight recorders are required to withstand an impact characterized by a half-sinusoidal pulse with a duration of 6.5 milliseconds and an amplitude of 3400 gs (EUROCAE 1993). This acceleration pulse is equivalent to an impact velocity of 138 m/s and a displacement of 0.448 meters. This impact velocity is higher than the impact velocity for Type C containers, but the peak acceleration is of similar magnitude to that seen by air transport packages. The reason for

**Table 1: Parameters and resulting velocities for impacts onto real targets**

Parameter, units	Wire Mesh Package	Perforated Aluminum Plate Package
Mass, kg	2816	842
diameter, meters	1.8	0.7
$KE_{\text{rigid}}$ , MJ	11.4	3.4
Force, MN	47	39
Acceleration, g	1700	4700
$E_{\text{runway}}$ , MJ	1.4	14.6
$E_{\text{total, runway}}$ , MJ	12.8	18.0
$V_{\text{runway}}$ , m/s	<b>95</b>	<b>207</b>
$E_{\text{soil}}$ , MJ	33.8	63.9
$E_{\text{total, soil}}$ , MJ	45.2	67.3
$V_{\text{soil}}$ , m/s	<b>179</b>	<b>400</b>

this is that most air transport packages do not have 0.448 meters of crush distance, so the impact event takes place over a shorter period of time. In the previous example, the crush distance of the wire mesh package for a 90 m/s impact onto a rigid target is 0.26 meters and the crush distance of the perforated aluminum plate package is only 0.094 meters. Using the simplified spring-mass method discussed here the wire mesh package would have an acceleration level of 1700 gs and the perforated aluminum plate package would have an acceleration level of 4700 gs. Both of these impacts would have durations shorter than 6.5 milliseconds.

## LIMITATIONS

To apply the method described in this paper for relating impacts with yielding targets to impacts with a rigid target the user must know the load-displacement properties of the target as well as the package. For many targets, such as vehicles and posts, the amount of energy they can absorb before failing is finite. In these cases, if the impact kinetic energy is greater than the energy absorbed by the package and target at the time the target fails, the package will not be stopped by the impact and will have a residual kinetic energy.

Modeling the package and the target as massless springs implies that the impact event is one-dimensional and quasistatic. At the interface between the package and the target it is quite likely that loads in the transverse direction will cause crushing of either the impact limiter or the target, and will result in some energy absorption. This fact will tend to reduce the severity of the impact on the yielding target compared to the impact modeled as one dimensional crush. Severe impact tests on small packages (Bonzon and Schamaun 1976) showed this result by differences in failure mode. Impacts onto soil targets that had deformations of the package similar to lower velocity impacts onto an unyielding target did not result in gross failure of the containment boundary, while the impacts on the unyielding target did. This result could also be caused by higher strain rates for the impacts onto the unyielding target. The change in failure mode caused

by transverse forces or strain rate effects is impossible to model as an impact onto an unyielding target at a lower velocity. The method of this paper considers the impact onto the yielding target to be more severe than it actually is. For the purpose of risk assessments or hazard communications this result is conservative.

## CONCLUSIONS

The Type C impact of 90 m/s onto an essentially rigid target has been compared to impacts onto real targets at higher velocities. For some air transport packages it is possible to have real targets, such as very strong concrete runways, that do not absorb much of the impact energy. For these package/target combinations the resulting impact velocity is nearly identical to the rigid target velocity. However, for a wide range of packages and targets there is a substantial increase in impact velocity required to produce damage that is equivalent to the damage from the regulatory impact. For the three examples given here with impacts onto hard soil targets the velocity required to give equivalent damage to the package as that from the regulatory 90 m/s impact ranges from 179 m/s to 400 m/s. The stiffer of the proposed air transport packages investigated here also required an impact velocity of 207 m/s onto the concrete runway target to yield damage that is equivalent to the damage in the regulatory impact.

Comparison of the Type C impact requirement to the requirement for flight recorders shows the two are very similar. For some packages the flight recorder requirements are more severe and for others the Type C requirements are more severe. In nearly all aircraft impacts the flight recorders are recovered. A similar result is expected for radioactive material packages designed to meet the Type C requirements.

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