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EVALUATING TYPE B PACKAGE RESPONSE TO IMPACTS ONTO DIFFERENT TARGETS

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ABSTRACT

The IAEA regulations for the safe transport of radioactive materials require a 9-meter free drop onto an unyielding target to demonstrate the robustness of the package to accident loads. This drop results in an impact velocity of 13.3 m/s (30 MPH), which is considerably lower than typical transport speeds for both truck and rail. This leads to the concern that the regulatory impact is not sufficiently severe to assure protection of the public and environment. Sandia National Laboratories and others have conducted both experimental and analytical research in the attempt to demonstrate the severity of the 9-meter impact onto an unyielding target by comparing this impact with higher velocity impacts onto other types of targets. Targets investigated have included soil, concrete roadways, concrete runways, bridge columns, sand, water, and other transportation vehicles. Impact velocities have ranged up to 110 m/s (246 MPH) Two important conclusions can be drawn from this body of research: 1) the hardness of a yielding target depends on the stiffness of what is impacting it and 2) that for most target types and most radioactive material packages the regulatory impact encompasses nearly all "real" impacts.

This paper will provide an overview of past research in the area of impacts onto yielding targets. A methodology for comparing these impacts to the regulatory impact will be presented and several examples will be given.

INTRODUCTION

The description of the regulatory impact accident condition in both the U.S. and international regulations is very specific. It requires a drop from a height of 9 meters onto a flat horizontal essentially unyielding target in the orientation that is most likely to cause package damage. With this description, the impact test is well defined and very repeatable, even at test facilities that are on different continents. This description also makes determination of package response by analysis very convenient, as there is no need to include deformation of the impact surface in the calculations—they can be assumed to be ideally rigid (note that this makes the analysis slightly conservative because no physical target is absolutely unyielding). However, the removal of the deformation of the target from the impact accident makes it complicated when trying to compare

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the regulatory hypothetical accident impact to actual accidents where a significant amount of the impact energy is absorbed by deformation of the target. There are two types of energy that are involved in an impact: the kinetic energy of the impacting body(ies), and the strain energy (absorbed energy) in the package and target. In the regulatory accident there is no strain energy absorbed by the target and the absorbed energy of the package is equal to the initial kinetic energy (even the kinetic energy associated with rebound is eventually absorbed during subsequent impacts). In actual accidents the absorbed energy of the target is not zero, and the strain energy absorbed by the package is less than the initial kinetic energy. However, only the strain energy absorbed by the package is associated with damage to the package. The job of the radioactive material transportation community when attempting to compare the regulatory impact to real accidents is to calculate the portion of the accident kinetic energy that becomes absorbed energy in the package.

EARLY COMPARISON BETWEEN REGULATORY IMPACTS AND REAL TARGET IMPACTS

From the beginning of radioactive material transportation risk assessments it has been recognized that real accidents are less severe than the regulatory accident. In NUREG-0170 [1] a relationship was developed to relate these impacts based upon the theoretical indentation of a rigid sphere into an infinite half-space of other material. This relationship leads to Equation 1, where the only parameters needed are the elastic modulus and Poisson's ratio of the target of interest and steel.

$$V_{yielding} = V_{regulatory}\left[\left[\frac{1-\upsilon_y^{\,2}}{1-\upsilon_s^{\,2}}\right]\left[\frac{E_s}{E_y}\right]\right]^{1/3} \qquad \text{Eq. 1}$$

In this simplified approach the regulatory impact is assumed to be onto a steel target and there is no recognition of the factor that is played by the stiffness of the impacting object, which will be shown later in this paper to play a major role. However, for accidents where a relatively stiff package impacts a relatively soft target this relationship results in a fairly accurate representation of the velocity required to achieve an equivalently severe impact. For example, if the impact is into a concrete target with ν_y=0.2, E_y=3,400,000 psi, ν_s=0.3, and E_s=29,000,000 psi, Eq. 1 gives a velocity of 65 mph (29 m/s) as equivalent to the regulatory impact.

In the Modal Study [2], the next U.S. assessment of transportation risks, involving only spent fuel casks, the stiffness of the package was taken into account. In this study the equivalent velocity was represented by Equation 2, where d_s is the deformation of the yielding target caused by an impact of a rigid cask and d_c is the deformation of the real cask caused by the regulatory impact.

$$V_{yielding} = V_{regulatory}\sqrt{1+\frac{d_s}{d_c}} \qquad \text{Eq. 2}$$

Using this equation, the Modal study reports that a 55 mph end impact onto concrete (or soft rock) is equivalent to the regulatory impact for their representative rail cask.

ENERGY BASED COMPARISONS

During the early 1990s Ammerman reported a method to compare real target impacts to the regulatory impact based upon absorbed energy comparisons [3,4]. With this method the impact is modeled as a set of non-linear massless springs in series. One spring represents the cask body, another the impact limiter, and another the target. Because the springs are connected in series, the force in each spring is the same. The energy absorbed by each spring is equal to the integral of its force-deflection relationship; therefore, the force-deflection curve for each spring must be known or assumed. Using this method the relationship between yielding and regulatory impact velocities is represented by Equation 3, where E_t, E_c, and E_i are the energies absorbed by the target, the cask, and the impact limiter. For impacts onto large surfaces the total kinetic energy is equal to the sum of these three energies and for impact onto a rigid target E_t is zero.

$$V_{yielding} = V_{regulatory}\sqrt{1+\frac{E_t}{E_c+E_i}} \qquad \text{Eq. 3}$$

For the case of linear springs this equation and Eq. 2 are identical. Mills et. al [5] utilized this method in a comparison between regulatory and concrete target impacts to determine that for a UF_6 package a 46 mph impact onto a 6-inch thick concrete slab in the end-on orientation would be equivalent to the regulatory impact.

This method was also used in [4] to show the range of target stiffness (assuming a linear relationship between target force and target deflection) that is of importance for seven sample spent fuel casks, four for truck transport and three for rail. This showed that targets with stiffness higher than $1x10^9$ N/m behave as essentially rigid and that targets with stiffness lower than $1x10^6$ N/m cannot cause significant cask damage at any credible accident speed. Figure 1 shows the results for the three rail casks.

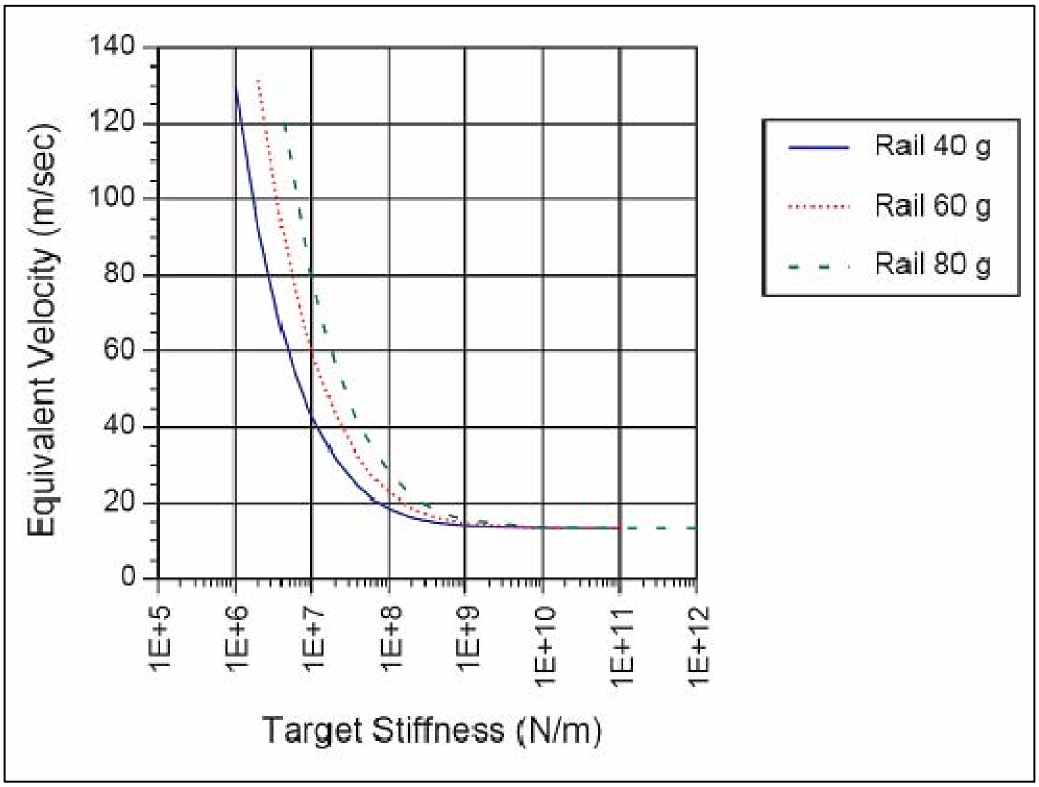

Figure 1 - Yielding target velocity that is equivalent to the regulatory impact test for three sample rail casks as a function of linear target stiffness

The most difficult part of using this method is developing the requisite force-deflection curves for the package (and impact limiter) and the target. The package response curve is generally available from the safety analysis report either from the results of physical testing or from finite element calculations. Target response can also be determined by physical tests or by analyses. A summary of the results from some of these types of tests are given in the following sections of this paper.

IMPACTS ONTO SOIL TARGETS

A companion paper at this conference [6] describes the helicopter drop test of the BE-83 and OD-1 casks. The BE-83 cask had a diameter of 62 cm, a length of 100 cm, and a mass of 3054 kg. This cask impacted the soil target in an essentially side-on orientation at a velocity of 110 m/s, resulting in a penetration of 2.44 m. The OD-1 cask had a diameter of 80 cm, a length of 120 cm, and a mass of 7410 kg. The cylindrical cask is welded to a 5-cm thick base plate that is 135x120 cm. This cask impacted the soil target with the base plate at a 30 degree angle at a velocity of 103 m/s, resulting in a penetration of 1.28 m. For both of these casks the high-speed impact onto hard soil was less severe than the regulatory impact onto an essentially rigid target. Another series of tests, conducted by Bonzon [7], involved an impact of an LLD-1 plutonium package (2R containment vessel in a outer container) with a mass of 34 kg at 206 m/s in a side-on orientation, three impacts of a 10-gallon 6M (2R containment vessel in a 38-cm diameter by 46-cm high drum with a mass of 25 kg) (128 m/s in a side-on orientation, 119 m/s in a corner orientation, and 231 m/s in a slapdown orientation), and an impact of a FL-10 package (steel pipe containment vessel in a 60-cm diameter by 175-cm high drum with a mass of 227 kg) at 142 m/s in a side-on orientation. In a series of tests conducted to determine target hardness effects, Gonzales [8] impacted a 50-cm diameter by 183-cm high test unit with a mass of 2500 kg into soil targets in an end-on orientation at velocities of 13.4, 20.1, and 26.8 m/s. These tests resulted in penetration depths of 48, 64, and 91 cm respectively. All of these impacts were onto hard desert soil in the Albuquerque, NM vicinity. This hard dry sandy soil with a small amount of clay requires a bar or pick to dig more than a few centimeters below the surface. Correlating these results to other soil types can be done by using the number of blows required to produce a penetration of 30 cm by a cone penetrometer. This hard soil requires 30 blows. Table 1 gives the number of blows for other soil types. Using the data from these tests, a general equation for a soil target force-deflection curve (Eq. 4) can be developed. In this equation D is the package diameter in meters, N is the number of blows required for a 30-cm penetration by a cone penetrometer, x is the displacement in meters, and F is the force in Newtons.

$$F = 33{,}300ND\left[18.85x^{0.922} - 4.92\left(e^{-4.92x} - e^{-9.84x}\right)\right] \qquad \text{Eq. 4}$$

For impact orientations other than end-on D must be replaced with an effective diameter. Engineering judgment must be used in determining the proper effective diameter. For cases with large penetration the effective diameter can be determined so that the area of the circular impact is equal to the projected area of the package.

Table 1 - Number of blows required to produce a 30-cm penetration

Soil Type	Number of Blows
Hard	30
Stiff	12
Medium	6
Soft	3

IMPACTS ONTO CONCRETE SLABS

The severity of an impact on a concrete target depends on the thickness of the concrete, the size and stiffness of the package, and the impact velocity. Gonzales' test series [8] also investigated impacts onto unreinforced concrete targets of two thicknesses. Using the same test unit design as for the soil targets, impacts of 13.4, 20.1, and 26.8 m/s onto a 46-cm thick concrete slab and impacts of 13.4 and 26.8 m/s onto a 23-cm concrete slab were performed. All of these impacts were less severe than the regulatory (13.4 m/s) impact onto an unyielding target.

Concrete targets resist penetration in two ways. First is by the shear stiffness of the concrete itself. After the concrete slab fails in shear, further penetration is resisted by the stiffness of the sub-grade material beneath the slab. The results from Gonzales' test indicate the force generated while creating the shear failure in the slab is a function of both the impact velocity and the slab thickness. This is because to generate the shear failure the concrete plug beneath the impact must be accelerated. For impacts other than end-on the concrete may fail in a mode other than by generation of a shear plug. Using energy principles for concrete failure it is possible to relate these other impact orientations to the simpler end-on orientation or Gonzales' tests.

IMPACTS BY VEHICLES

Not all impacts are onto large surfaces. In fact, most accidents involve impacts with other vehicles. For most RAM transportation packages impacts with smaller vehicles, such as cars and motorcycles, do not even come close to the severity of the regulatory test. For some packages it is possible that an impact with a truck could generate forces similar to those from the regulatory impact. Figure 2 shows a force-deflection curve for a tractor-trailer impact into a large concrete target at 24 m/s [5]. The peak force is about 6.5 MN. This is considerably less than the inertial force seen in the regulatory impact of most large packages. If a truck impacts a small package, such as a fissile material package, the contact area would be much less than the entire front of the truck and the resulting force would also be much less than what is shown in Figure 2.

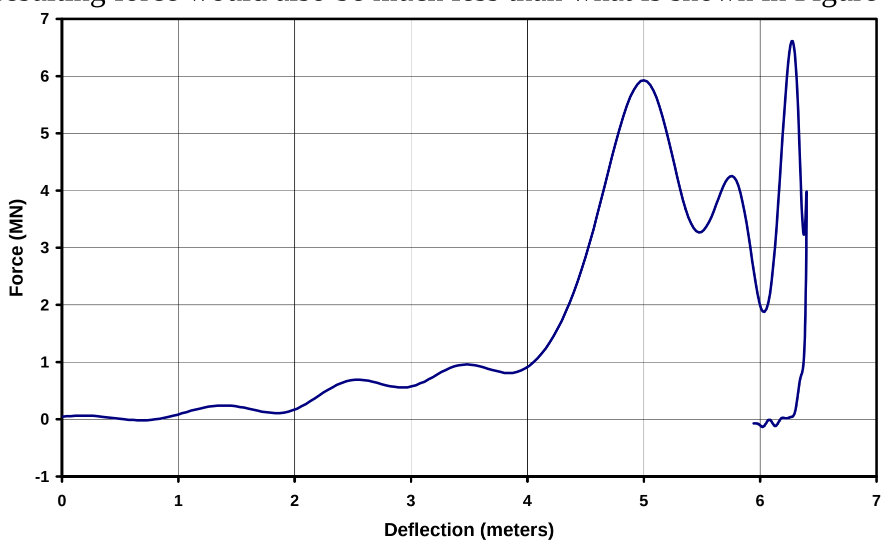

Figure 2 - Force-deflection curve from a 24 m/s impact of a tractor-trailer into a large concrete block

A vehicle impact that is more of a concern for many RAM packages is impact by a train. During the 1970s, Sandia performed a test of this type with a locomotive impacting a spent fuel cask on a flat-bed trailer at a speed of 81 mph [6]. The cask and locomotive positions were determined at each frame of the high-speed film. The cask position information was used to generate an acceleration time history. Multiplication of these accelerations by the mass of the cask gives a force time history. The difference in position between the cask and the locomotive was used to determine the amount of locomotive crush. Figure 3 shows the resulting force-deflection curve for the locomotive derived from the data. The maximum force was about 8.2 MN, which is less than the force from a typical cask regulatory impact test. As can be seen from the figure, the stiffness of the locomotive is nearly constant up to the point of maximum load with a value of about 9×10^6 N/m. From the results shown in Figure 1, this stiffness would imply that a locomotive like the one used in the Sandia test would have to be traveling at a speed of 45 m/s (100 mph) to have an equivalent impact to the regulatory test for even the softest rail cask.

For a perfectly plastic collision between a vehicle and a RAM package, the amount of energy that must be absorbed between the two bodies can be calculated from conservation of momentum and conservation of energy. To get a vehicle impact velocity that is equivalent to the regulatory impact test, the absorbed energy from the perfectly plastic collision must be equal to the energy absorbed by the RAM package in the regulatory impact test plus the energy absorbed by the vehicle in reaching the same contact force.

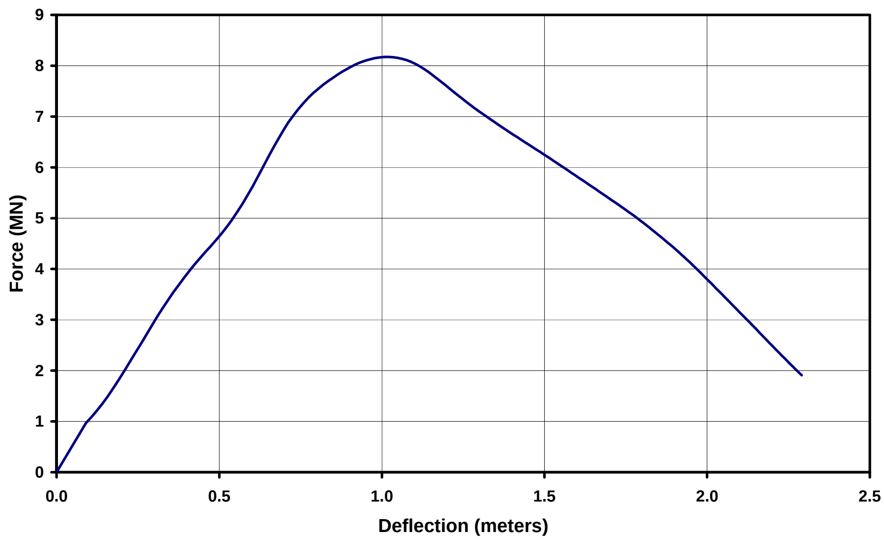

Figure 3 - Force-deflection curve for a locomotive impact into a spent fuel truck cask

DEFINITION OF AN UNYIELDING TARGET

The IAEA defines an essentially unyielding target as one that an increase in the target stiffness would not result in a substantial increase in the damage to the package being tested. A guideline to achieve this is a armor-plated concrete block with a mass equal to at least ten times the mass of the package being tested. Figure 4 shows a schematic of the unyielding target used for package tests at Sandia National Laboratories. In an effort to demonstrate what is meant by an unyielding target, Sandia performed a pair of tests impacting a mini-van onto this unyielding target and an identical mini-van onto a concrete target that was 28-cm thick. Figure 5 shows the deformations of the two mini-vans at the time of maximum crush. The two tests were nearly identical. This result demonstrated that for a mini-van a 28-cm thick concrete target is essentially unyielding. As a further comparison two tests of a RAM package using the same target types (these tests were at ½-scale) were also conducted. Figure 6 shows the results from these tests. The RAM package punched a hole through the concrete slab with no visible deformation to the package. This demonstrates that for a RAM package a 28-cm thick concrete target is definitely a yielding target.

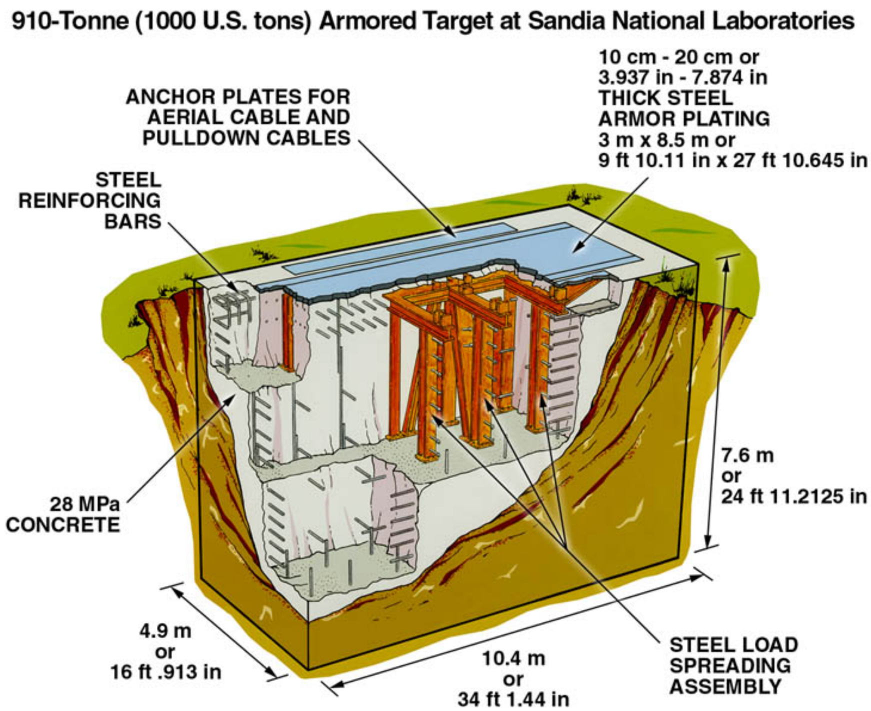

Figure 4 - Schematic of the unyielding target at Sandia National Laboratories

SUMMARY

The regulatory requirement that impact tests have to be conducted onto an essentially unyielding target provides a precise definition of the impact environment. Most surfaces that a RAM package could impact in real life are not essentially unyielding. For the damage to the package to be the same from an impact onto a yielding target as it is for the regulatory impact the impact speed must be increased. The number of possible impact targets in the real world is limitless. In this paper several classes of yielding targets were discussed and means for relating impacts onto these targets to the regulatory target were given. In general, most real targets are soft relative to RAM packages, so much higher speed impacts are required to achieve equivalent damage.

Figure 5 - Comparison of mini-van impact onto an unyielding target (left) and a 28-cm thick concrete slab (right)

Figure 6 - Comparison of RAM package impact onto an unyielding target (left) and a 28-cm thick concrete slab (right)

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