Comparison of Pad Hardness Study With Drop Test Results

R.E. Nickell[1] and Y.R. Rashid[2]

[1]*Applied Science & Technology, Poway, California*
[2]*ANATECH Research Corporation, San Diego, California, United States of America*

INTRODUCTION

Title 10, Part 71, of the Code of Federal Regulations (10 CFR 71) contains requirements for the construction and operation of spent nuclear fuel and high-level waste transport packagings that are considered prescriptive; e.g., the designer is required to demonstrate, either through performance testing or analysis, that the packaging can withstand a well-defined sequence of hypothetical accident events without exceeding limits on the release of its radioactive material (RAM) contents.

The performance testing option is often chosen by designers, even when detailed stress analysis of the packaging containment boundary is performed for the hypothetical accident conditions. Testing of full-scale packagings carries a significant economic penalty, however, both due to cost of the test articles themselves and to the cost of testing at facilities able to handle typical truck and rail casks. Furthermore, the selection of the most damaging orientation is not readily apparent, since a center-of-gravity-over top corner drop may be most damaging for one portion of the containment boundary, while a side drop may be more damaging for another. For these reasons, the use of scale models of the packagings for drop testing is preferred, with full-scale testing reserved for only the most critical of design issues.

The particular choice of scaling used in the industry is called velocity scaling by Duffey (1971); i.e., the dimensions of the packaging are scaled downward, as are the deformations, while the accelerations are scaled upward. The velocities, strains, and stresses in the scale model remain identical to those in the full-scale packaging, provided that the materials used to construct the model are the same as those used to construct the full-scale packaging (i.e., replication). In addition, strain rate effects must not be significant. Velocity scaling in terms of the hypothetical accident drop events also implies that the scale model must be dropped from exactly the same height as the full-scale article (e.g., 30 feet or 9 meters), so that the initial velocity at impact, and thus the impact stresses, is identical.

The stiffness and mass of the scale model and full-scale article are not the same, however, with the mass ratio of the two equal to the cube of the scale factor (a one-third scale cask would weigh 1/27 of the full-scale cask). The dynamic response of the scale model takes place faster than the full-scale article by the scale factor itself; i.e., if the duration of the impact event is fifteen milliseconds for a full-scale cask, the corresponding duration is five milliseconds for a one-third scale model. If the peak acceleration in a full-scale cask drop test is 250 g, the corresponding acceleration in a one-third scale model drop test would be 750 g.

TARGET HARDNESS EFFECTS

The issue of scaling becomes somewhat more complex when impact surfaces other than the essentially unyielding surface is used. Essentially unyielding surfaces, as defined by IAEA Safety Standards, Safety Series No. 37, are able to transmit essentially all of the impact energy to the packaging, because of both the stiffness of the steel plate surface and the large reaction mass beneath the steel surface. For deforming impact surfaces, however, the dynamic characteristics of both the falling body and the surface must be taken into account.

Real impact surfaces have been of interest in recent years because of the need to assess actual risks of RAM shipment by air, as described by Bonzon and Schamaun (1976) and Schamaun and Von Riesemann (1976), and for severe truck and rail accidents, as described by Fischer, et al. (1986). The latter study was based upon a probabilistic risk assessment of conventional truck and rail shipping casks constructed of austenitic stainless steel for the containment boundary and lead gamma shielding, subjected to a full spectrum of severe transportation accidents. The theoretical impact surfaces ranged from water to soft soil to hard soil to concrete to hard rock, with the cask damage assessment based on sophisticated finite element analysis.

More recently, drop tests and associated finite element analyses have been carried out by Gonzales (1987) and Gonzales, et al. (1987), with the intent to determine the effects of impact surface stiffness and mass on the dynamic structural response of RAM transport packagings. The test article in these studies was an approximate 1/2-scale model of a legal-weight truck cask, having an outer diameter of about 20 inches, a length of 72 inches, and a weight of about 5,500 pounds. This implied full-scale cask dimensions of 40" outer diameter, 144" length, and 44,000-lb weight. No special gamma shielding was included in the scale model, so the full-size wall thickness of seven inches of A-36 ferritic steel provided a simulation of combined containment and gamma shielding for monolithic design steel cask construction. The test article is shown schematically in Figure 1. The contents were simulated by a series of internal steel plates weighing about 2300 lb -- implying contents in the full-scale cask of 18,400 lb.

The scale model shown in Figure 1 was dropped from various heights, corresponding to 1.0, 1.5, 2.0, and 2.5 times the regulatory impact velocity, onto surfaces of varying hardness, including soil, concrete, and the regulatory unyielding surface of 10 CFR 71. Attempts were made to compare the damage to the cask models and the impact surfaces with that from the regulatory event, in order to quantify the severity of real targets relative to the essentially unyielding surface. Such results cannot be compared directly, however, because of scaling considerations, especially the scaling of the failure mechanisms of the targets. In this report the results of these scale-model drop tests are re-examined, with particular emphasis on the scaling of failure mechanisms in soil and concrete targets, and the effect of this scaling on the damage to be expected in full-scale cask drop tests.

EPRI TARGET HARDNESS STUDIES

The experimental results from the target hardness studies by Gonzales (1987) and Gonzales, et al. (1987) should be compared to the somewhat related study by Rashid (1986), sponsored by the Electric Power Research Institute (EPRI). In the latter work, the concern was the effect of impact surface stiffness on the loads imparted to metal casks for the dry storage of nuclear spent fuel. A target hardness similitude parameter was developed that takes into account both the dynamic properties of the cask and those of the impact surface. Equivalent static deceleration loads were calculated using state-of-the-art concrete cracking and soil deformation constitutive behavior in a nonlinear finite element code. Relatively small drop heights and associated impact initial velocities were analyzed, since handling accidents rather than transport accidents were of interest.

Aircraft Runway Target Analysis

The target hardness study by Gonzales (1987) examined a number of targets of varying hardness, ranging from the regulatory surface that is essentially unyielding to relatively soft, uncompacted soils. One of the targets of prime interest to electric utilities is the aircraft runway target shown in Figure 2, composed of a standard Federal Aviation Agency runway cross section — 18 inches of reinforced concrete on top of ten inches of compacted subsoil. Such a target is not greatly dissimilar to a dry metal spent fuel storage cask pad, such as that analyzed by Rashid (1986).

However, the differences between the measured/calculated decelerations by Gonzales (1987) and those calculated by Rashid (1986) are substantial. At least part of this difference is directly attributable to the scaling of the cask model. The measured/calculated decelerations for the scale model need to be reduced by a factor of two prior to comparison. Another part of this difference is due to the higher velocities at impact (i.e., greater drop heights) used in the Gonzales study, compared to the velocities at impact for spent fuel storage casks. For example, the peak acceleration seen by the half-scale truck cask model following impact onto a concrete runway target at a velocity of 44 ft/sec was measured at about 480 g. Velocity scaling would imply that the peak deceleration for the full-scale cask would be 240 g. The measured deceleration for this particular test is shown in Figure 3. Note that the "steady" deceleration, obtained by averaging the transient deceleration during the time 0 to 3 msec, has a value of about 280 g, which implies a value of about 140 g for the full-scale cask. A typical steady deceleration for a spent fuel storage cask dropped from a height of 80 inches (impact velocity = 21 ft/sec) onto a reinforced concrete storage pad is about 60 g.

At first glance, the difference between 60 g, at 21 ft/sec, and 140 g, at 44 ft/sec, could be attributed to the difference in initial velocities. In order to determine the validity of that argument, finite element analysis was used to extend the results of Rashid (1986) to greater drop heights, and to specifically include the characteristics of the Gonzales scale-model cask and concrete airport runway target. Figure 4 shows the total force imparted to the 5,500-lb scale model by the concrete runway target as a function of drop height. Figure 4 covers the drop height range up to 30 feet (44 ft/sec), showing gradually increasing steady decelerations from about 20 g to about 300 g. Figure 5 extends the drop heights to 120 feet (corresponding to an initial velocity of about 88 ft/sec); however, the figure shows that the steady decelerations becomes asymptotic to about 380 g, because of progressive failure of the concrete slab.

This asymptotic limit to the cask deceleration is the average of the peak and steady decelerations measured in the Gonzales experiment at 44 ft/sec initial velocity, which corresponds to a drop height of 30 feet. At this drop height, calculations indicate progressive slab cracking and failure. Figures 6 and 7 show the slab cracking patterns at 300 g and 380 g steady deceleration, with tensile splitting and shear cracks extending through the entire slab thickness and propagating away from the impact area at an angle. The deformed shape of the crushed surface for these two decelerations is shown in Figures 8 and 9. (Note that the penetrations plotted in Figures 8 and 9 are multiplied by factors of ten and two, respectively, in order to enhance the visual presentation of the calculated results.) Figure 10 is taken from Gonzales (1987) and shows the damage to the concrete surface from the actual experiment. The actual crushing is about 0.25 inches, which would correspond to 300 g for the steady deceleration model (see Figure 8, which has about 0.2 inches of crushing).

The SAFECRACK steady deceleration model should be considered to be conservative from the point of view of damage to the concrete slab, since no credit is taken for the relative motion of different portions of the slab or of the cask. As Figure 3 indicates, a dynamic deformation mode with a frequency of about 600 Hz dominates the acceleration response. This deformation mode is most likely due to axial ringing of the scale model and its internal masses. The average deceleration is in agreement with the SAFECRACK steady deceleration, as is the damage to the concrete slab, even though the peak decelerations are 25% higher. However, these peak decelerations can be attributed to a portion of the packaging mass being in or out of phase with the remainder of the packaging mass, while the damage to the slab correlates with the average deceleration. Another way of expressing this is that the damage to the concrete slab is caused by the total impulse of the applied load, i.e., the integral of acceleration trace multiplied by the packaging weight.

The Gonzales experimental program also involved impact onto the concrete runway target at 66 ft/sec and 88 ft/sec, with penetrations into the target of 4 inches and 8 inches, respectively. Significantly higher peak decelerations were recorded — of the order of 1,000 g — but the records do not appear to be valid. The SAFECRACK calculations indicate that the steady decelerations for 66 ft/sec is about 360 g, and about 380 g for 88 ft/sec. The slab penetration predicted at 380 g is 3.5 inches, which is in general agreement with the experimental results. Figure 11, taken from Gonzales (1987), shows the penetration measured for an initial velocity of 66 ft/sec. This figure can be compared to the SAFECRACK calculation in Figure 9. Figure 12 shows the displacement of the scale model, as calculated by SAFECRACK, as a function of the total deceleration force. Note that the penetration displacements of 0.2 inches and 3.5 inches calculated by SAFECRACK are measured as the relative displacements between the footprint and the unloaded surface of the target. The displacement shown in Figure 12 is the total footprint displacement which approaches (from above) the penetration displacement as the target approaches failure.

From this evaluation we conclude that the target damage correlates with the steady deceleration of the cask or, equivalently, with the total impulse delivered by the cask to the target. The peak decelerations measured on the scale-model cask are dominated by relative motion of various cask component masses, and are not representative of target hardness. The steady decelerations, however, reflect both the hardness of the target and the damage/failure to the target caused by cask impact. Therefore, it is crucial that both the cask and the target be scaled properly, so that the target dimensions, stiffness, and failure modes match those of the full-scale target being impacted by the full-scale cask.

Assuming that the Federal Aviation Agency runway cross section (see Figure 2) is a full-scale target, which is almost certain, the actual steady decelerations that would be observed for a full-scale cask can then be determined. First, we specify a given drop height (say 30 feet), a cask diameter (say 88 inches), and a cask weight (say 200,000 lb). Second, we will assume that the load versus drop height curves of Figures 4 and 5 are valid, except that the impact footprint must be scaled properly, i.e., stress levels cause failure, not load. From a drop height of 30 feet, Figure 4 gives a load of about 1,600,000 lb -- for an equivalent pressure of 5,000 psi. The equivalent load for the full-scale cask, assuming that the slab failure mode remains the same, is 25,600,000 lb. The corresponding deceleration would be 128 g. This can be compared to the 60 g deceleration that would be observed for such a cask dropped from a height of 80 inches onto a much less robust concrete dry storage pad. The comparison is reasonable.

REFERENCES

Duffey, T.A. "Scaling Laws for Fuel Capsules Subjected to Blast, Impact, and Thermal Loading", Proceedings of the Intersociety Energy Conversion Engineering Conference, Society of Automotive Engineers, New York, pp. 775-786, (1971).

Bonzon, L.L. and Schamaun, J.T. "Container Damage Correlation with Impact Velocity and Target Hardness", Sandia National Laboratories, Report No. SAND76-5363, (1976).

Schamaun, J.T. and Von Riesemann, W.A. "Effects of Target Rigidity on Impact Behavior of Shipping Containers", Sandia National Laboratories, Report No. SAND76-0207, (1976).

Fischer, L., et al. Shipping Container Response to Severe Highway and Railway Accident Conditions, Volume I: Main Report, Volume II: Appendices, U.S. Nuclear Regulatory Commission, NUREG/CR-4829, (1986).

Gonzales, A. "Target Effects on Package Response: An Experimental and Analytical Evaluation", Sandia National Laboratories, Report No. SAND86-2275; and "Comparison of the IAEA Unyielding Surface to Various Yielding Targets", Sandia National Laboratories, Report No. SAND86-2802, (1987).

Gonzales, A., Pierce, J.D., and Stenberg, D.R. "Target Hardness Comparisons with the IAEA Unyielding Target", Proceedings, Packaging and Transportation of Radioactive Materials (PATRAM), Vol. 2, Paper No. IAEA-SM-286/114P, Vienna, pp. 545-551, (1987).

Rashid, Y.R. "The Effects of Target Hardness on the Structural Design of Concrete Storage Pads for Spent-Fuel Casks", EPRI Report No. NP-4830, (1986).

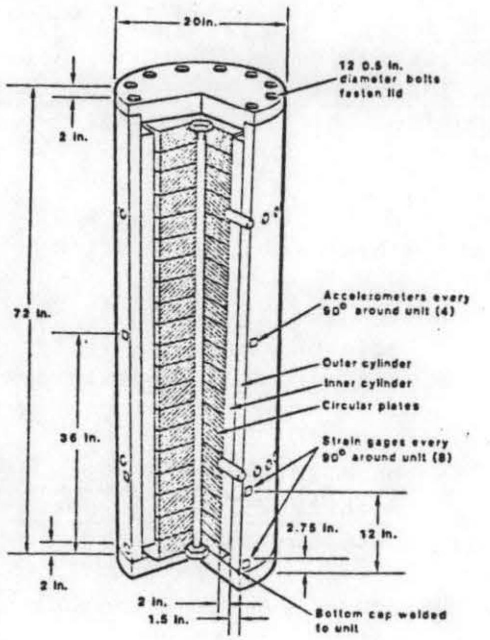

Figure 1. Test Unit Used for Experimental Program

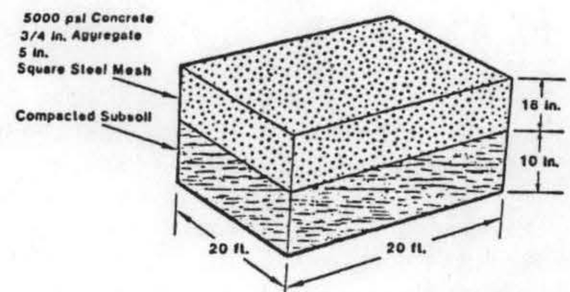

Figure 2. Federal Aviation Agency Runway Cross Section

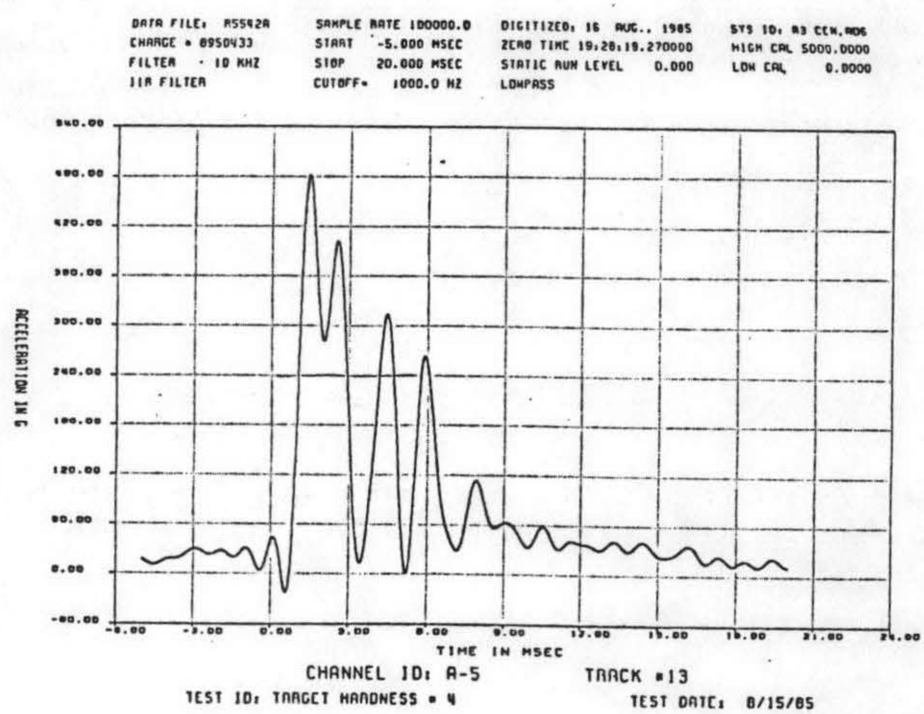

Figure 3. Acceleration Data for 44 ft/s Impact Velocity into Concrete Runway Target

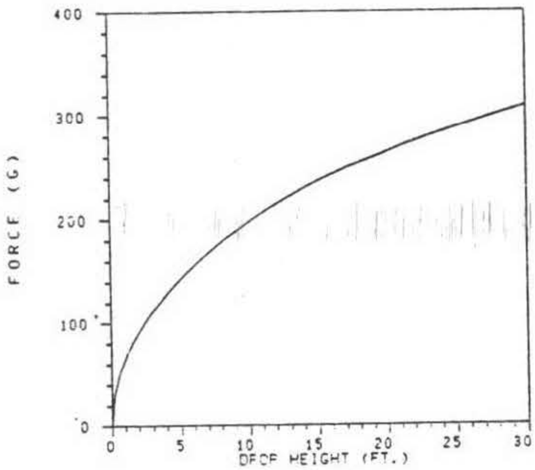

Figure 4. Force vs. Drop Height for the Sandia Half Scale Cask Concrete Runway Target

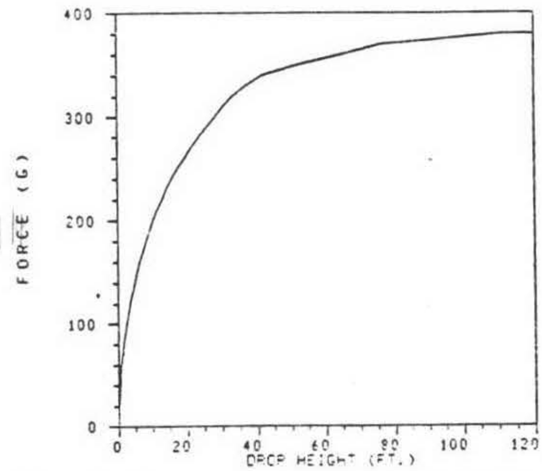

Figure 5. Force vs. Drop Height for the Sandia Half Scale Cask Concrete Runway Target

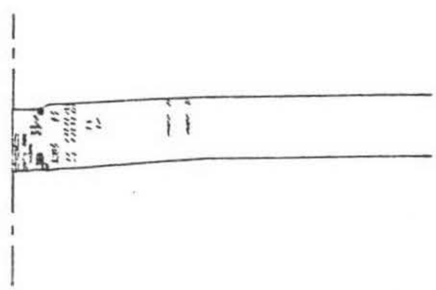

Figure 6. Cracking Patterns at a Drop Height of 30'

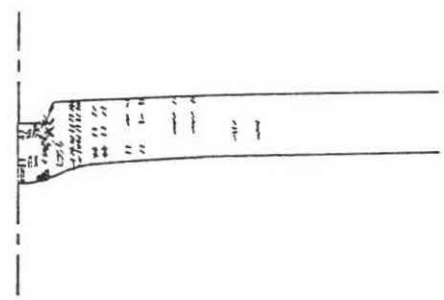

Figure 7. Cracking Patterns at a Drop Height of 120'

Figure 8. Deformed Shape at a Drop Height of 30'
Indentation = 0.2"

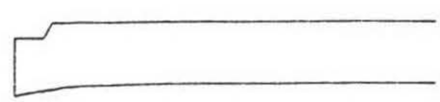

Figure 9. Deformed Shape at a Drop Height of 120'
Indentation = 3.5"

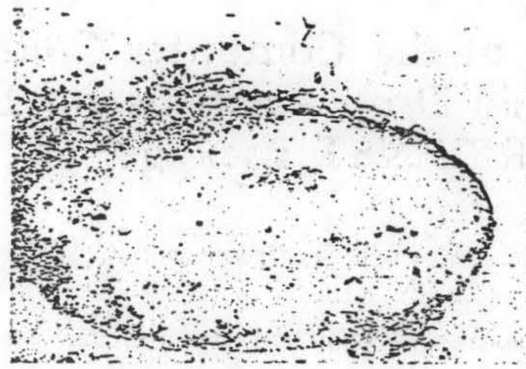

Figure 10. Concrete Runway Surface After an Impact at a Velocity of 44 ft/s

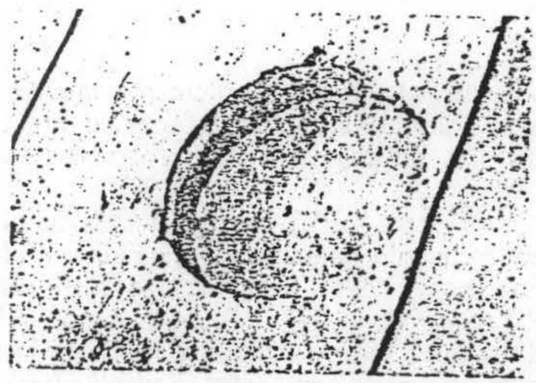

Figure 11. Shear Plug Formed in Concrete Runway After Impacting at a Velocity of 66 ft/s

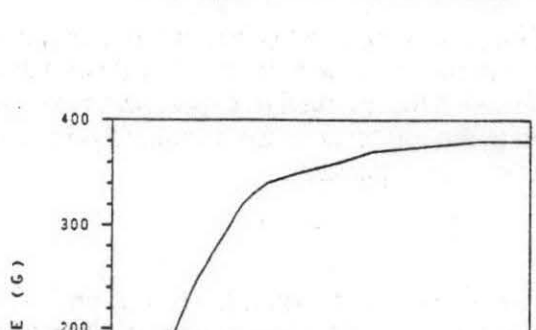

Figure 12. Force vs. Footprint Displacement for the Sandia Half Scale Cask