Analytical Determination of Package Response to Severe Impacts.*

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INTRODUCTION

An important aspect of radioactive material transportation risk assessments is the amount of release from packages subjected to accidents more severe than the design basis accident (US NRC 10CFR71 1995) defined as a free fall from 9 m or 30 ft. onto an essentially unyielding target. Current risk assessments generally use very conservative estimates of release rates for extra-regulatory accidents. To remove some of this excessive conservatism and more realistically predict transportation risks, the response of a large number of packages to extra-regulatory impacts must be determined.

Cost considerations preclude testing as the means for this determination. Many tests at many different velocities or orientations would be required to obtain a sufficient amount of experience at predicting leakage. Therefore, an analytical tool, such as the finite element method must be used. For a finite element code to be relied upon it must first be qualified for performing analyses resulting in large plastic deformations of the containment boundary of radioactive material transportation packages.

An effort to qualify the finite element method as an accurate and reliable method to predict cask performance has been ongoing at Sandia National Laboratories by comparing analytical results to test measurements of the Structural Evaluation Test Unit (SETU) cask. Comparisons of deformed shapes, strains and accelerations have been made for impact velocities of 13.4, 20.1 and 26.8 m/s (30, 45 and 60 mph). The SETU cask was designed following the method and guidance of U.S. NRC Regulatory Guide 7.6 (US NRC 1978). The unit met the requirements of this guide with as little margin as practical, in order to make the package have a high probability of plastic deformation. The 13.4 m/s impact corresponds to the regulatory 9 m (30 ft.) free fall, and the others correspond to impacts with 2.25 and 4 times the kinetic energy of the regulatory impact. One other analysis at an impact velocity of 38.0 m/s (85 mph) or 8 time the kinetic energy of the regulatory impact will be included to extend the predictions to even higher energies.

DESIGN OF TEST UNIT

NRC regulatory Guide 7.6 lists design criteria for the structural analysis of shipping cask containment vessels. These criteria were followed in the design of the test unit wherever possible. The basic configuration of the test unit has a lead shielding layer sandwiched between two stainless steel structural shells. Since a common location for a failure is at the closure, and it was not determined if the impact end or the opposite end closure was most vulnerable, the test unit has a lid on both ends. One of the possible failure mechanisms for this type of package is caused by the impact of the contents against the lid. For this reason the contents were made very stiff, thereby maximizing the amount of damage that it can cause when impacting the lids. A schematic of the Structural Evaluation Test Unit (Ammerman, 1993) and photograph is shown in Figure 1.

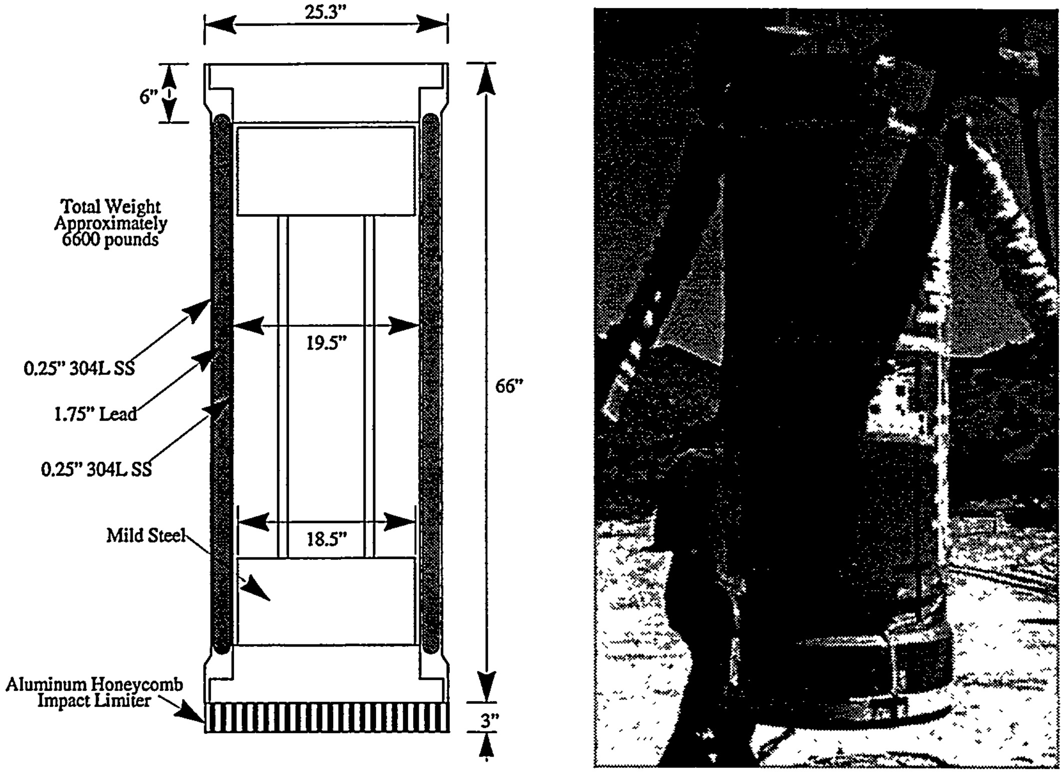

Figure 1. Schematic and Photograph of the Structural Evaluation Test Unit.

The test package is loosely based (approximately one-third scale) on current casks used in rail transport. The impact limiters used with these casks typically yield accelerations in the 60 G's range for the 9 m (30 ft) free fall onto an unyielding target. Therefore an impact limiter that would yield a peak acceleration of about 180 G's (three times full-scale) for the one-third scale test unit was chosen. Metallic honeycomb was used for construction of the impact limiters to be used in this program. Honeycomb materials provide good repeatability in crush behavior. The major disadvantage of anisotropy in the honeycomb is eliminated because of the end-on drop orientation.

The honeycomb impact limiter crush strength and thickness were initially selected assuming rigid-perfectly-plastic behavior of the honeycomb and a crush at lock-up of 70 percent. Using the maximum crush strength of 22.1 MPa (3200 psi) versus a nominal crush strengthen 16.6 MPa (2400 psi), a required thickness of 6.6 cm (2.6 in) is obtained. It was decided to use a honeycomb thickness of 7.6 cm (3.0 in) in the design of the impact limiter.

The major task in design of the test unit was the establishment of the inner and outer wall thickness. The wall thickness had to be sufficient to withstand the loading imposed by the 9 m (30 ft) drop onto an unyielding surface with the impact limiter in place. For manufacturing considerations, the outer stainless steel wall was given an outside diameter of 0.61 m (24 in) and the inner stainless steel wall was given an outside diameter of 0.51 m (20 in). These dimensions are consistent with available pipe sizes. The test unit wall design problem was thus reduced to determining the required thicknesses. An iterative design procedure was used to select the inner and outer wall thicknesses of 6.4 mm (0.25 in). This thickness of stainless steel tubing is commonly available and the stresses for this design would be very near the allowable stress values from Regulatory Guide 7.6.

The typical method for design of bolted closures is to assume the package contents impacts the closure lid with the same acceleration as the steady-state acceleration of the cask. For the test unit, where the contents weigh 7.34 KN (1,650 lbs) and the acceleration value is 180 G's, a required total bolt force of 1.32 MN (297,000 lbs) is calculated. Typical grade 8 bolts (material SAE 4140) have a nominal yield strength of 938 MPa (136,000 psi), resulting in an allowable bolt stress of 234 MPa (34,000 psi). This results in a required bolt area of 56.4 cm^2 (8.74 in^2), or assuming 24 bolts a required area of 2.35 cm^2 (0.36 in^2) per bolt. Bolts with 19 mm (3/4 in) diameters and fine threads having a cross section area of 2.39 cm^2 (0.37 in^2) were chosen.

FINITE ELEMENT MODEL

In order to accurately capture the acceleration time history and correctly account for the inertial effects, the nonlinear, transient dynamic computer programs PRONTO2D and PRONTO3D (Taylor, 1987, Taylor 1989, Attaway, 1992) were used. PRONTO2D and PRONTO3D are explicitly integrated codes that steps through time, predicting the next time step conditions from the present conditions.

The stainless steel, carbon steel and the lead in the cask were modeled using a realistic analytical material model based on a power law relationship (Stone, 1990). The honeycomb was modeled as low density foam, a material model that adequately captures its volumetric and deviatoric behavior. The material parameters were chosen based on pretest measurements and estimates of strain rate sensitivities. The stainless steel, carbon steel and the honeycomb materials are well characterized for both static and dynamic conditions. The lead is not a well characterized material under dynamic conditions, so the material parameters were chosen based on available data and experience gained during testing.

The 2D axisymmetric finite element model used a total of 7115 - four-node quadrilateral elements. The boundary conditions for the model consisted of a rigid impact plane and an initial velocity applied to the model. The contents were modeled to be in contact with but not attached to the bottom lid. Contact was modeled between the honeycomb and the bottom lid, both lids and the cask body, both lids and the contents, the contents and the cask body and the lead with the interior cavity surfaces. The bolts were modeled as an equivalent ring that was attached to the lids and the cask body with coincident nodes at each end of the ring.

The same test specimen was used for all four drop tests. Only the impact limiter was replaced after the first 13.4 m/s (30 mph) test. The small permanent deformations from the first test were present at the start of the second test. The second test impacting at 26.8 m/s (60 mph) hit at a slight angle to vertical on the corner of the cask. The deformations from the second test were large in the stainless steel walls near the impact corner. For the third test, the cask ends which were not significantly damaged, were reused with new wall sections, new lead, new contents and a new impact limiter. The third test impacted at 20.1 m/s (45 mph) on end. The fourth test used the same cask retaining the permanent deformations from the third test with the exception of a new impact limiter. This test hit with a velocity of 26.8 m/s (60 mph) on end as designed

COMPARISON OF PREDICTIONS AND TEST MEASUREMENTS

The first, third and fourth tests impacting at 13.4, 20.1 and 26.8 m/s (30, 45 and 60 mph) hit flat on end as designed. A 2D axisymmetric finite element analysis was performed and compared to the test results. The second test which hit at a slight angle required a 3D finite element model to capture the non-axisymmetric loading conditions. The results from all four tests and the corresponding predictions are compared in the following sections.

The deformed shapes from the first, third and fourth tests are compared to the 2D axisymmetric analysis predictions in Figure 2. Also shown in the figure are the vertical midheight accelerations from both the analysis and the test measurement. The deformations for the first and third test are relatively small. The fourth test experienced more plastic deformation with a single buckle on the outside wall and a double buckle on the inside wall. The analysis matched the actual deformations very well for all three tests. As shown in the figure the accelerations filtered with a Butterworth lowpass filter at 500 Hz. were also matched well in both magnitude and timing for these tests.

The prediction of the deformation in the fourth test needed to include the permanent deformations from the third test. This was accomplished in the finite element analysis by using the deformed shape from the 20.1 m/s (45 mph) analysis as the initial shape in the 26.8 m/s (60 mph) analysis. The honeycomb impact limiter portion of the finite element model was input with no initial deformations to coincide with its replacement in the fourth test. This method of analysis ignored the residual stresses that were present in the cask after the 20.1 m/s (45 mph) impact test. Because of the explicit solution scheme there was no way to extract the residual stresses from the analysis. Residual stresses are usually not known and are generally ignored in most analyses. For example any residual stresses from the manufacturing of the casks was unknown and ignored in the initial 20.1 m/s (45 mph) analysis.

The second test impacted on a corner about 6.3° from vertical. To model the behavior of this test a 3D finite element model was needed. The model retained all the contact surfaces in the 2D model. One change was that shell elements were used in the cask thin walls instead of solid elements. The deformed shape predicted in the analysis matches

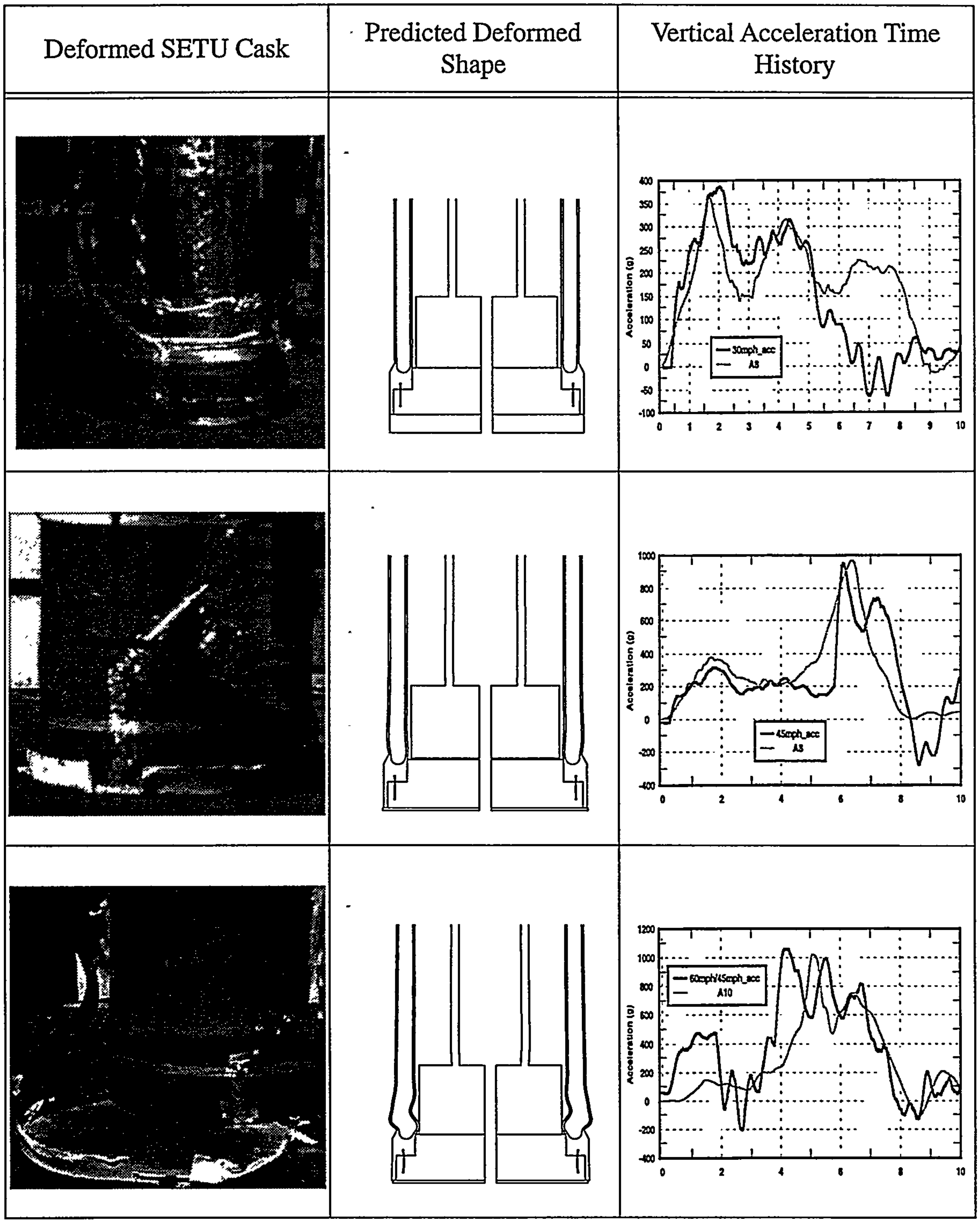

Figure 2. Actual and Predicted Deformed Shapes and Measured vs. Predicted Vertical Accelerations for the 13.4, 20.1 and 26.8 m/s (30, 45 and 60 mph) Impact Tests.

very well with the deformed shape from the impacted cask. The strains near the intersection of the wall and the cask bottom were predicted to be near but still below the failure strain of the stainless steel material. The SETU cask did not fail at this location. Figure 3. shows the deformed shape of the cask and the prediction from the analysis.

Note the large deformation in the thin stainless steel walls near the impact corner in both the test photo and in the analysis.

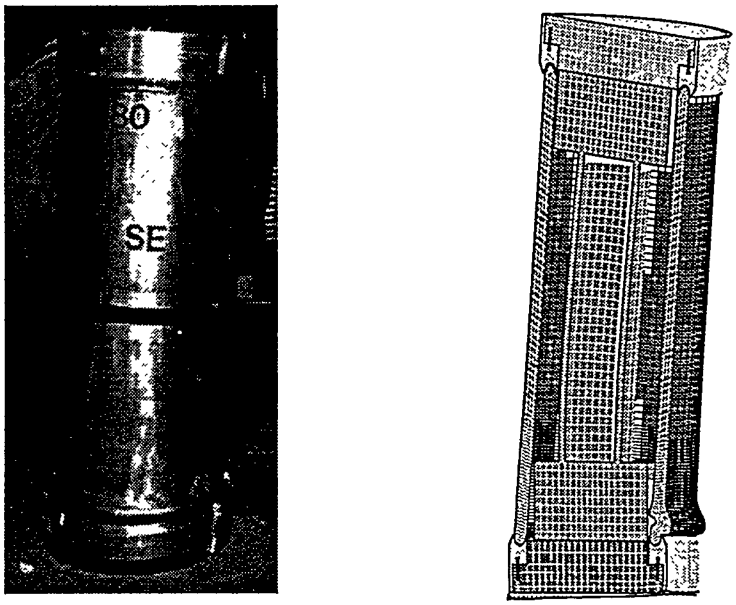

Figure 3. Actual and Predicted Deformed Shapes for Test Number 2.

To examine the performance of the cask at higher energies the finite element model was run with an impact velocity of 38 m/s (85 mph). This corresponds to an energy level of eight times the regulatory impact velocity. The deformed shape of the cask from the analysis is shown in Figure 4. For this analysis the bolts were re-meshed with a much finer mesh and allowed to fail when their strain exceeded 20%. This analysis predicts substantial strains in the cask walls and failure in the bolts in the bottom lid. The walls also received large strains and would likely tear in the outer thin wall just above the stiff end fixture. The analysis was stable throughout the entire impact event and returned very reasonable predictions for strains, accelerations and deformations. Since this cask has not been tested at this high of an impact velocity, there are no measured results to compare the analysis with.

The analysis of this cask at such a high impact velocity was performed to determine the stability and the limits of the finite element method. Modeling of complex behaviors such as tearing of thin wall sections and shearing of bolts can be predicted with reasonable accuracy at energy levels of eight times or more of the regulatory drop energy. Knowledge of the behavior of casks at impacts that far exceed the regulatory impacts can help lead to a much greater understanding of the performance of casks with regard to possible leakage and structural failure.

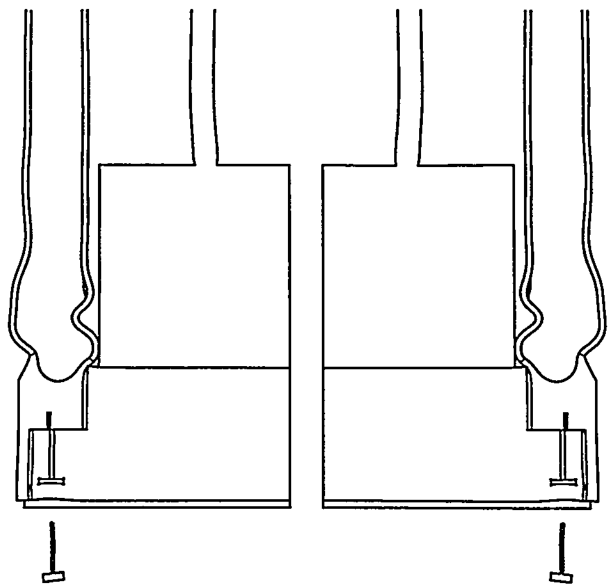

Figure 4. Predicted SETU Deformed Shape for a 30 m/s (85 mph) Impact.

CONCLUSIONS

Modeling of the cask used in this program required an accurate mesh of the cask, analytically correct treatment of the contact problem and accurate material models. The cask used in this series of tests was very complex from a finite element modeling viewpoint. The model included prestressed lead and bolt material, honeycomb material that experienced lock-up conditions, two different types of steel, lids on both ends of the cask and many different contact surfaces. The cask was also purposely designed to just meet the regulatory impact conditions, so the deformations experienced are more than would normally be expected. To be able to accurately model the behavior of this cask in an impact with 4 times the kinetic energy of the regulatory impact and extend the analysis to an impact with 8 times the energy shows that finite element methods are very capable at predicting cask behavior at high impact velocities.

The 2D mesh used for this analysis was reasonably refined with five elements used through the thin wall sections to accurately capture bending in the walls. The 3D analysis used shell elements that also accurately capture the bending. The accurate modeling of the contact problem is one of the strengths of the PRONTO2D and PRONTO3D codes. The behavior due to the contact between the elements of the cask and the contents was correctly captured in these analyses. The material models used for the stainless steel, carbon steel, lead and the honeycomb materials accurately modeled the material behavior.

The predicted deformed shape of the cask for all four tests matched well when compared to the actual deformed casks. The accelerations and the strains also matched well both in timing and in magnitude. By employing finite element analysis techniques to a large number of different cask designs, a great deal of information can be gained about extra-regulatory impact behavior. Predictable behavior in extra regulatory impact conditions can be used to make more accurate assessments of leakage potential. This data can then be used to support risk analyses of transportation systems.

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