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RECENT ASSESSMENTS IN THE U.S. OF TYPE B PACKAGES TO IMPACTS BEYOND THE REGULATORY PACKAGE TEST STANDARDS

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ABSTRACT

The regulatory-driven design of radioactive material transportation packages leads package vendors to perform analyses that demonstrate the package's ability to meet the regulatory requirements. However, for risk assessment and communication, the response of packages to impacts that are more severe than the regulatory impact is required. Traditionally, the task of performing assessments of package response to impacts more severe than the regulatory ones has been performed in the U.S. by the Department of Energy national laboratories. These assessments have been both experimental and analytical.

This paper will provide a brief history of extra-regulatory package impacts and then focus on recent analyses performed by Sandia National Laboratories for the U.S. NRC and the U.S. DOE. The analyses have been primarily in support of two large studies; "Reexamination of Spent Fuel Shipment Risk Estimates" and "Package Performance Study". The first of these examined the response of four generic spent fuel casks to impacts onto rigid targets at speeds up to 53.6 m/s [120 mph]. The second examined the response of two certified spent fuel cask designs to impacts up to 33.5 m/s [75 mph]. Analyses have been performed for closure-end impacts, closure-end CG-over-corner impacts, and side impacts. The analyses and testing of packages to beyond regulatory impact standards has shown that the packages have a considerable margin of safety against release of radioactive material. This fact reinforces the adequacy of the packaging requirements of the U.S. NRC and IAEA and the methods currently used to certify that spent fuel casks meet these requirements.

Of increasing concern to the transportation community is the response of the fuel assemblies themselves in both regulatory and extra-regulatory impacts. In risk assessments this information is needed to calculate the source term available for release.

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HISTORICAL PERSPECTIVE

The response of radioactive material transportation packages to accidents that are (or appear to be) more severe than the regulatory impact has been of concern since the early days of spent fuel transportation [1,2,3]. However, in risk assessments it was generally assumed that packages did not have any margin of safety and would have some degree of failure for any impact more severe than the regulatory 9-meter drop onto an unyielding target. In the U.S., the environmental impact statement that governs radioactive material transportation is, “Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes,” NUREG-0170 [1], published in 1977. This risk assessment, like most of that time, assumed that packages began to fail when subjected to any extra-regulatory impact. The degree of failure was assumed to progress as the impact severity increased. The degree of failure was based upon expert judgment.

With the advent of computer analyses, more accurate assessments of the degree of failure (and release of radioactive material) from extra-regulatory impacts became possible. The Modal Study [2], published in 1987, used finite element analyses to determine the level of strain in cask walls when they were subjected to extra-regulatory impacts. The release of radioactive material was assumed to be correlated with strain, with release beginning whenever the strain was greater than 0.2%.

As computers became more powerful, it became possible to model packages with more detail, and it is now possible to include details of the closures and actually model the deformations that can lead to release of radioactive materials. The next sections of this report will discuss several recent analyses that included this level of detail.

ANALYSES FOR “REEXAMINATION OF SPENT FUEL SHIPMENT RISK ESTIMATES”

In “Reexamination of Spent Fuel Shipment Risk Estimates” or NUREG/CR-6672 [3], four generic casks were analyzed for impacts onto rigid targets at velocities of 13.4 26.8, 40.2, and 53.6 m/s [30, 60, 90, and 120 mph]. Impact orientations of closure end, closure CG-over-corner, and side on were considered. These 48 analyses were the basis for determining cask response to a much broader set of impact accidents.

All of the analyses were performed using the Sandia-developed non-linear transient dynamics finite element program PRONTO-3D [4, 5, 6]. This type of code updates the position of each node at each time step, which allows for both material and geometric non-linearities. One result of this approach is that strains reported are true strains, rather than engineering strains that are based upon the undeformed geometry. PRONTO has been extensively benchmarked for analyses of cask response [7, 8].

To shorten the analysis times and avoid calculation of the very large shear strains that occur in the impact limiter, the assumption that the impact limiter has already been driven into the lock-up region (the point at which the material stops behaving in a crushable manner) at the start of all of the analyses was made. The amount of energy absorbed by the impact limiter prior to lock-up is assumed to be equivalent to the kinetic energy from the regulatory drop test (no design margin in the impact limiter). Using the pre-crushed impact limiter, analyses with impact velocities of 13.4 26.8, 40.2, and 53.6 m/s [30, 60, 90, and 120 mph] were conducted for each cask and orientation. If the energy required to crush the impact limiters is added to the initial kinetic energy of the cask, these analysis velocities correspond to actual impact velocities of 19, 30, 42, and 55 m/s [42, 67, 95, and 124 mph]. Figure 1 shows a partial detail of the finite element model of the closure end of the steel-lead-steel rail cask. The models for the other casks were similar.

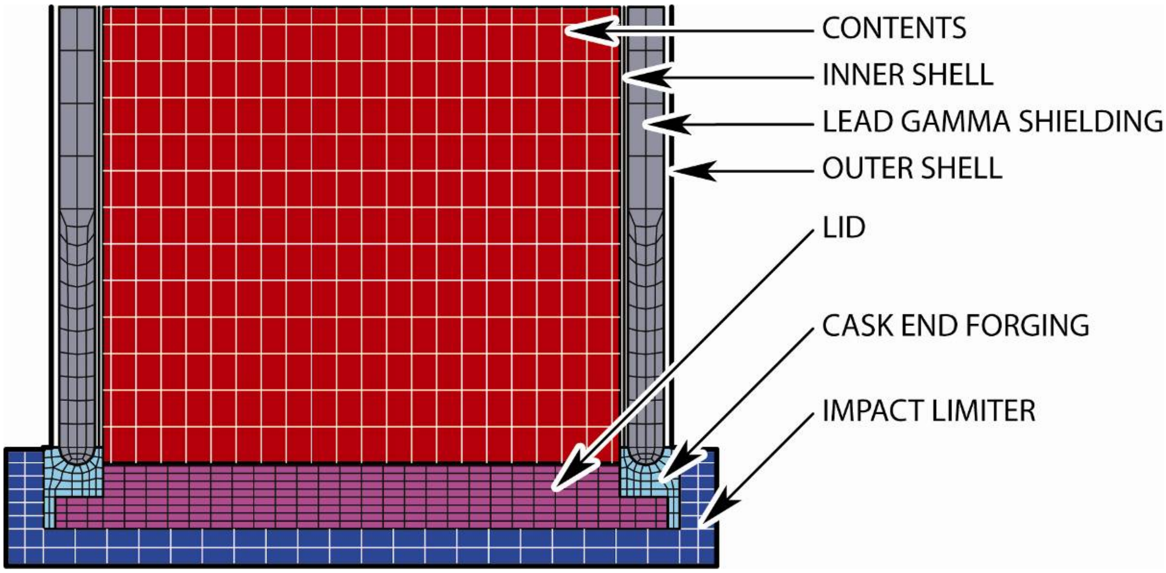


Figure 1 - Detail of the closure end of the steel-lead-steel rail cask

In the models, shell elements were used for the inner and outer shells. Solid elements were used to model the gamma shielding, the end forgings, the lid, the pre-crushed impact limiter, and the contents. The contents were treated as a homogenized mass of crushable material; no attempt was made to represent the basket structure or the details of fuel elements.

The failure point in most cask impacts is at the bolted closure. For this reason the closures of the casks were explicitly modeled. The lid is recessed into the body of the cask and held in place with either 12 25-mm [1-inch] diameter bolts for the truck casks or 24 44-mm [1.75-inch] diameter bolts for the rail casks. The bolt model cross-section is square with square heads. The area of the square bolt shank is the same as the area of a round bolt. The edges of the heads are rigidly attached to the cask lid, and the bottom of the shank is rigidly attached to the cask body. Figure 2 shows the cross-section through the center of a typical bolt and an isometric view of a single bolt. All of the contacts are tied via coincident nodes. The initial preload in the bolts caused by the torque applied to them when the cask is closed is neglected. Neglecting this preload is conservative because the preload must be overcome by loading from the contents before there is any deformation to the bolts. This factor makes a preloaded closure have smaller openings than a closure without preload.

Using finite element analyses to determine the ability of the casks to maintain containment requires investigation of all of the areas and factors that may result in a loss of containment. For these casks, the main factors to consider are maximum tensile plastic strains in the containment boundary, maximum tensile plastic strains in the closure bolts, and deformations in the region of the seals. For the sandwich-wall casks, the containment boundary is the inner shell, but the development of a tear in this shell does not necessarily imply a loss of containment if the outer shell remains intact. None of the finite element impact analyses indicated strains above 70% in this shell, so no tearing is predicted to take place (the true strain at failure for 304L is greater than 120%). Table 1 shows the maximum level of plastic strain observed in the inner shell for the three sandwich-wall casks. The strain levels in the other portions of the cask were lower than those in the shells. Strain fringe plots showing the increase in damage due to increase in velocity for the steel-lead-steel truck cask in a side-on orientation are shown in Figure 3.

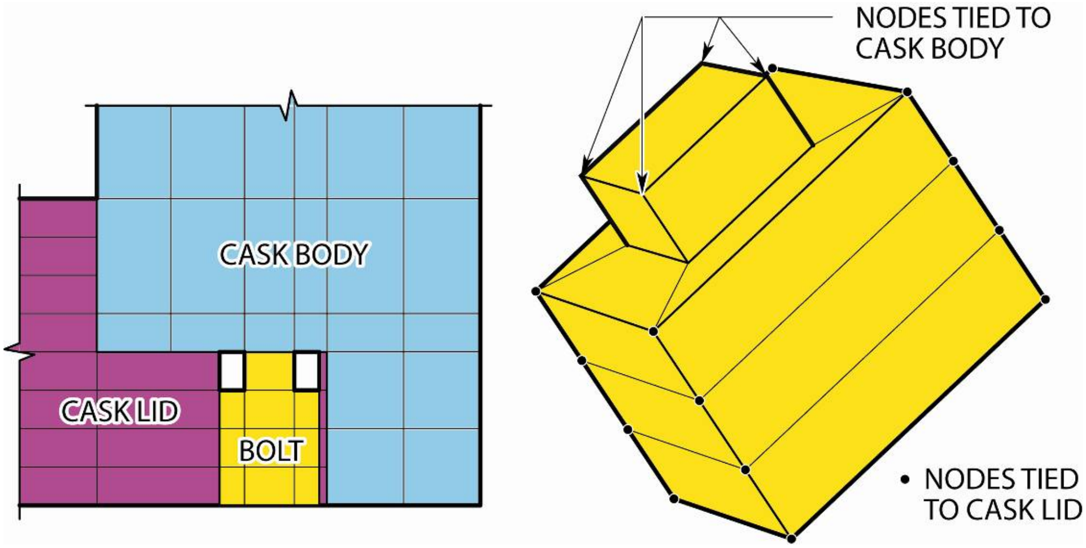
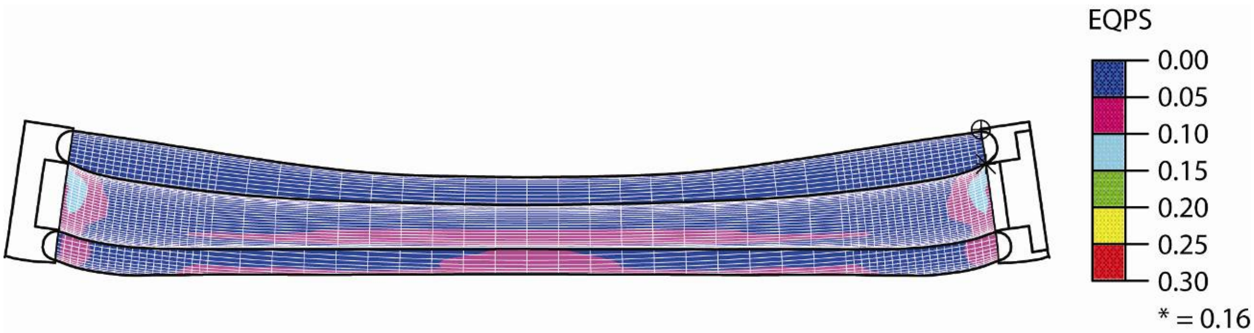


Figure 2 - Typical model of a bolt used in the finite element analyses

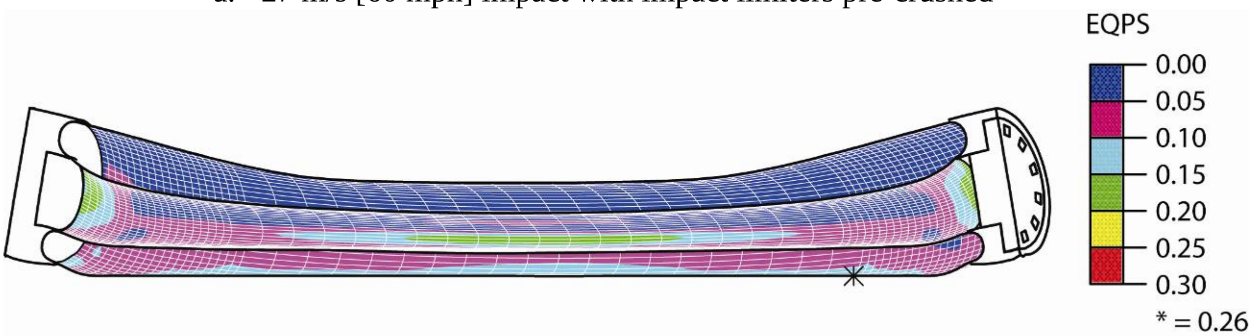
Table 1 - Maximum plastic strain in the inner shell of the sandwich wall casks

Cask	Corner Impact Speed	Corner Impact Strain (%)	End Impact Speed	End Impact Strain (%)	Side Impact Speed	Side Impact Strain (%)
Steel-Lead-Steel Truck	30 mph	12	30 mph	3.9	30 mph	n.a.
	60 mph	29	60 mph	12	60 mph	16
	90 mph	33	90 mph	18	90 mph	24
	120 mph	47	120 mph	27	120 mph	40
Steel-DU-Steel Truck	30 mph	11	30 mph	1.8	30 mph	6
	60 mph	27	60 mph	4.8	60 mph	13
	90 mph	43	90 mph	8.3	90 mph	21
	120 mph	55	120 mph	13	120 mph	30
Steel-Lead-Steel Rail	30 mph	21	30 mph	1.9	30 mph	5.9
	60 mph	34	60 mph	5.5	60 mph	11
	90 mph	58	90 mph	13	90 mph	15
	120 mph	70	120 mph	28	120 mph	~21

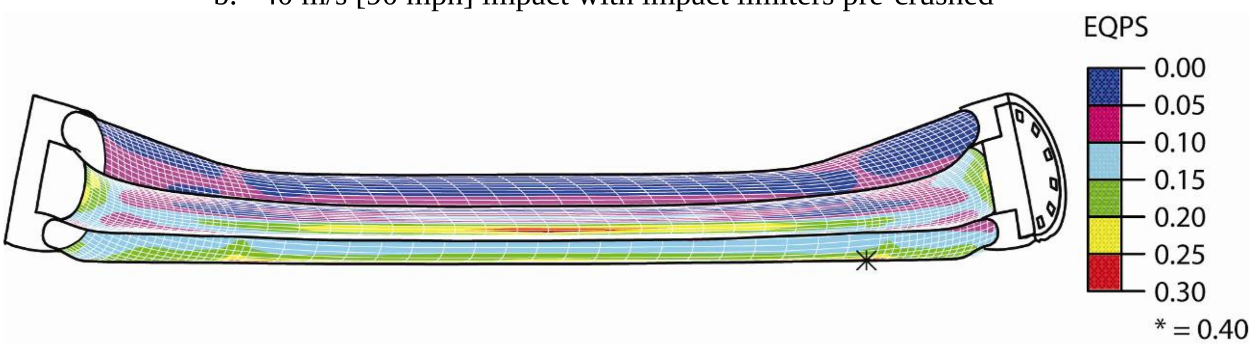
The other possible point of failure, the closure, was also investigated. Strains in the closure bolts as well as sliding and opening displacements were quantified. The strain in the closure bolts and deformation in the region of the seals is due to displacement incompatibility between the cask body and the closure lid, not an overload. This means that failure of one bolt is not likely to increase the load on the other bolts in the lid, leading to a progressive failure of the entire closure. The analyses indicated that some of the lid bolts would fail in the steel-lead-steel rail cask for impacts above 40 m/s [90 mph] in the corner orientation and impacts above 27 m/s [60 mph] in the side orientation and for the monolithic rail cask for corner impacts above 40 m/s [90 mph], end impacts at 54 m/s [120 mph], and side impacts above 40 m/s [90 mph]. However, in all of these cases only a few bolts failed, and the closure lid remained attached to the cask body. A better measure of the ability of the closure to retain the radioactive contents is the displacements in the seal region. Figure 4 shows an enlargement of this area for the 40 m/s [90 mph] end-on impact of the steel-lead-steel rail cask. Table 2 lists the maximum opening and sliding displacement for each analysis.



a. 27 m/s [60 mph] impact with impact limiters pre-crushed



b. 40 m/s [90 mph] impact with impact limiters pre-crushed



c. 54 m/s [120 mph] impact with impact limiters pre-crushed

Figure 3 - Strain fringe plots for the steel-lead-steel truck cask

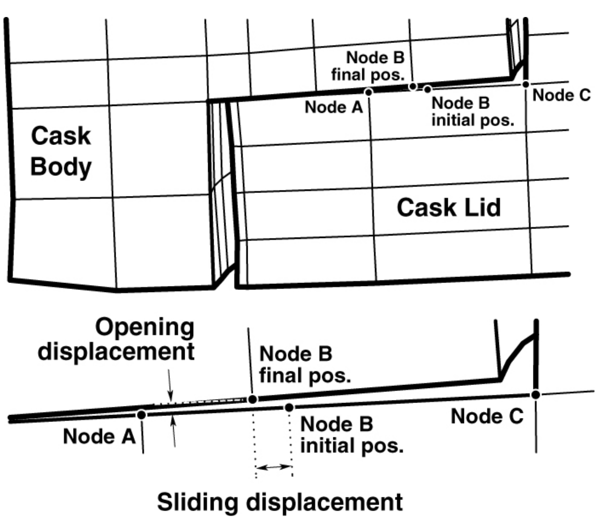


Figure 4- Seal region displacement for the 40 m/s [90 mph] end impact of the monolithic rail cask

Table 2 - Seal region displacements, in inches

Cask	Analysis Velocity	Corner Impact		End Impact		Side Impact	
		Opening	Sliding	Opening	Sliding	Opening	Sliding
Steel-Lead-Steel Truck	30 mph	0.02	0.01	0.000-0.002	0.000-0.002	-	-
	60 mph	0.02	0.03	0.001-0.003	0.001-0.004	0.01	0.02
	90 mph	0.02	0.06	0.000-0.002	0.003-0.005	0.02	0.02
	120 mph	0.04	0.04	0.002	0.02	0.02	0.01
Steel-DU-Steel Truck	30 mph	0.02	0.07	0.005-0.012	0.001-0.005	0.01	0.02
	60 mph	0.08	0.07	0.01-0.02	0.003-0.006	0.01	0.01
	90 mph	0.02	0.10	-	-	0.01	0.02
	120 mph	0.03	0.15	0.013	0.03	0.004	0.02
Steel-Lead-Steel Rail	30 mph	0.01	0.14	0.001-0.022	0.009-0.012	0.01	0.02
	60 mph	0.08	0.32	0.000-0.016	0.01-0.02	0.02	0.01
	90 mph	0.24	0.74	0.004-0.005	0.097-0.101	0.02	0.02
	120 mph	0.51	1.18	0.001-0.018	0.20-0.22	-	-
Monolithic Rail	30 mph	0.04	0.20	0.007-0.053	0.04-0.05	0.01	0.01
	60 mph	0.10	0.36	0.04-0.12	0.09-0.10	0.04	0.01
	90 mph	0.22	0.48	0.03-0.13	0.38-0.39	0.08	0.09
	120 mph	0.44	0.59	0.09-0.16	0.668	0.12	-

All of these generic casks were assumed to have elastomeric seals that could tolerate 0.10 inches of opening displacement without release of radioactive contents. The analyses that resulted in opening displacements greater than 0.10 inches were the 40 and 54 m/s [90 and 120 mph] corner impacts for the steel-lead-steel rail cask and the 27, 40, and 54 m/s [60, 90, and 120 mph] corner impacts and the 54 m/s [120 mph] side impact for the monolithic steel rail cask. The sliding displacements are only significant if they are so large that both seals deform to a position inboard of the cask cavity. This distance is approximately 1 inch, and only the 54 m/s [120 mph] corner impact of the steel-lead-steel rail cask had a sliding displacement greater than this.

ANALYSES FOR "PACKAGE PERFORMANCE STUDY TEST PROTOCOLS"

In "Package Performance Study Test Protocols," or NUREG-1768 [9], two real cask designs were analyzed to determine .possible accident scenarios to use as tests for the Package Performance Study. The casks analyzed were the Holtec HI-STAR 100 rail cask equipped with a MPC-24 canister and a GA-4 truck cask. The HI-STAR 100 is an all-steel cask, although the steel walls are made up of several layers rather than a single thick layer. In the finite element model all of these layers were assumed to be perfectly attached to each other. The GA-4 cask is a steel-DU-steel sandwich-wall cask with a rounded square cross section. The DU is in the form of cast rings with shear keys. These multiple rings were included in the model and the contacts between the rings and between the shells and the rings were assumed to be frictionless. The impact scenario analyzed for the HI-STAR 100 was a cg-over-corner impact onto the lid end, impacting a flat, rigid target. Impact velocities of 27 and 34 m/s [60 and 75 mph] were analyzed. The impact scenario analyzed for the GA-4 cask was a side-on impact onto a rigid half-cylinder midway between the two ends of the cask. Again, impact velocities of 27 and 34 m/s [60 and 75 mph] were analyzed. Unlike the generic casks of NUREG/CR-6672, the HI-STAR 100 impact limiter was modeled in detail. Figure 5 shows an exploded view of the impact limiter model. The closure of the HI-STAR 100 (with 54 41-mm [1.625-inch] closure bolts) was modeled in a similar manner to that for the analyses in NUREG/CR-6672. The only differences were that the bolt shank was modeled as its real length, with four elements along the length and the radial gap between the lid and the cask body was included. For the GA-4 analysis, the impact was well away from the closure, so no plastic deformation in the closure region was expected. Therefore, the details of the closure were not included in the model.

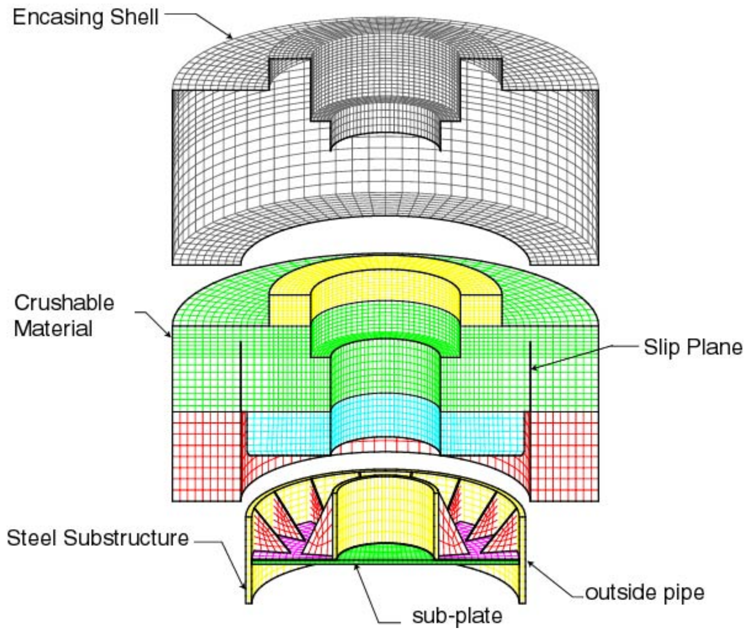
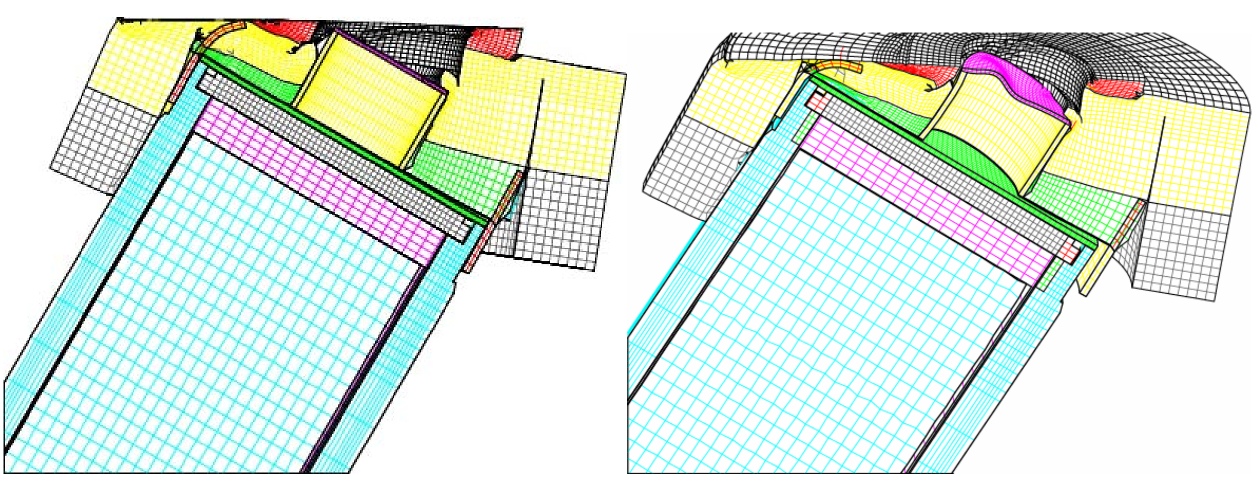


Figure 5 - Impact limiter model of the HI-STAR 100 rail cask

Figure 6 shows the results from the 27 and 34 m/s [60 and 75 mph] analyses of the HI-STAR 100. In the 27 m/s [60 mph] impact, all of the energy was absorbed by the impact limiter, and there was no plastic deformation in the cask body or closure. In the 34 m/s [75 mph] impact analyses, there was a small amount of plastic deformation in the cask body. Figure 7 shows the contours of plastic strain. In both analyses there was no permanent elongation in the closure bolts, and the cask would have continued to prevent release of radioactive material (the HI-STAR 100 cask is certified for canistered fuel, so there is even an additional barrier beside the closure lid to prevent release of radioactive material). These results compare very favorably with the results from NUREG/CR-6672, where the monolithic rail cask showed plastic strain of about 20%, closure bolt strains of about 40%, and closure opening displacement of 0.10 inches. This illustrates the large margin of safety that is built into the HI-STAR 100 impact limiter.



27 m/s [60 mph] **34 m/s [75 mph]**

Figure 6 - Deformation to the HI-STAR 100 cask after impacts onto a rigid target

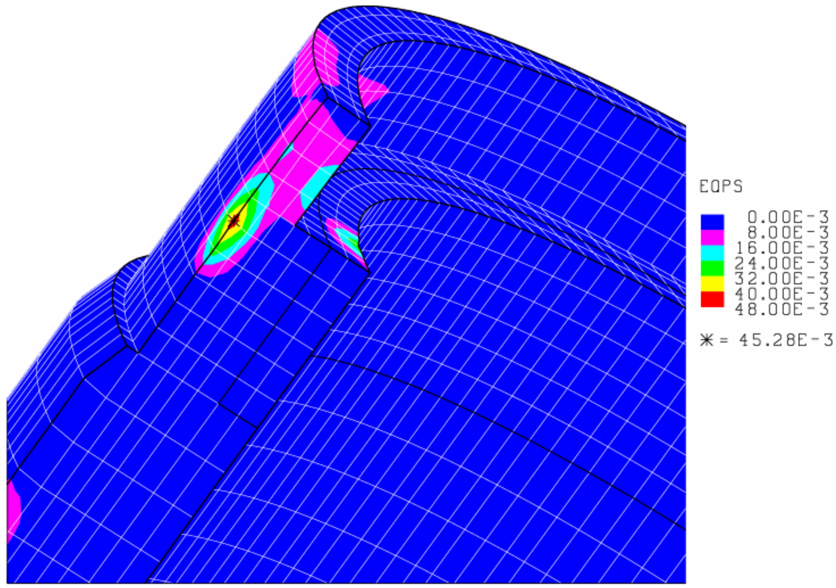
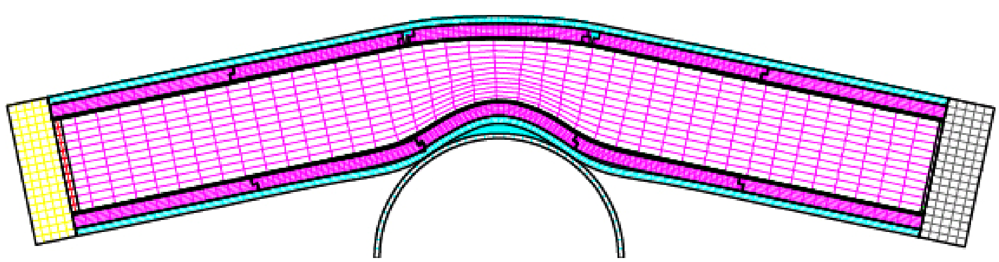
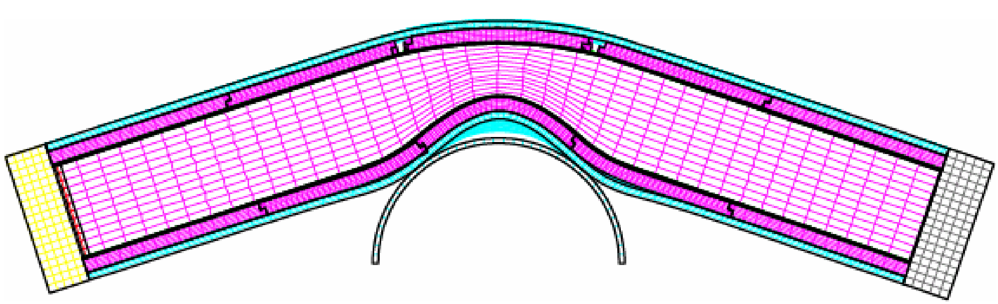


Figure 7 - Plastic strain in the HI-STAR 100 after a 34 m/s [75 mph] impact onto a rigid target

Figure 8 shows the results from both the 27 m/s [60 mph] and 34 m/s [75 mph] analyses of the GA-4. In this “back-breaker” impact configuration, there is no impact limiter to absorb energy, and the entire impact energy must be absorbed by plastic deformation of the cask body. The deformation is more severe for the 34 m/s [75 mph] impact, and there are larger gaps between the DU segments. Figure 9 shows the contours of plastic strain for the two analyses. The peak plastic strain is nearly 50%, but is below the true strain to failure for the XM-19 stainless steel shell. There is no plastic strain near the closure, so there would be no release of radioactive material. The gaps in the DU segments would lead to some radiation streaming following this impact.

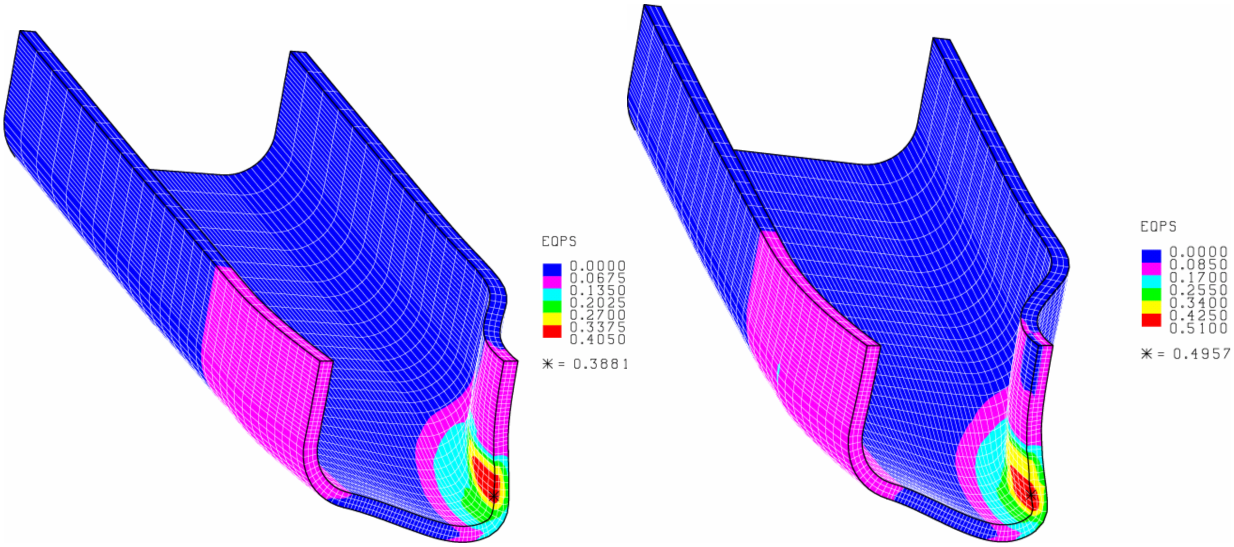


27 m/s [60 mph]



34 m/s [75 mph]

Figure 8 - Deformations in the GA-4 cask after impact onto a rigid half-cylinder



27 m/s [60 mph] **34 m/s [75 mph]**

Figure 9 - Plastic strain contours in the GA-4 cask after impact onto a rigid half-cylinder

ANALYSES OF THE STRUCTURAL EVALUATION TEST UNIT

The Structural Evaluation Test Unit (SETU) [7, 10] was a minimally designed cask. It was designed to just meet the allowable stresses from Reg. Guide 7.6 following a 9-meter end-on impact. In keeping with this philosophy, the impact limiter was also designed not to have any excess capacity, and would be at the lock-up strain following the 9-meter [30-foot] impact. The purpose of the SETU program was to demonstrate the margin of safety inherent in the design of radioactive material transportation packages. The package was then subjected to end-on impacts from drop heights of 9 meters [30 ft] (13.4 m/s [30 mph] impact velocity), 20 meters [67 ft] (20 m/s [45 mph]), and 36 meters [120 ft] (27 m/s [60 mph]) and a corner impact from a drop height of 36 meters. This set of extra-regulatory impacts provides a good benchmark with which to compare finite element analyses. Figure 10 shows the dimensions of the SETU. Figures 11and 12 show comparisons between the finite element analyses and the tests. As can be seen from the figures, there was excellent agreement. In all of the tests, the package remained leak-tight, and there was very little plastic deformation in the closure bolts.

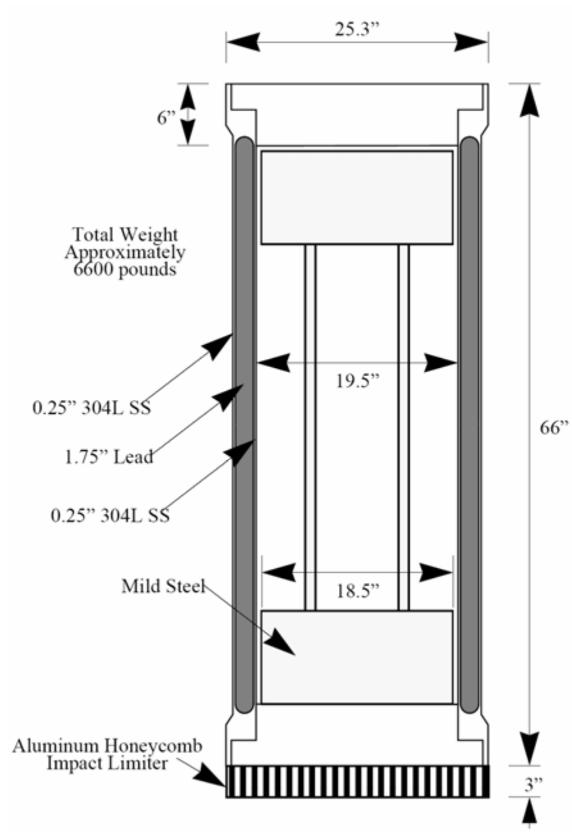


Figure 10 - Dimensions of the Structural Evaluation Test Unit

CONCLUSIONS

The analyses discussed in this paper clearly demonstrate the concept of graceful failure and the large margin of safety the spent fuel transportation casks have against release of radioactive material. Analyses and tests have shown that, even following an impact of 27 m/s [60 mph] onto a rigid target, there would be no release of radioactive material. As the ability of finite element analyses has improved so has the fidelity of the models used to analyze cask impacts. Increasing the fidelity of the finite element models has reduced the need to make conservative assumptions when performing the analyses. The effect of this measure can be seen in the differences in results for the analyses from the Modal Study (assumed release of radioactive material at impacts greater than 13.4 m/s [30 mph]), to NUREG/CR-6672 (release of radioactive material beginning at an impact speed of 27 m/s [60 mph]) and to NUREG-1768 (no release of radioactive material at 40 m/s [75 mph]).

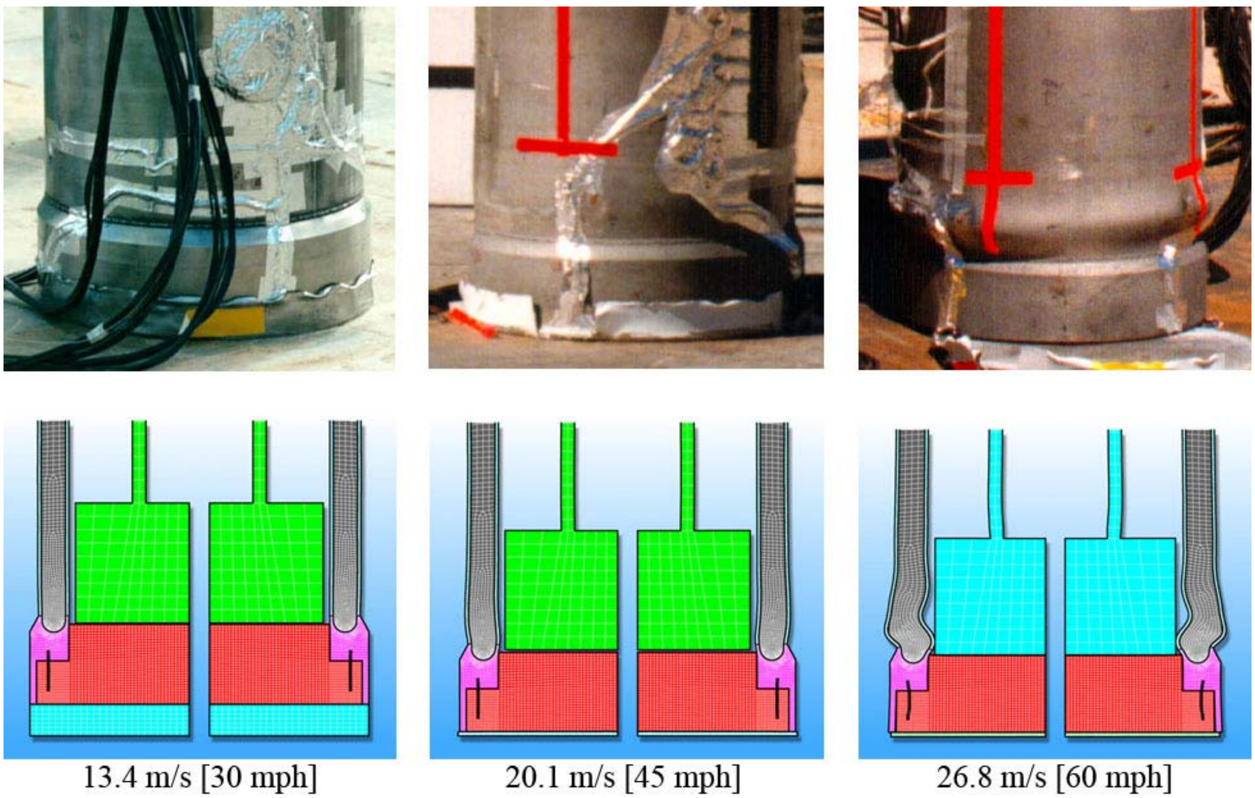


Figure 11 - Comparison between test and analysis results for the SETU end impacts

ACKNOWLEDGMENTS

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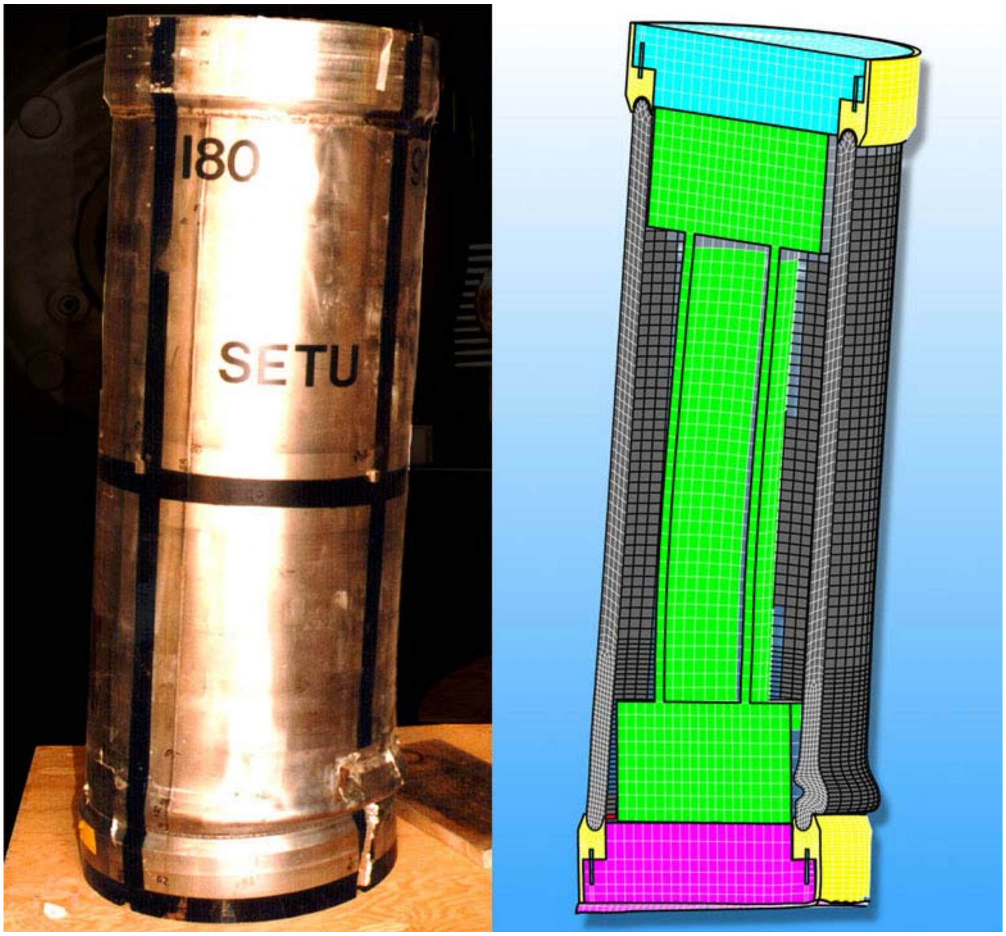

Figure 12 - Comparison between test and analysis results for the SETU 26.8 m/s [60 mph] corner impact