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Dynamic Non-Linear Impact Analysis of Fuel Cask Containment Vessels

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ABSTRACT

Large fuel casks present challenges when evaluating their performance in the accident sequence specified in 10CFR 71[1]. Testing is often limited because of cost, difficulty in preparing test units and the limited availability of facilities which can carry out such tests. In the past, many casks were evaluated without testing using simplified analytical methods.

This paper details the use of dynamic non-linear analysis of large fuel casks using advanced computational techniques. Results from the dynamic analysis of two casks, the T-3 Spent Fuel Cask and the Hanford Un-irradiated Fuel Package are examined in detail. These analyses are used to fully evaluate containment vessel stresses and strains resulting from complex loads experienced by cask components during impacts. Importantly, these advanced analytical analyses are capable of examining stresses in key regions of the cask including the cask closure. This paper compares these advanced analytical results with the results of simplified cask analyses like those detailed in NUREG 3966[2].

INTRODUCTION

Fuel casks are typically the largest transportation packages carrying radioactive material in commerce. Casks carrying spent fuel are the heaviest of these casks since they use lead, depleted uranium or other dense material to provide shielding. All packages containing radioactive material must be evaluated in severe impact and fire testing specified in 10 CFR 71. The impact testing includes thirty foot drop and puncture testing in the orientations which cause the most damage to the cask containment vessel. Since casks weigh tens of thousands of pounds, the logistics of executing impact testing is difficult and costly requiring large lifting equipment, high load release mechanisms, and extremely robust impact points. Each test unit is also more costly than the average test package because of its size and weight.

Given the limited testing inherent with fuel casks, analytical methods have always played an important role in demonstrating cask performance in dynamic impacts. The methods available to perform these evaluations have become extremely advanced in the last twenty years. In 1987, the Nuclear Regulatory Commission published Regulatory Guide 3966 entitled “Methods for Impact Analysis of Shipping Packages” as a guide for performing these analyses. This guide uses linear elastic analysis or principals which are well behind the current capabilities in non-linear analysis software. The following comparisons demonstrate that the NUREG is badly in need of an update.

DISCUSSION

T-3 Cask Analysis

The T-3 Cask is a spent fuel cask designed for transporting fuel from the Fast Flux Test Facility (FFTF). FFTF was a sodium cooled test reactor that was used to test experimental fuels and fuel cladding to be used in the U.S. breeder reactor program. The T-3 cask was designed in the late 70s and early 1980s when dynamic analytical capabilities were more limited than they are today. This analysis is documented in a Safety Analysis Report first published in 1985.[3] In 2007, an addendum was prepared to allow the transport of sodium bonded fuel in the T-3 cask. The Addendum[4] required an internal containment vessel to ensure no in-leakage of moderator would contact the fuel. It also required a re-evaluation of the cask to the dynamic accident sequence using modern detailed modeling with the latest ABAQUS explicit code. This re-evaluation offers a comparison of the more basic methods of the NUREG with the results from the latest analytical tools available.

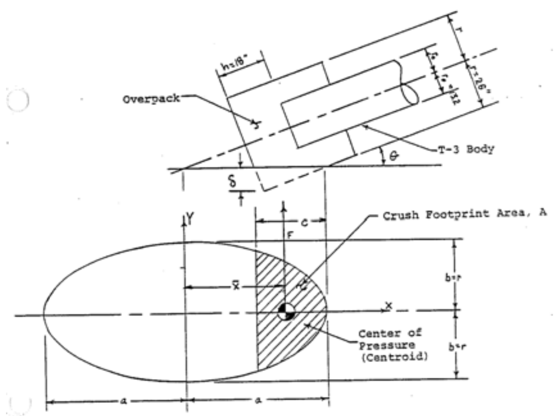

Figure 1
T-3 SAR schematic of Impact limiter Deformation

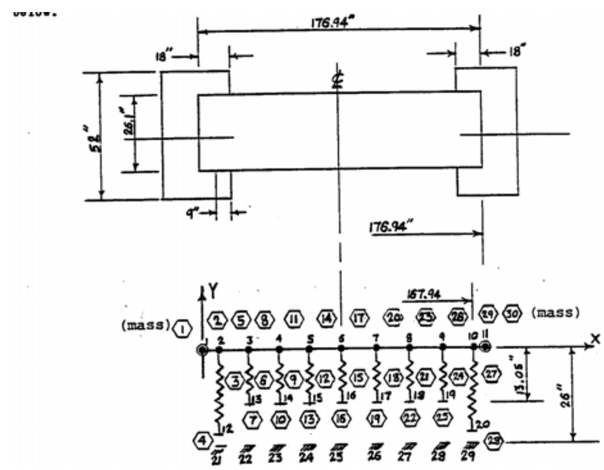

Figure 2
T-3 SAR Side Drop Finite Element/ Lumped Parameter Model

Both the SAR analysis and the ABAQUS analysis conclude that the worst can deceleration of the cask occurs in the side drop configuration. In all orientations but the bottom down drop orientation, the SAR analysis under-predicts the ABAQUS analysis as shown in Table 1. The SAR analysis uses proprietary computer codes which equate the strain energy of the crushed foam with loss in kinetic energy of the impacting cask over the impact sequence. This computer code accounts for the increased crush foot print contact area but must assume a uniform crush stress and does not account for the constraining effects of the impact limiter skin The ABAQUS model uses the latest numerical techniques for evaluating crushable foam and also models the constraining effects of the impact limiter skin. The SAR end drop analysis assumed that only the foam under the shaft of the cask provided impact absorption leading to a higher cask deceleration than the ABAQUS analysis.

Table 1. Comparison of Maximum Acceleration Values for T-3.

Orientation	SAR Section	Accelerations, g *(see note1)*			Max Displacement, in		
		SAR	75°F	-20°F	SAR	75°F	-20°F
Flat Bottom Drop	2.7.1.3	87.80	69.1	82.2	14.0	7.80	6.51
Center of Gravity Over Corner (CGOC)	2.7.1.1	50.20	67.8	74.1	13.5	11.20	9.84
Flat Side Drop	2.7.1.2	94.50	109.7	126.8	9.2	5.43	4.64
Side Drop with Slapdown	n/a	n/a	103.6	120.2	n/a	14.6 *Note (2)*	13.8

(1) Maximum accelerations taken from plots in Attachment 1, divided by 386.4 in/sec² for acceleration in g's.
*(2) Displacement for side drop slapdown includes 5 degrees of rigid body rotation (~ 80*sin(5) ~ 7 inch*

The SAR analysis used an ANSYS finite element model similar to the lumped parameter method described in NUREG 3966 to investigate the bounding side impact. This crude model, shown in Figure 2 consisted of a nine beam elements each with a discrete mass and stiffness. Elements simulating the impact limiters were used at either end of the cask shaft. The load deflection characteristics of the impact limiter elements were determined with the proprietary crush footprint programs described earlier. The cask body beam element load deflection characteristics were determined by considering the cask body as an equivalent tube with composite properties of lead and stainless steel. This model was used in both a linear elastic analysis and a plastic analysis since the elastic analysis concluded that both the inner and outer shell yielded through the entire section of the equivalent tube.

The ABAQUS finite element model[6] from the 2007 Addendum is a half symmetric ABAQUS nonlinear dynamic finite-element analysis using explicit time integration. Each cask component was separately examined in a detailed mesh model consisting of three dimensional Type S4R shell elements and Type C3D8R brick elements. The model included a sensitivity study of the dynamic properties of lead on the overall stresses and strains of the model. The model also accounts for non-uniformity in the impact limiter foam stress, the constraining effects of the impact limiter skins, loads on contact surfaces between components and energy absorbed through plastic deformation of all components. A depiction of the ABAQUS model is shown in Figure 3 at the conclusion of the HAC side drop with no scale factor applied to the deformations. While the SAR analysis used about 30 elements in all to represent the entire cask, the ABAQUS model used thousand of elements for each component. An example of the finite element mesh of one impact limiter foam is shown in Figure 4. The ABAQUS model was also used in both a linear elastic analysis and a detailed plastic analysis to compare with the SAR results.

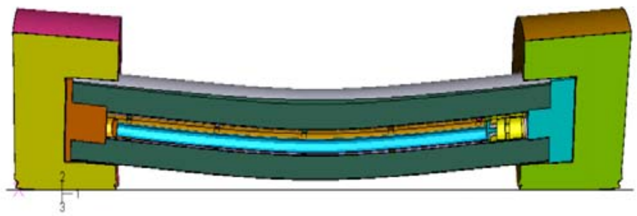

Figure 3
ABAQUS model of T-3 HAC Side Impact

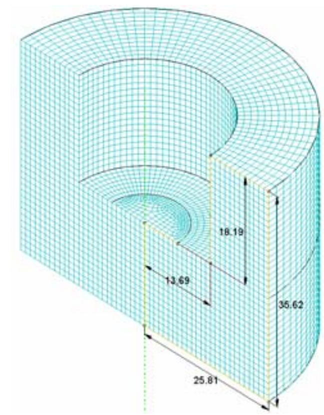

Figure 4
Example of T-3 ABAQUS Finite Element Mesh for the Impact Limiter

T-3 Linear Elastic Analysis Comparison

The lumped parameter analysis from the SAR concludes that the maximum primary membrane stress of the T-3 containment vessel is slightly over the proportional limit of the 304 stainless material or about 29.1 ksi when cask materials (excluding impact limiters) are assumed to remain linear elastic (Reference 3, page 2-204). Thus the SAR authors concluded that the maximum primary membrane stress of the T-3 containment vessel meet the Regulatory Guide 7.6[7] requirements for primary membrane stress ($0.7S_u$ or 46.2ksi) for an HAC side drop of a T-3 Cask for a linear elastic analysis.

The results of the ABAQUS analysis reach a far different conclusion when cask materials other than the impact limiters are assumed to remain linear elastic (linear modulus applies regardless of stress). The primary membrane stress for the cask containment vessel determined by this analysis is approximately ten times higher than the stress determined in the SAR or about 331.9 ksi , well above the Regulatory Guide 7.6 stress limit for linear elastic analysis. The ABAQUS results indicate that linear elastic analysis and criteria are not appropriate for cask drops using modern simulation techniques. These modern techniques can capture high stresses imposed when stress relief from material yielding is not present during impacts. This was often not possible with the crude models used when NUREG 3966[2] and Regulatory Guide 7.6[7] were developed.

T-3 Plastic Analysis Comparison

The SAR repeated the ANSYS model side drop in a plastic analysis using the same equivalent tube model for the cask body but considering plastic strains when material stress exceeded yield strength in the time integration. The results of the SAR plastic analysis of the side drop impact indicated a maximum strain of 0.02 in/in at the exterior of the equivalent tube and a strain of 0.0064 in/in at the interior of the equivalent tube representing the cask containment. This under-predicted the ABAQUS[6] results which found a peak tensile strain in the outer shell of 0.05 in/in and 0.02 in/in in the containment vessel. Although still below the limit for ductile tearing, the cruder SAR model is clearly not conservative when evaluating ductile tearing in a plastic analysis. The cumulative plastic strains for the cask body from the ABAQUS analysis are shown in Figure 5.

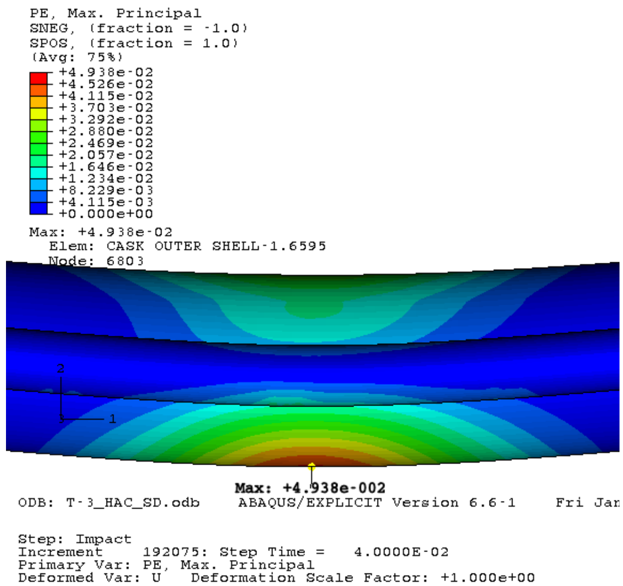

Figure 5
T-3 ABAQUS Side Drop Plastic Equivalent Strain Results

Hanford Un-irradiated Fuel Package

The Hanford Un-irradiated Fuel Package (HUFP) is an unshielded fresh fuel cask with a thin wall (0.56 inch) stainless steel containment shell designed to ship un-irradiated Driver Fuel Assemblies (DFA)[8]. The HUFP utilizes the same containment body and impact limiters as those used for the Mixed-Oxide Fresh Fuel Package (MFFP, Docket No. 71-9295) although the HUFP has a different internal structure making up about half the total package weight of 14,000 pounds. The MFFP was certified by full scale testing in free drop and puncture to ensure compliance with the requirements of 10 CFR 71[1].

A confirmatory analysis using an ABAQUS non-linear dynamic finite element model was used by the Packaging Certification Program to verify the performance of the HUFP design in the accident sequence. As part of this analysis, a 60 inch[*] puncture simulation was produced to determine the maximum stress and strain experienced by the containment vessel in a mid body impact. Figure 6 shows the impact configuration along with a maximum von-mises stress plot of the cask body. Figure 7 shows a close up of the impact point with a contour plot of maximum plastic strain in the containment vessel.

[*] Approximately 20 inches were added to the 40inch drop height required by the regulations for the puncture test.

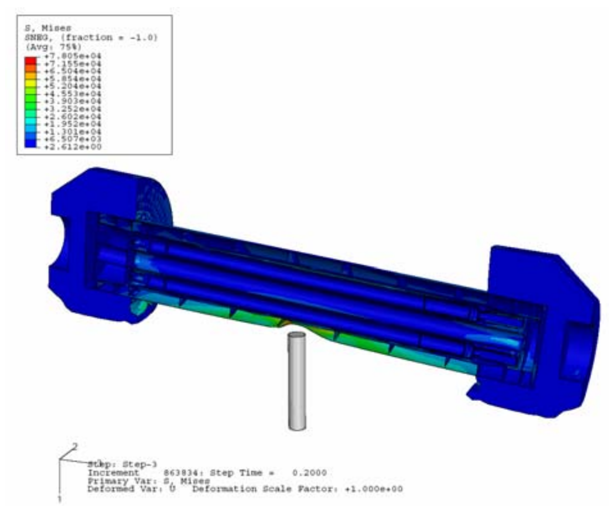

Figure 6
HUFP ABAQUS Puncture Configuration
Equivalent Strain Results

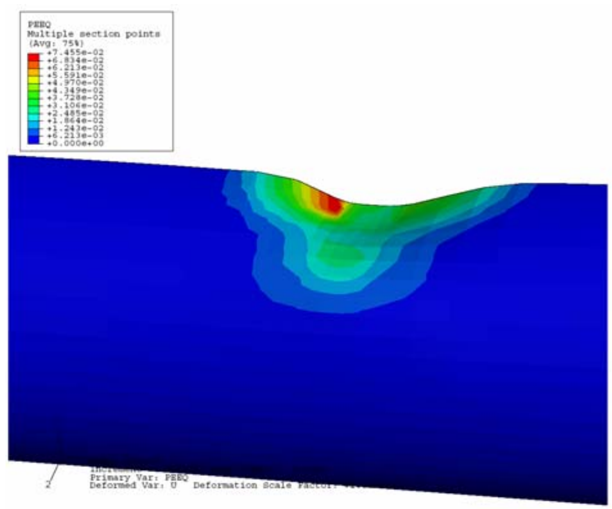

Figure 7
HUFP ABAQUS Puncture Equivalent Strain
Results

The maximum true stress shown in Figure 6 is about 78 ksi while the maximum true strain shown in Figure 7 is approximately 0.075 in/in. Both these values can be compared to appropriate stress and strain failure limits to establish the margin of safety from for package design for a puncture event. Determining package margin of safety is more difficult when interpreting the physical test results of dynamic impact tests. Figure 8 shows two views of the actual MFFP puncture pin test with a measurement of the dent depth. Strain gages are often not used in dynamic tests since the impact point is difficult to control and gage orientation is difficult to determine prior to the impact. The type of damage evaluation shown in Figure 8 is often the only type of quantitative damage evaluation allowed. In this case, the depth of deformation in the puncture test correlates well with the model results when the added 20 inches of drop height is considered.

The HUFP ABAQUS analysis actually involved a combined 30 foot drop followed by the 60 inch puncture as a continuous sequence. The variation in Energy of the HUFP cask system during the entire sequence is shown in Figure 9 which is a plot of kinetic, plastic strain and elastic strain energy over time. The 30 foot drop occurs over the first 0.02 seconds of the graph where kinetic is momentarily reduced to zero before rebounding. This is followed by a small adjustment in velocity to setup the puncture drop. The puncture drop occurs between 0.03 and 0.20 seconds. Since the impact limiters are not involved, the cask takes longer to come to rest from the puncture event. For the puncture event, the increase in plastic strain energy is entirely within the cask body material since the impact limiters are not involved.

Figure 8
MFFP Puncture Pin Damage

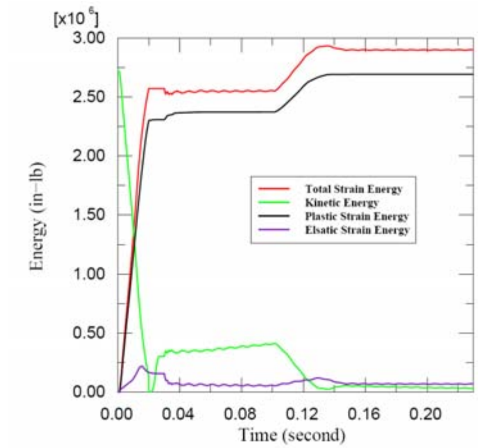

Figure 9
HUFP ABAQUS Energy Variation for 30-Foot Drop and Puncture

CONCLUSION

Dynamic non-linear analysis of large fuel casks using advanced computational techniques is essential in evaluating the performance of large shipping casks even when full or partial scale testing has been performed. These analyses more accurately determine localized stresses and strains than the methods outlined in NUREG 3966[2].

As stated previously, linear elastic analysis and criteria are not appropriate for cask drops using modern simulation techniques. These modern techniques can capture high stresses imposed when stress relief from material yielding is not present during impacts. This was often not possible with the crude models used when NUREG 3966[2] and Regulatory Guide 7.6[7] were developed. Both this NUREG and Regulatory Guide are in need of a significant update to remain relevant for use with the latest analytical tools.

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