

Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

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Fuel Cask Impact Limiter Vulnerabilities

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Abstract

Cylindrical fuel casks often have impact limiters surrounding just the ends of the cask shaft in a typical “dumbbell” arrangement. The primary purpose of these impact limiters is to absorb energy to reduce loads on the cask structure during impacts associated with a severe accident. Impact limiters are also credited in many packages with protecting closure seals and maintaining lower peak temperatures during fire events. For this credit to be taken in safety analyses, the impact limiter attachment system must be shown to retain the impact limiter following Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) impacts. Large casks are often certified by analysis only because of the costs associated with testing. Therefore, some cask impact limiter attachment systems have not been tested in real impacts. A recent structural analysis of the T-3 Spent Fuel Containment Cask found problems with the design of the impact limiter attachment system. Assumptions in the original Safety Analysis for Packaging (SARP) concerning the loading in the attachment bolts were found to be inaccurate in certain drop orientations. This paper documents the lessons learned and their applicability to impact limiter attachment system designs.

Introduction

Impact Limiters are used to absorb energy from the impacts associated with transportation accidents. The fuel casks they typically protect are designed for structural strength rather than energy absorption. As safety analysis for packaging has developed over the years, the secondary function of these impact limiters in thermal protection of cask components has become more prominent. The thermal protection provided by the impact limiters in the regulatory fire scenario can include preventing over-temperature of elastomer seals as well as preventing melting and/or phase changes of cask components and maintaining structural materials at temperatures required for strength rating.

Early designs of impact limiter attachment systems often involved simple attachments on the cask shaft away from potential impact points. The implicit assumption seems to have been that the impact limiter would compress around the end of the cask in an impact and any attachment along the cask shaft would be in a low stress region not subject to significant loading. A review of Cask SARPs also shows an emphasis on demonstrating retention of the impact during the puncture pin test rather than the nine meter drop. Because of these assumptions, the impact limiter attachment points in many packages were shown to retain the impact limiter in place for the nine meter drop only by a simple, cursory analysis.

The Model T-3 Cask is a Type B spent fuel cask designed in the late seventies for transport of Fast Flux Test Facility (FFTF) fuel. Neither full scale nor partial scale impact testing was performed in the original certification process. The analytical tools available at the time were limited, but the cask was certified with the assumption that the impact limiters would remain in place to protect the cask in the regulatory fire event.

In 2007, an addendum was prepared to allow the transport of sodium bonded fuel in the T-3 cask. The Addendum¹ 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. Although, no testing was conducted to support the addendum, concerns by the regulatory reviewer led to a detailed analysis of the impact limiter attachment system in all orientations which could challenge it. The results called into question the original assumption in the Safety Analysis with regard to impact limiter retention.

T-3 Cask

The Model T-3 Cask is a Type B package designed specifically to contain, shield and ensure sub criticality of irradiated fuel pins and assemblies from the Fast Flux Test Facility (FFTF) for transportation over public highways.² The major design features of the T-3 Cask, shown in Figure 1, include two cylindrical and concentric stainless steel shells separated by 7¾ inches of lead gamma-shielding material. The inner shell is a length of 8-inch Schedule 40 pipe with a full diameter opening on one end for loading and unloading contents and a smaller diameter opening on the opposing end for use with a push rod for removing warped or expanded contents from the cask cavity. The full diameter cask containment vessel opening is closed with shield plug sealed by viton elastomer O-rings. The push rod plug on the opposing end of the cask containment is also sealed by viton O-rings.

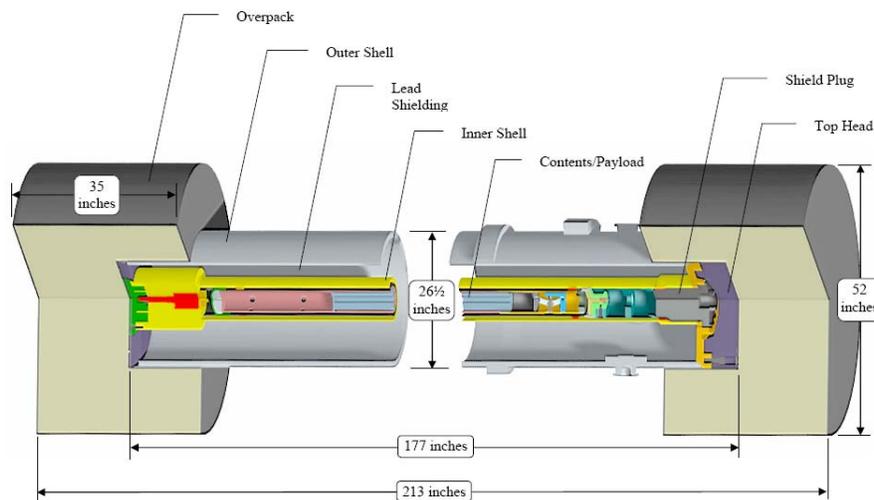


Figure 1
T-3 Cask

The outer shell of the T-3 cask is composed of 1-inch thick stainless steel with an outer fire shield made up of 0.080 inch diameter wire spiral wound on the outside surface of the cask capped with 10 gage stainless steel sheet. The shield plug end of the cask has a closure plate (labeled as the top head in Figure 1) which provides protection for the cask closure. A smaller cover plate protects the push rod plug on the opposing end of the package.

The impact limiters shown in Figure 2 consist of low-carbon steel shells filled with rigid polyurethane foam each mounted via four 5/8-inch bolts equally spaced around the circumference of the cask. The cross-section of an impact limiter is depicted in Figure 2 which shows two of the four attachment bolts. Each bolt is about four inches long and

passes through an unthreaded lug on the cask body. The end of the bolt threads into an insert in the impact limiter that is attached to steel channel embedded in the polyurethane and runs parallel to the shaft of the cask as shown in Figure 2.

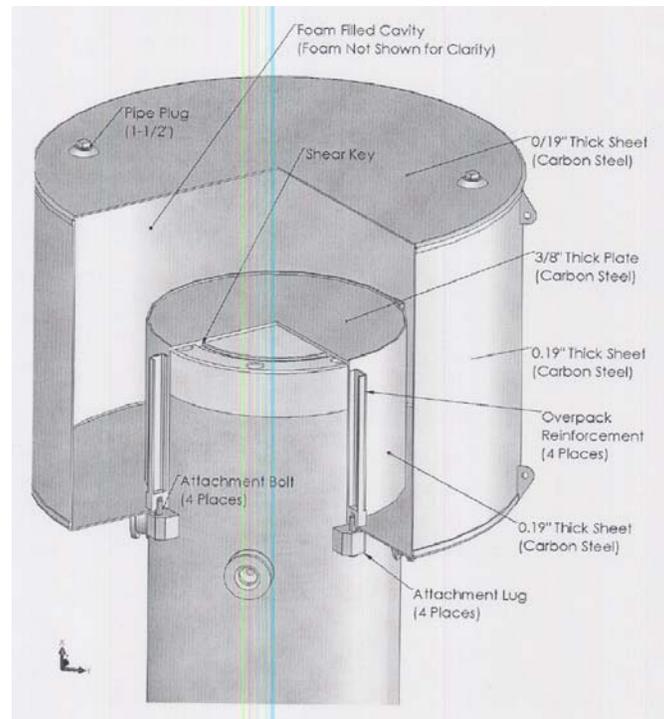


Figure 2
Impact Limiter Detail

The finite element model shown in Figure 3 is an advanced dynamic model depicting the cask in a steep angle drop just before impacting from a 30 foot drop in the vertical direction. Impact limiter components are fully modeled in a detailed mesh as are the bolts and lugs. Each component was modeled in ABAQUS with elements consisting of three dimensional Type S4R shell elements and Type C3D8R brick elements. The model 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 components. The cask itself is composed of rigid elements since this model specifically evaluates the impact limiters and the attachment system.

The output of the steep angle drop analysis indicated some unexpected results which were not documented in the T-3 existing Safety Basis. The existing Safety Basis considered that the only significant impact limiter bolt loads in a steep drop (CGOC) would be axial loads from the moment applied to an impact limiter by an assumed linearly increasing crush force across the impact limiter face.(Figure 4). The detailed finite element analysis revealed that the shear load on the bolts is much more significant than any tensile force applied.

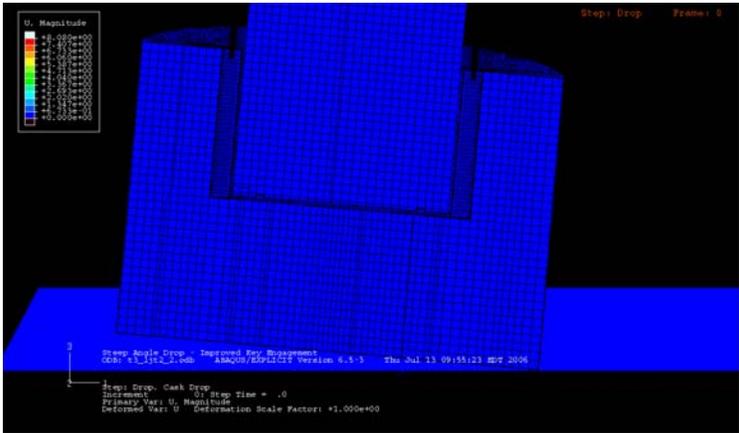


Figure 3
Finite Element Model

Figure 5 shows the results of the detailed finite element analysis. As the cask impacts in a steep angle drop, the shaft of the cask rotates slightly more than the impact limiter pocket. This creates displacements between the bolt attachment point and the lugs which creates large shear strains in the short bolts.

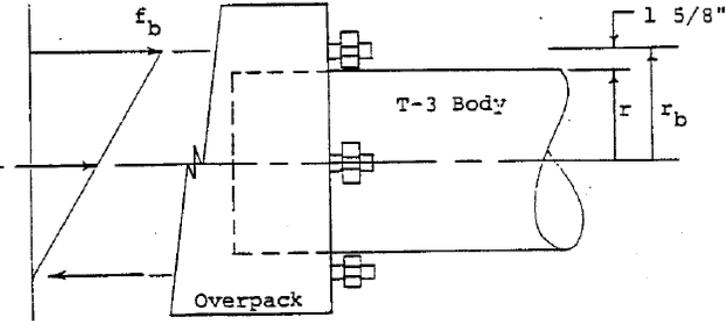


Figure 4
Original Analysis of Impact Limiter

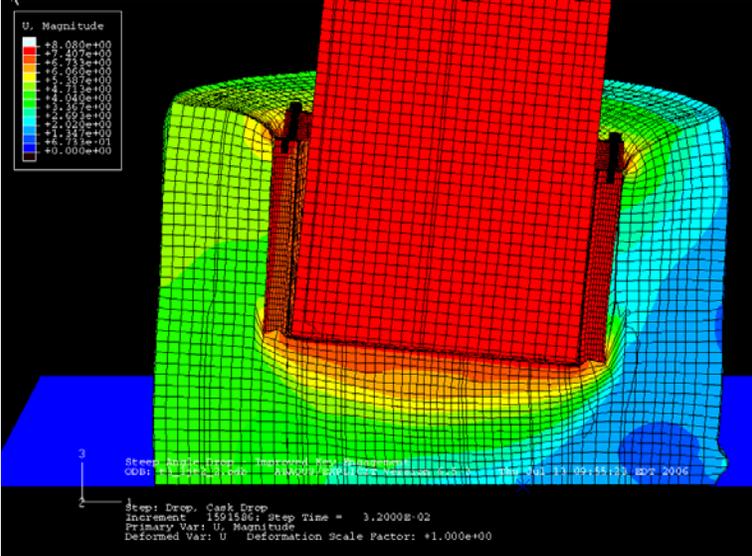


Figure 5
Results of Steep Angle Drop

Figure 6 is a close up of the far left bolt showing the shear load placed on it by the relative displacement between the cask shaft and the impact limiter insert. The impact limiter insert is well reinforced by the steel channel which is both embedded in the polyurethane foam and welded to the skin of the impact limiter pocket. The lug welded to the cask body is also a relatively stiff component and the gap between the insert and lug is less than an inch when the impact limiter is secured in place. The attachment bolts are therefore in a highly constrained condition that makes them susceptible to high strains.

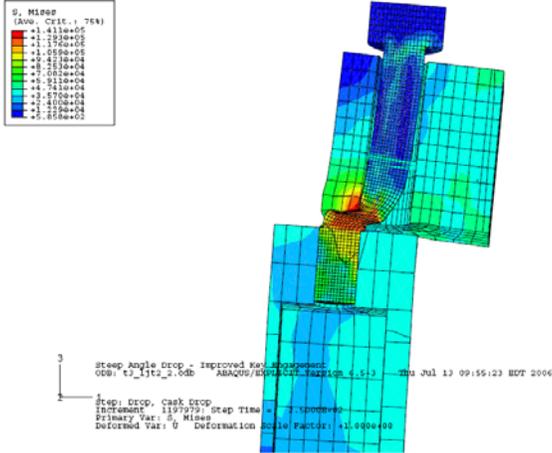


Figure 6
Deformation of Bolt Opposing Initial Impact Point

The other three impact limiter attachment bolts also reached the failure strain of the bolting material. Figure 7 is a close up of the far right bolt which has the lowest strain of

the four attachment bolts in this scenario but was still considered to be failed. The same analysis was repeated for a NCT drop of one foot. The results demonstrated that the attachment system would retain the impact limiter in place for the start of the HAC impact scenario.

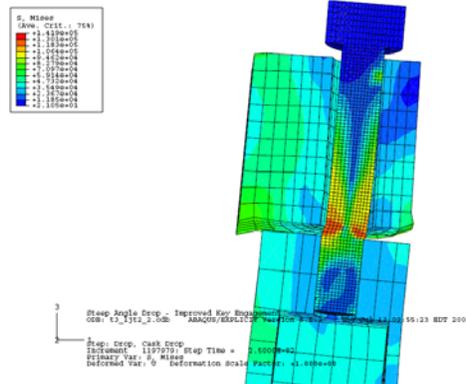


Figure 7
Deformation of Bolt Nearest Initial Impact

These analysis results called into question the assumption that the impact limiters would be in place for a post HAC impact fire event. The SARP Addendum for shipment of the sodium bonded fuel addressed this issue by analyzing the cask without the impact limiters in place for the fire event. O-ring seals and other component temperatures for both the cask and 6CVL were found to be acceptable in the fire event without the protection of the impact limiters.

Design Improvements

Two U.S. Certified Casks which made changes to the impact limiter attachments during development included the Nuclear Assurance Corporation Legal Weight Truck (LWT) Cask³ and the U.S. Department of Energy Radioisotope Thermoelectric Generator Transportation System (RTG)⁴.

The LWT uses a clevis pin arrangement with the center lug embedded in the impact limiter and the surrounding lugs attached to the cask surface. Although different than the T-3 design, this has the same potential for highly constrained attachment components vulnerable to failure by what might otherwise be considered relatively small relative displacements between the cask and the impact limiter. The thickness of the lug material was increased to address test failures. The RTG Package design was modified at least in part to ensure concerns with constrained attachment bolts were addressed.

One cask design where attachment point constraint is addressed is the Hanford Unirradiated Fuel Package (HUFP) design whose impact limiter is shown in Figure 8⁵. Although this design has a similar layout as the T-3 cask with four bolts passing through lugs on the shaft of the cask, there are several key difference. The first notable difference

is that the length of the bolts extends the full depth of the impact limiter pocket. Also, the bolt pockets in the impact limiter are large enough to allow for significant bending in each bolt before concentrated shear loads are imposed on the bolts. Relative displacements between the cask body and impact limiter on the order of those seen in the T-3 Cask, lead to much smaller bolt strains in this design as validated by testing and analysis³.

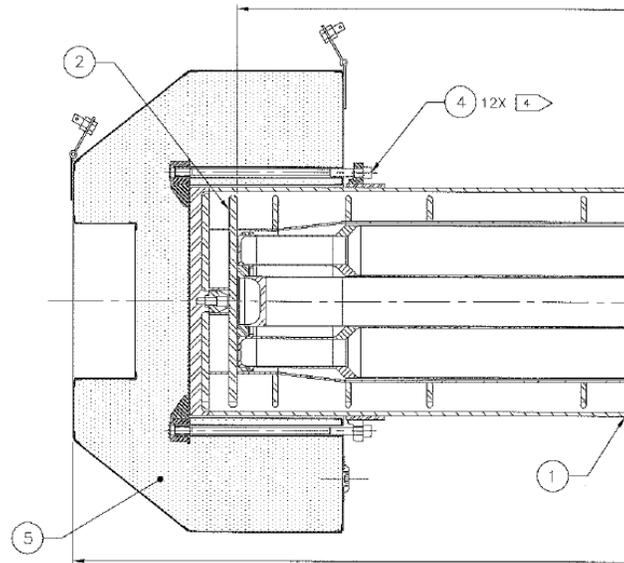


Figure 8
HUFPP Impact Limiter Detail

Conclusions

Many older casks have impact limiter attachment systems which may fail in certain drop test orientations required by 10CFR 71.73. Care should be taken to ensure that the assumptions in Safety Analysis Reports for Packaging (SARPs) are correct. New cask designs should consider attachment bolt or pin loading conditions carefully when impact limiters are credited with remaining in place in the post impact regulatory fire.

References

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