Response of Spent Fuel Transportation Casks to Explosive Loadings*

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ABSTRACT

Casks for the transportation of spent power reactor fuel can be exposed to explosive loadings from several causes. Exposure can come from an accident involving a propane or other hydrocarbon tanker, from an accident involving military or industrial explosives, or from deliberate sabotage. The regulations for the design of these casks do not specifically include requirements for resistance to blast loadings, but the hypothetical accident sequence that the casks are required to survive assure some measure of blast resistance. To perform accurate risk and security assessments, this blast resistance must be quantified.

This paper will discuss the methodology used to determine the blast resistance of a representative rail and a representative truck spent fuel transportation cask. The methodology discussed in this paper can be used to determine the response to explosive loadings other than the one discussed in this paper or to determine the effect of explosive loadings on other casks. Due to the sensitive nature of this topic, this paper is intentionally vague on a number of parameters used in the analyses.

INTRODUCTION

Using numerical analyses, the present study examines the response of representative shipping casks to large explosions. Detailed models of the casks, including transport and support structures were constructed. A homogenized material represented the fuel assemblies inside the cask. The goal of the analyses was to determine the extent to which the cask would be damaged and if there would be loss of containment.

The numerical analyses were performed with the Eulerian shock physics code, CTH [1,2], in which the explosion, incident pressure on the casks, local collapse of the cask walls, and behavior of the homogenized fuel were modeled. In these Eulerian simulations the computational mesh must define both the space containing the explosive material as well as the region into which explosive product gases and material might move. The models of the cask and associated structures are constructed by inserting a large set of simple geometric objects into the spatial mesh. Selection of an appropriate set of these simple objects allows complex structures to be readily represented. The objects are not defined by body-fitted meshes as they would be in a Lagrangian code. Instead, interfaces consist of mixed cells within the mesh – the finer the mesh, the more precise the definition of the interfaces; that is, interfaces are defined to within a cell dimension. If the interface between two materials falls within a cell, that cell is a mixed cell. The user has some control over the way mixed cells are treated within the code. For these analyses, mixed cells were treated with material properties equal to the ratio of the properties of the materials that make up the cell (e.g., if a cell is 50% steel and 50% air, the yield strength of the mixed cell will be 50% of the yield strength of steel). The CTH code used in this study has been successfully compared with performance data from many very high-speed impact conditions and explosive ordnance applications. The current application represents a class of problems that required some preliminary work to establish a comparable level of confidence in the CTH numerical results.

CASK GEOMETRY, MODEL, AND MATERIAL DEFINITION

The representative rail shipping cask included a PWR fuel basket filled with a homogenized material representing the spent nuclear fuel assemblies. Appropriate material properties were used for the cask components. The large dimensional scale of the cask and explosion severely limit the level of detail (resolution) that can be accommodated in these simulations. Spatial features significantly less than the cell dimension can be inserted into the computational mesh, but become part of the mass in a mixed cell (cell with multiple materials), and thus lose their distinctive character. For the fuel rods, an average density was determined for an individual fuel element assembly tube, and then representative properties were assigned to this unit. The average density of the fuel assembly was determined to be approximately 5.1 g/cm^3. The fuel assembly was treated as a homogeneous porous material, with this average reference density from which the void (free volume within the unit) could be crushed as the material is compressed. When the void is fully removed, the material then responds with the fully dense uranium oxide behavior. The solid density of the fuel was taken to be that of uranium dioxide fuel pellets – about 10.3 g/cm^3. Although this approach permits the fuel to respond nominally as if the full definition of the fuel were included, the behavior of the cladding was not included in this material approximation. The basket structure supporting the fuel assemblies can contribute significantly to the loading path through the fuel region, so this structure was included in the cask model.

The main body of the cask is about 2m [80 in] in diameter and 5m [200 in] long. The wall of the cask has an equivalent areal density of about 175 g/cm^2 (integral of material density through the thickness). The impact limiters were modeled as a low density, homogeneous porous aluminum. Portions of these are stripped off by explosive loading, and they do not contribute to the cask loading. The mass of this cask model is about 80,000 kg [180,000 lbs], with a payload of about 40,000 kg [90,000 lbs]. Ancillary structures such as tie-downs, support blocks, and railcar bed features were also modeled, but the personnel barrier was not. It was presumed that the center of the explosion would be essentially level with the cask centerline, above the railcar surface. Although no significant moderation of the blast by the railcar was expected to occur, this structure was included to validate that assumption. The duration of the blast event is sufficiently short (a few milliseconds) that the cask deformation will be complete prior to any gross cask displacement from its support on the railcar. Figure 1 shows the complete cask/skid/railcar model.

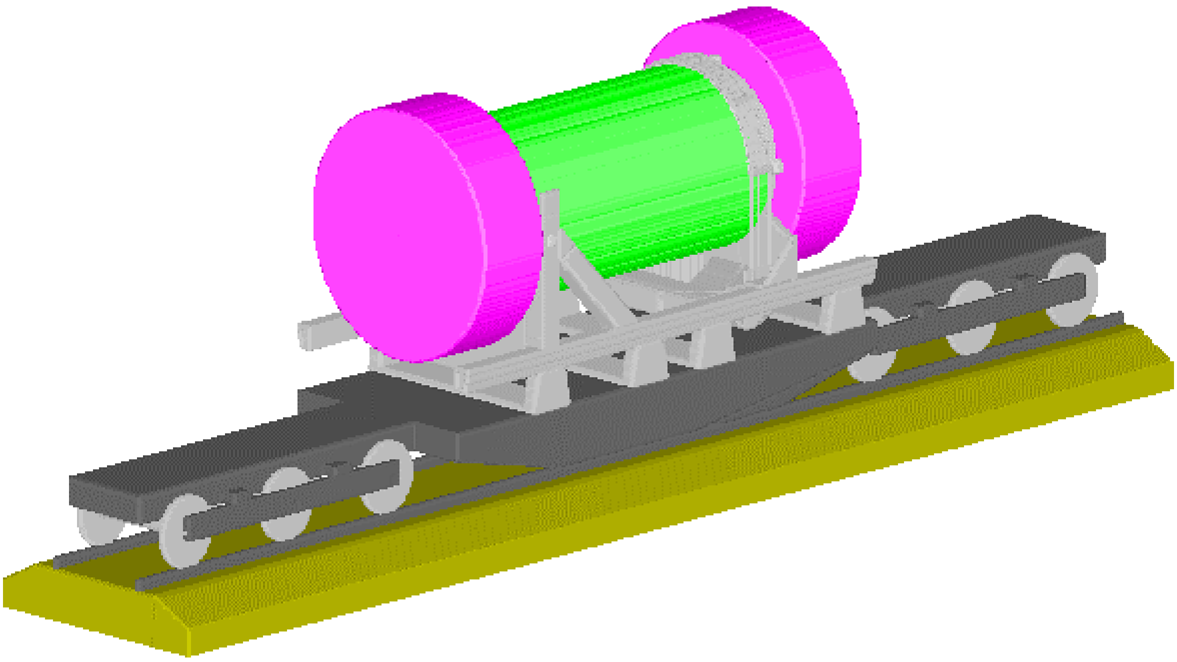

Figure 1. The computational model for the cask, railcar, and cask support structure.

Typically, the desired resolution of the CTH mesh is tied to the minimum characteristic dimension of some feature of the device being modeled. In general, one would like to have several cells across the thickness of a material layer. For this analysis, nominal cell dimensions of 5 cm [2 in] resolution were used, constrained by the magnitude of the associated database and the long duration of the calculations. Although the detonation is complete in a short time, the time to impart the impulse and come to some equilibrated deformational state in the cask is on the order of 10's of ms (problems were often run to 25 ms to confirm that no further deformation was occurring). A mesh resolution of 5 cm [2 in] leads to about 5 million computational cells, and requires 384 processors 90 CPU hours to calculate a 25 ms event. This relatively coarse resolution was adequate to resolve the main cask features. A much finer mesh would be required to accurately resolve the smaller cask and fuel basket details.

The truck cask is a much smaller container than the rail cask, and contains only a single fuel assembly. The nominally square fuel assembly is assumed to be positioned in the center of the cylindrical cask cavity by a solid aluminum basket with a circular outer surface. The fuel assembly is again modeled as an homogenized mass. Figure 2 illustrates the cask mounted on the trailer truck bed. As with the rail cask, the center of the explosion was assumed to be at the same height as the center of the cask.

The numerical resolution of this simulation was 2.5 cm [1 in], leading to 26 million cells over the computational space. Computing platform resources utilized 2048 processors for 125 hrs of CPU time to reach 26 ms of problem time. The total memory size of the problem database was about 53 Gbytes.

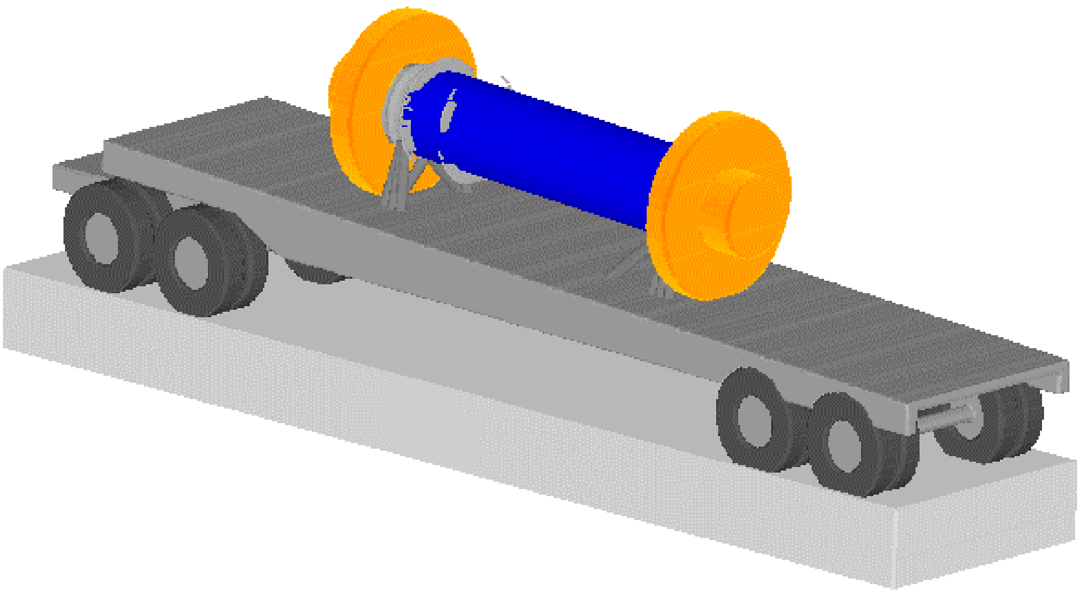

Figure 2. The computational model of the truck cask and trailer.

RAIL CASK RESPONSE TO A LARGE EXPLOSIVE CHARGE

As the pressure pulse from the explosion loads the exposed surface of the cask, the weak exterior steel skin and the polyethylene neutron shield that it covers are quickly stripped away, leading to local deformation of the steel outer shell of the sandwich-wall cask body. Figure 3 shows the damage to the cask and railcar resulting from the explosion. There is significant damage to the neutron shield and impact limiter, but only slight depression of the cask immediately next to the location of the explosive charge. The incident pressure at the surface of the cask is on the order of 800 MPa [100 ksi]. Such local pressures are more than sufficient to permanently deform these structural stainless steel materials, which have yield strengths of less than 400 MPa [60 ksi]. Even though the pressure pulse is basically unloaded after only a few milliseconds, there ensues a long ‘coasting’ period in which the effects of the locally induced deformations are transmitted through the cask as exterior and interior motions, leading eventually to general cask translation. The cask support structures have also been stripped away on the charge side of the railcar. In this time frame, the displacement of the cask is minimal. There is clearly some internal crushing of the fuel elements near the mid-section of the cask, with less crushing at increasing distances away from that region.

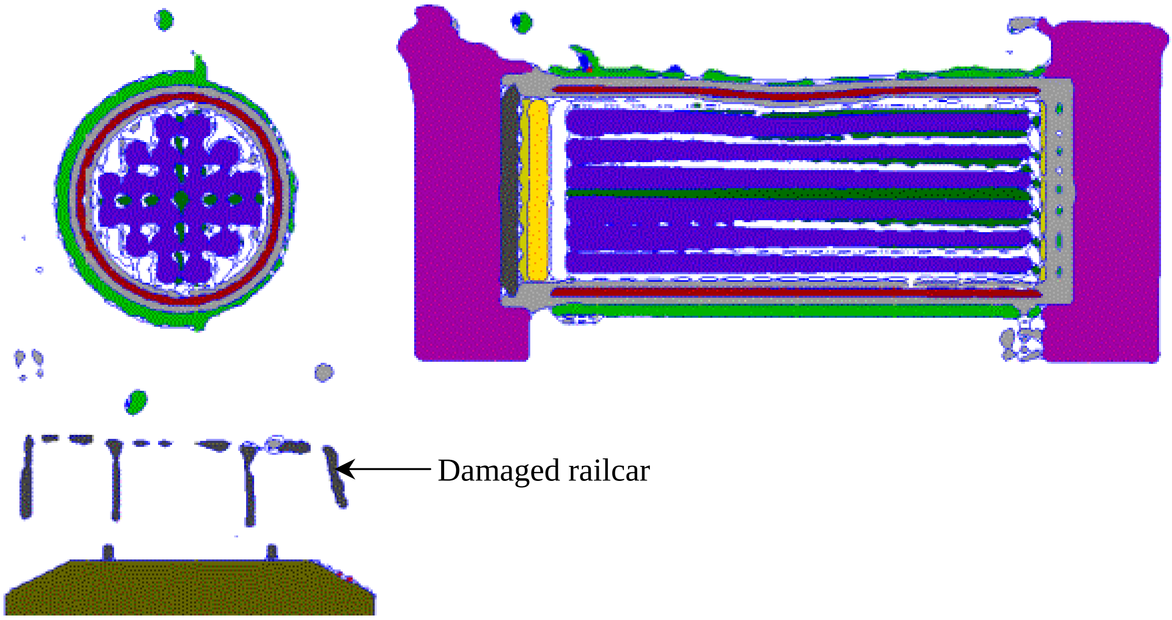

Figure 3. Final deformation of the cask (25 ms).

When the railcar is not included in the simulation, there is very little difference in the overall cask deformation, as seen in the comparisons in Figures 4 (perspective views at 25 ms) and 5 (transverse and longitudinal cross-sections at 25 ms). Thus, the rail car and cask supporting structure cause little interference with the primary blast loading of the cask.

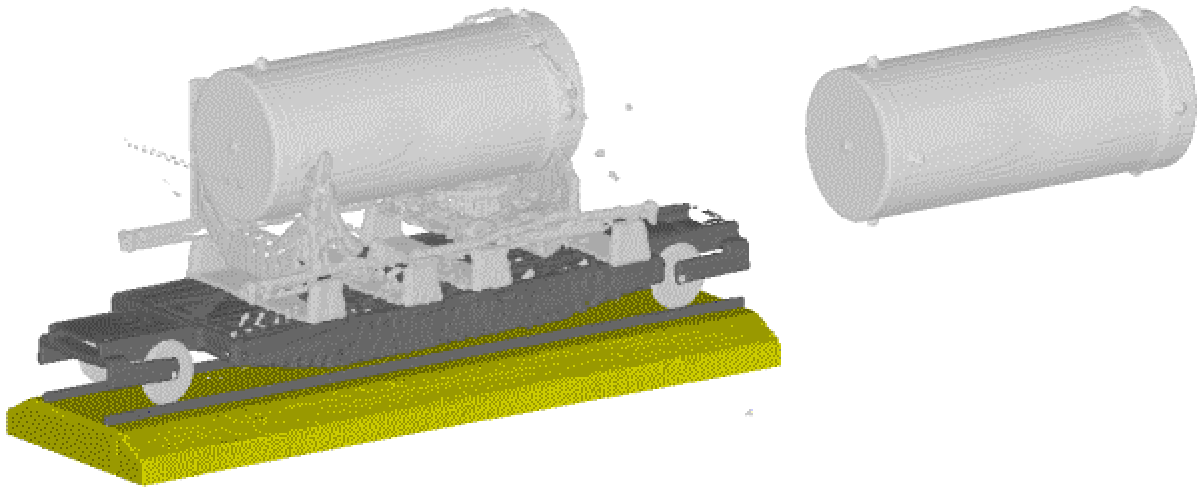

Figure 4. Perspective views of the cask with the railcar (left) and free-standing (right).

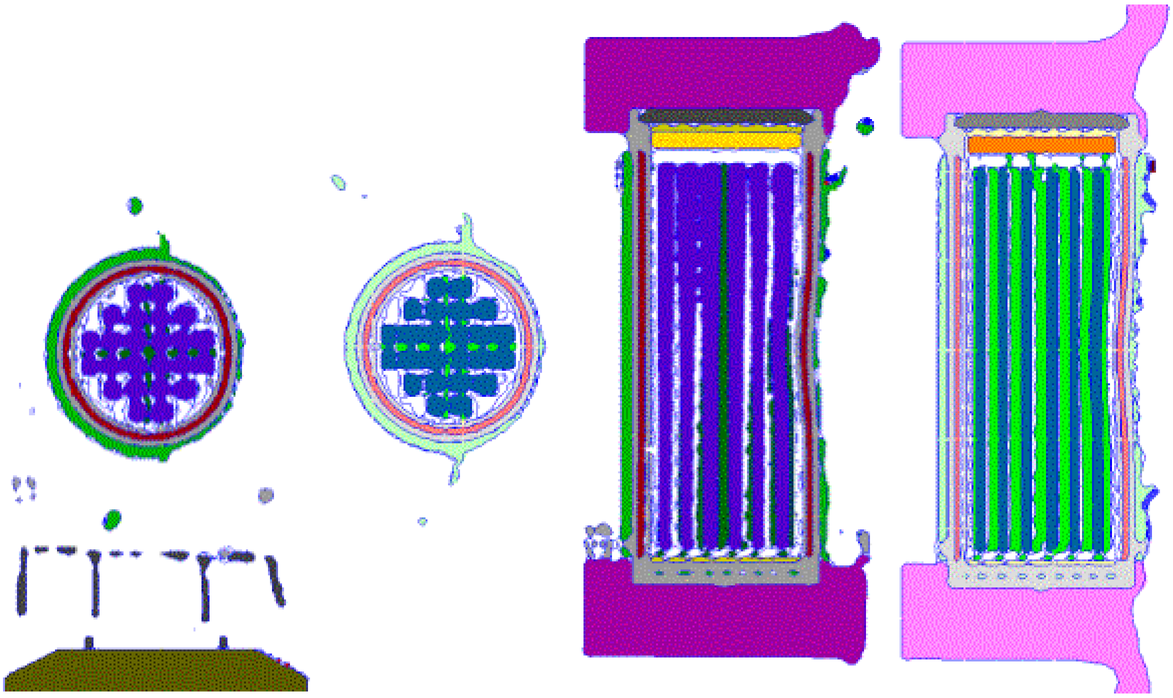

Figure 5. Transverse (left) and longitudinal (right) pair views of the cask at a time of 25 ms. Within each pair, the cask with the railcar is on the left and free-standing cask is on the right.

These plots of the cask structure indicate that the cask has not been breached for the charge analyzed.

TRUCK CASK RESPONSE TO AN EXPLOSIVE CHARGE

Figure 6 shows a sequence of longitudinal cross-section views of the truck cask through the plane of the charge. The charge products incident on the cask cause the cask to bend. That bending deformation is basically complete in about 10 ms. (The white areas around the red explosive products are regions where the gases are expanded to states that are at very low density, and are removed from the simulation to prevent numerical time-step reduction problems that unduly slow the simulation.

A comparable suite of transverse cross-sectional views, also through the plane of the explosive charge, is shown in Figure 7. In this view, the stripping away of the external water jacket can be clearly seen in the first 5 – 10 ms, and beyond this time, no further deformation of the cask is occurring. Enlarged views of the cask itself are shown in Figure 8, where except for the loss of the water jacket, the cask appears to have retained its integrity. That is, no fractures of the main steel containment have formed in the cask.

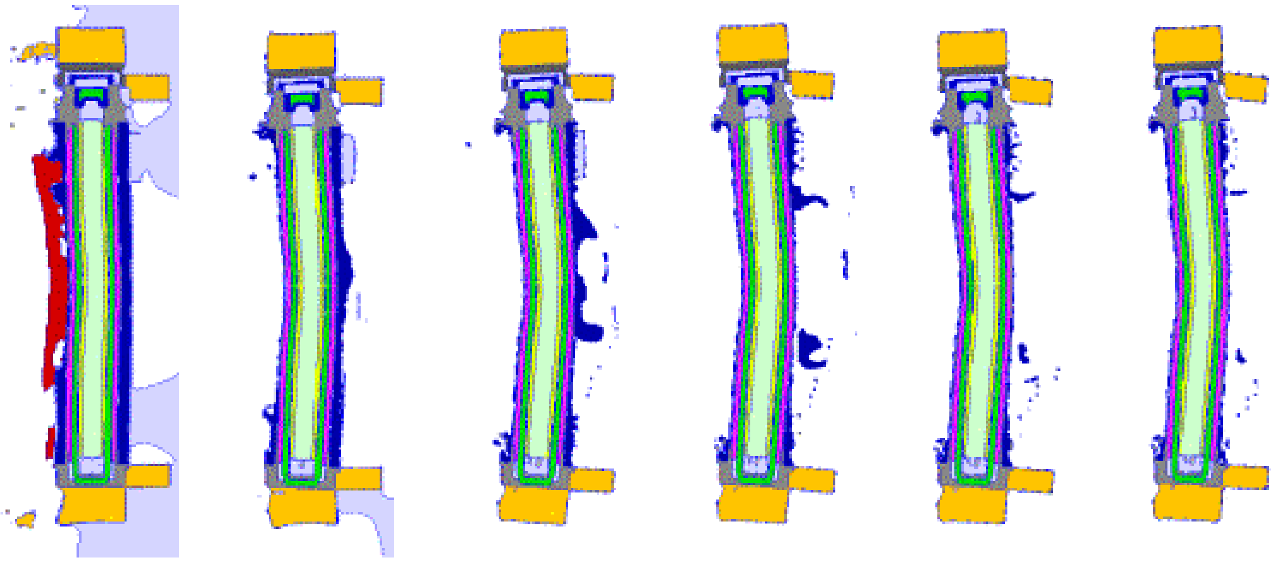

Figure 6. Longitudinal cross-section views of the deformation of the cask at 2, 5, 10, 15, 20, and 25 ms

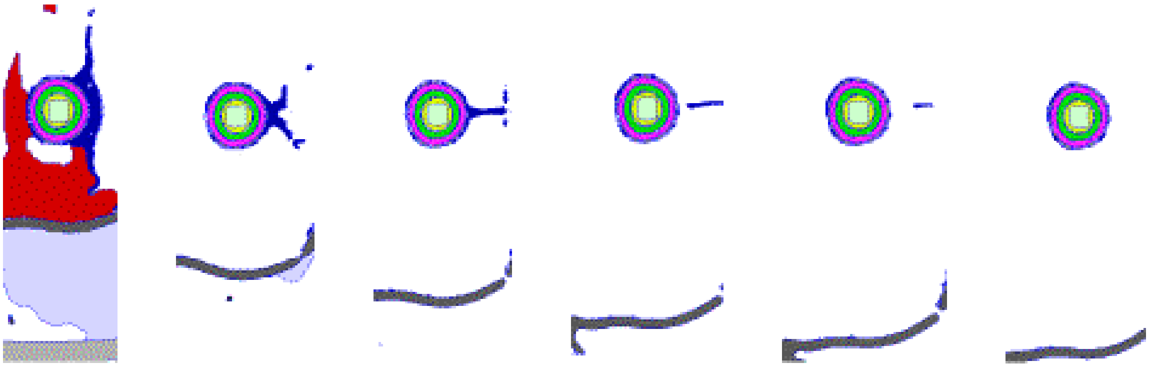

Figure 7. Transverse cross-section views of the deformation of the cask at 2, 5, 10, 15, 20, and 25 ms

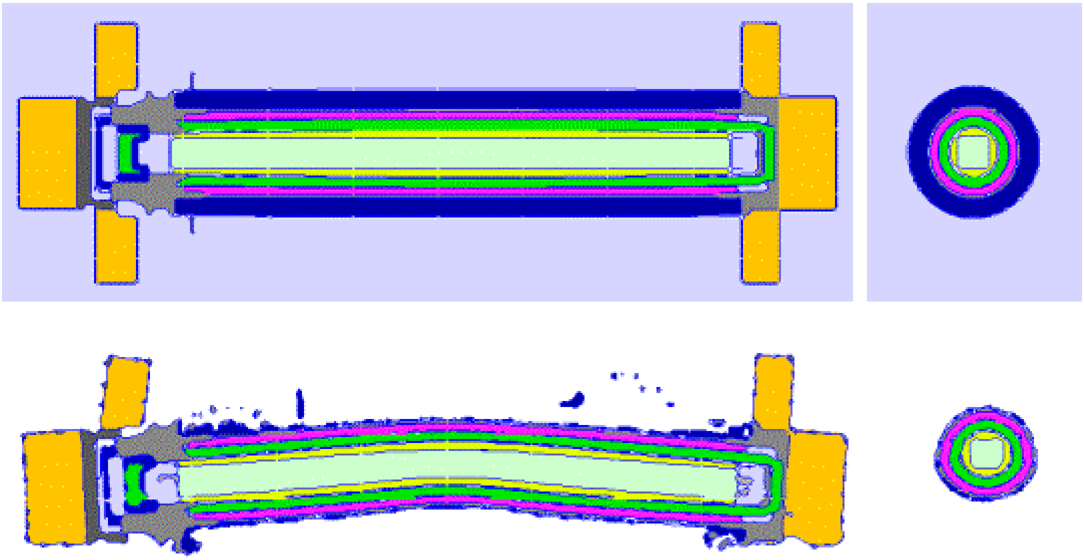

Figure 8. Enlarged views of reference (time 0) and deformed (time 25 ms) conditions of the cask.

DISCUSSION OF RESULTS

The simulations of cask response to large explosive charges discussed in this paper reflect the capabilities of current analysis code and computing platforms. Considerable background work was made to define code parameter settings and computational flags appropriate for this class of applications. In particular, the nature of the Eulerian code used in the analyses (CTH) required that the mixed cell yield and fracture options be carefully evaluated so the code would reproduce deformations of objects for which experimental results were available. Setting the yield in mixed cells to the average of the constituent materials in the cell leads to a slightly more stiff response of the overall structure.

For problems of this scale, where there is a large spectrum of characteristic dimensions, computing platform limitations govern the level of detail that can be represented. The available numerical resolution is a compromise that permits inclusion of the major features of the cask and its internal components, but is insufficient to resolve the finer features (*e.g.*, fuel cladding, rod assembly structure). If it were necessary to determine the response of these finer features a coupled Eularian/LaGrangian analysis would be necessary. This can either be done with a one-way coupling, in which CTH is used to calculate the blast pressures incident onto the cask and these are applied as a boundary condition in a traditional finite element analysis, or with a closely coupled code that uses a LaGrangian method to calculate the structural response and updates the Eularian model for the next time step to calculate the flow of the explosive products around the cask.

REFERENCES

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* This work was sponsored by the US NRC Spent Fuel Project Office, under the direction of B. White.

** Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.