Accidental Drop of a Carbon Steel/Lead Shipping Cask (HFEF 14) at Low Temperatures

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ABSTRACT

A shielded cask is used to transport radioactive materials between facilities at the Idaho National Laboratory. The cask was fabricated with an outer and inner shell of A36 carbon steel with lead poured in the annular space between the shells to provide radiation shielding. Carbon steel is known to be susceptible to low-temperature brittle fracture under impact loading. This paper will present the analysis results representing postulated transportation accidents during on-site transfers of the cask at subzero temperatures. The accident scenarios were based on a series of cask drops onto a rigid surface from a height of 1.83m (6 ft.)

Finite element models of the cask and its contents were solved and post processed using the ABAQUS software. Each model was examined for failure to contain radioactive materials and/or significant loss of radiation shielding.

Results of these analyses show that the body of the cask exhibits considerable ruggedness and will remain largely intact after the impact. There will be deformation of the main cask body with localized brittle failure of the cask outer shell and door structure. The cask payload outer waste can remains in the cask but will experience some permanent plastic deformation in each drop. It will not be deformed to the point where it will rupture, thus maintaining confinement of the can contents.

INTRODUCTION

The Materials and Fuels Complex (MFC), located at the Idaho National Laboratory (INL), uses a shielded cask for intrasite transport of radioactive materials between buildings inside the facility. The facilities operate year round, dictating that some transfers take place in the cold Idaho winter. For safety reasons, transfers do not normally occur during extreme cold weather; however, an equipment failure could leave the cask exposed to subzero temperatures. Major components of the cask were fabricated using A36 carbon steel, which is known to be susceptible to brittle fracture under impact loading at low temperatures. This paper demonstrates that brittle fracture resulting from a transportation accident will not prevent the cask from performing its necessary functions of providing radiation shielding to nearby personnel and confinement of the radioactive payload inside the outer waste can.

Description

The HFEF-14 cask is essentially a cylinder with an inner chamber (Fig. 1). The outside and inside shells of the cask are 9.5 mm (3/8 in.) and 6.3 mm (1/4 in.) thick carbon steel respectively. The interior portion of the cask is filled with lead cast in place. The 25.4 mm (1 in.) thick top lid of the cask is bolted to the 38.1mm (1-1/2 in.) thick upper ring with eight 19.0 mm (3/4 in.) diameter grade 5 bolts. The bottom door is also a weldment with 9.5 mm (3/8 in.) thick carbon steel outside shells and a 12.7 mm (1/2 in.) thick bottom plate. This door is 133.3 mm (5-1/4 in.) thick and rolls in and out of the cask like a drawer on rollers. The lower door is held in place during shipping with two 25.4 mm (1 in.) diameter grade 5 bolts. The lower door rolls over a door support structure and out through a removable door support. The door support structure is fabricated from 12.7 mm (1/2 in.) thick carbon steel as is the removable door support. The door support is attached with four 12.7 mm (1/2 in.) diameter grade 5 bolts to the door support structure. The cask has two lifting lugs near the top of the cask. The cask also has 3 equally spaced support lugs which are used to support the cask in a fixture during transportation or storage. The cask dimensions and weight are given in Table 1.

Material Considerations

The cask is primarily fabricated from various thicknesses of A-36 steel. For this analysis the actual Certified Material Test Report (CMTR) was used for yield strength, tensile strength and elongation when available. Minimum specified strengths were used for all other materials. All steels use a modulus of elasticity (E) of 206.8 Gpa (30 x 10^6 psi) and poisson's ratio (μ) of 0.29.

The lead used for this analysis has a yield strength of 17.2 Gpa (2500 psi) and an ultimate strength of 22.9 Gpa (3325 psi) [1] with no limit on the strain. The density of the lead was adjusted to bring the cask to the required weight

Plain carbon and low alloy steels typically have body centered cubic (BCC) lattice structures. BCC are known to lose impact resistance with decreasing temperatures and have increased risk of brittle failure [2]. Without a sample of the cask materials, and in the time available, the ductile-brittle transition temperature could not be exactly determined. Therefore the material was conservatively modeled as elastic at small strains (up to the yield point) and then assumed to fail by brittle fracture.

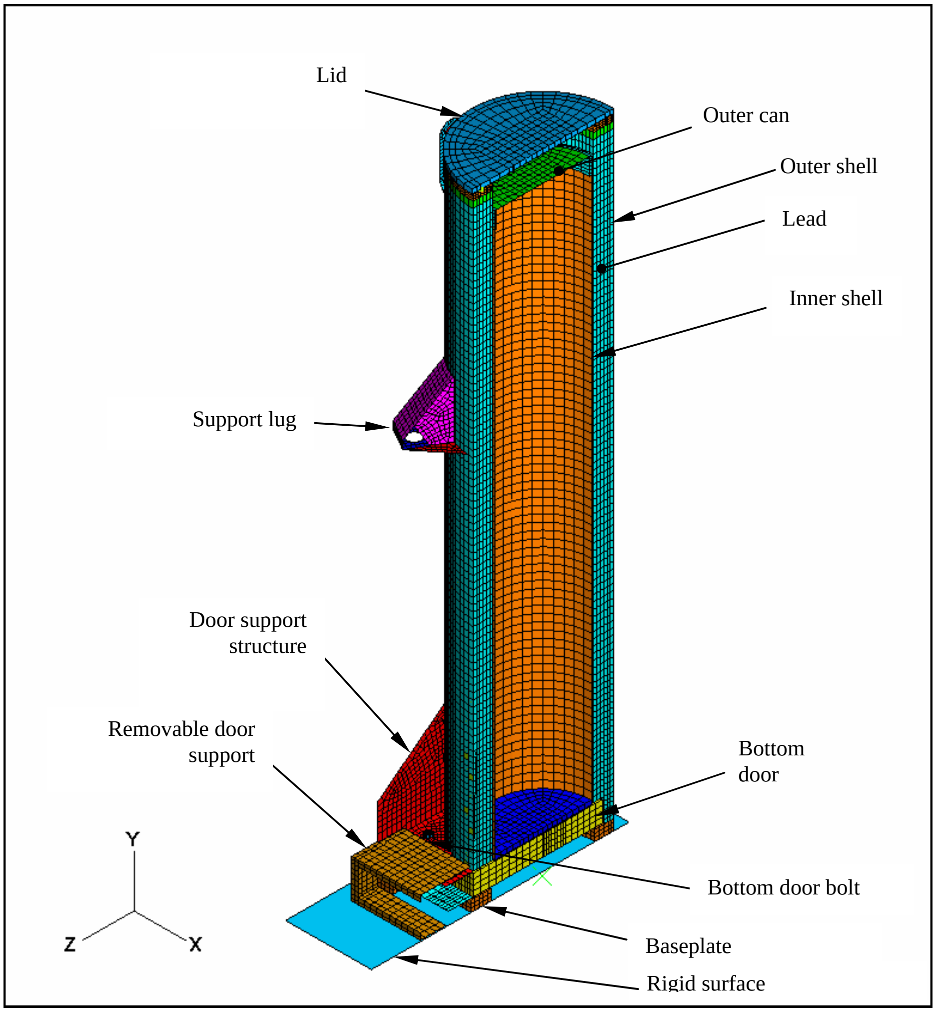

Figure 1. Cutaway view of the HFEF-14 cask showing various features.

Table 1. Cask Dimensions

Cask Dimension/Weight	Value
Outside diameter	0.84 m (33 in)
Inner diameter	0.58 m (23 in)
Height	3.71 m (146 in)
Gross weight	14,130 kg (31,150 lbf)
Outer shell thickness	9.5 mm (3/8 in.)
Inner shell thickness	6.3 mm (1/4 in.)
Other plate thickness (typical)	12.7 mm (1/2 in.)

Accident Scenarios

The cask is transferred at speeds of 16.1 km/h (10 mph) or less, using a large 20 t forklift with a C-frame to raise the cask clear of the ground. Operating procedures keep the center of gravity (cg) of the cask within 1.83 m (6 ft) of the travel path surface. The travel path of the cask traverses asphalt pavement, rock and gravel roadways, compacted soil, and the concrete aprons in the immediate vicinity of the facility buildings.

The accident scenarios assume that the cask will fall from a maximum height of 1.83 m (6 ft) and impact on concrete. Four orientations were selected to represent the impacts that would most severely damage the cask components or the payload in the waste can.

1. Cask in a vertical orientation impacting on the flat bottom.
2. Cask in a tilted orientation impacting on a bottom edge with the cask cg over the impacting bottom corner.
3. Cask in a horizontal orientation impacting on its side.
4. A 1.01 m (40 in.) side drop on a 152 mm (6 in.) diameter steel pin at an unreinforced location

If the cask is dropped, the horizontal velocity will cause the cask to skid along the concrete, asphalt or gravel. The horizontal deceleration would be small compared to the vertical deceleration arising from the impact. This would not be true if the cask was dropped near a massive structure that would act as a rigid body and rapidly decelerate the cask horizontally. This is not a plausible event considering how the cask is transported and the facility layout. As damage arising from the decelerations from 16.1 km/h (10 mph) horizontal velocity is expected to be relatively minor, they were not included in the analysis.

None of the accident scenarios examine how well the cask resists penetration. Although not required by site conditions, a 1.01 m (40 in.) side drop onto a 152 mm (6 in.) diameter rigid pin [3] at an unreinforced location on the cask was added. This was a precaution against unforeseen puncture events such as by the forklift.

The cask must provide two functions to satisfactorily survive these events. (1) Since the shielded cask itself is not sealed, the outer waste can must undergo the impact without tearing or breaching in order to ensure that radioactive contents do not escape to the environment. (2) The cask must also maintain its gross geometry well enough to provide adequate shielding to nearby personnel and keep the waste can captive inside the cask.

Finite Element Model

A finite element model of the cask was created using the I-DEAS 12 NX [4] software and translated into an ABAQUS/Explicit [5] input file.

The cask was modeled using brick elements for the lead and then coated with shell elements for the inner and outer low carbon steel shell elements. Typical element length is about 32 mm (1.25 in.). The doors were modeled using the same method. It was also assumed that the lead and steel plates were bonded. This assumption simplified the creation and of the finite element model and reduced the solution time. This simplification was judged to have a small influence in the outcome of the analysis because the damaged shell elements will be removed from the analysis when it would begin to make a difference whether they were bonded or not.

The outer can was modeled with thin shell elements with their density increased to account for the weight of the contents. This is conservative in that the stiffness of the contents does not add to the strength of the outer can. Also, all the energy will be absorbed by the can and not the contents. However, larger than actual deformation of the outer can is expected when using this technique.

Failure of the outer layer of carbon steel was defined in the ABAQUS/Explicit model as tensile failure for brittle materials. The cutoff stress was defined as $\sigma_y/3$ per the discussion in the ABAQUS Theory Manual [6]. This failure theory (tensile failure) assumes failure when the pressure stress component is higher than the cutoff stress. This means that there is no plastic behavior in this material and when the cutoff stress is used, failure occurs when σ_y is reached. This model was chosen because it more closely represents the brittle behavior of the outer steel shell. Failed elements were removed from the finite element model.

Welds were included in the model where the baseplate is attached to the cask and also where the lifting plate is welded to the cask. These welds are modeled with thin shell elements with the shell thickness equal to the fillet weld throat length.

The 28.8 mm (1-1/8 in.) door bolts were modeled as circular beams with a radius of 12.517 mm (0.4928 in.), which is the radius of the thread stress area. These beam elements were monitored during the analysis to determine whether or not failure occurred.

ABAQUS/Explicit general contact was used to simplify the contact for this analysis

ANALYSIS RESULTS

Paper length constraints preclude the detailed discussion of all impact scenarios analyzed. However, the side bottom corner case is used to illustrate typical results for all analysis cases. Summaries of the other case results are presented following the bottom corner drop case.

Side Bottom Corner (Typical results)

This impact scenario is depicted in Figure 2.

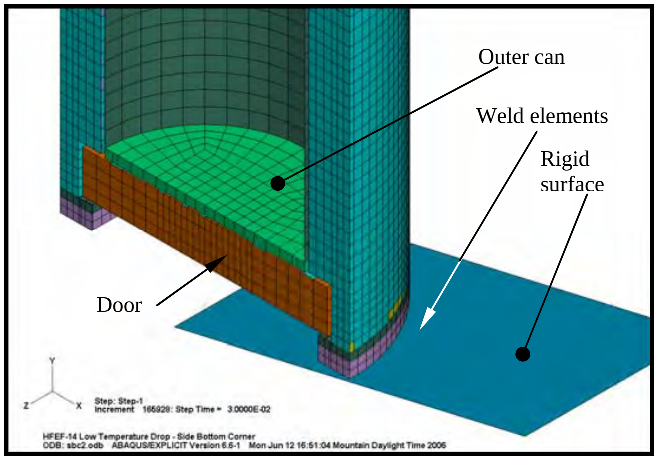

Figure 2. Cutaway view of the drop configuration for the side bottom corner drop.

Figures 3 and 4 show the energy expended during the drop and the displacement of selected model nodes, respectively. Plastic strain in the elements in the vicinity of the impact is shown in Figure 5.

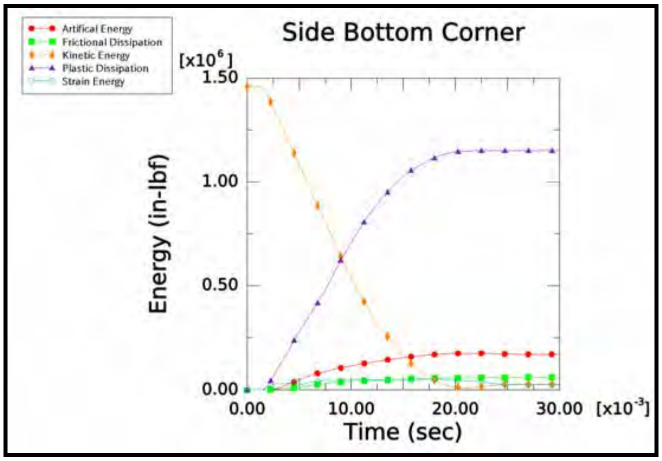

Figure 3. Energy expended during the bottom corner drop drop.

Figure 6 shows the door bolts have failed by the end of the analysis. The damaged elements have been removed and do not contribute their strength to the model after they have failed. Figure 7 shows the strain in the outer can, which does not predict failure or breaching since the plastic strains are very low (6.2%).

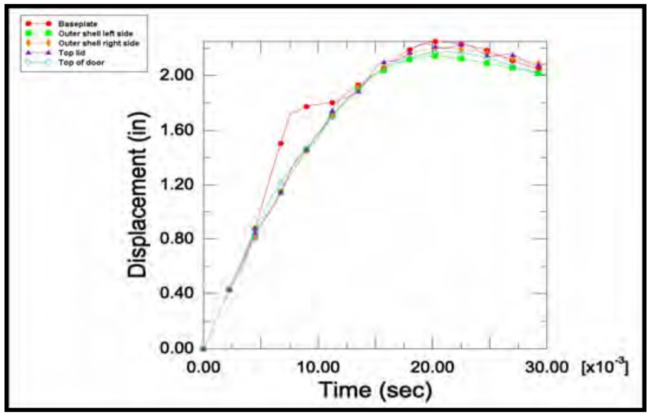

Figure 4. Displacement of various nodes during the bottom corner drop.

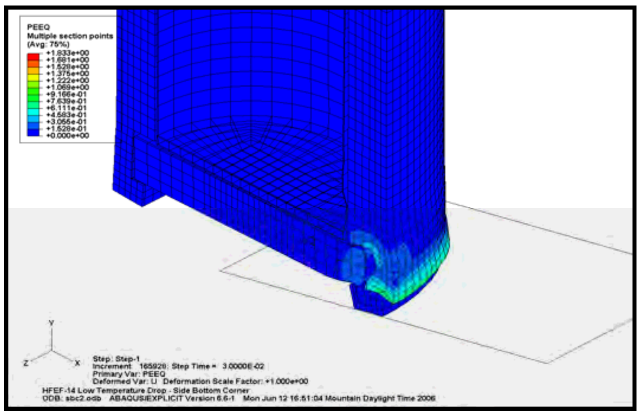

Figure 5. Cut away view of the plastic strain in the elements at the end of the bottom corner drop.

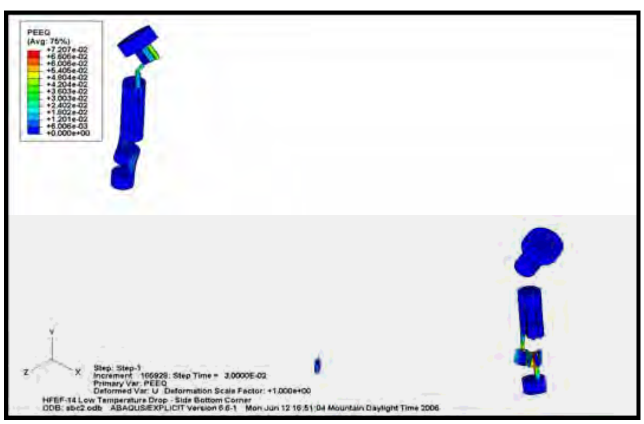

Figure 6. Plastic strain in the door bolts at the end of the analysis of the bottom corner drop. Note the elements removed after failure.

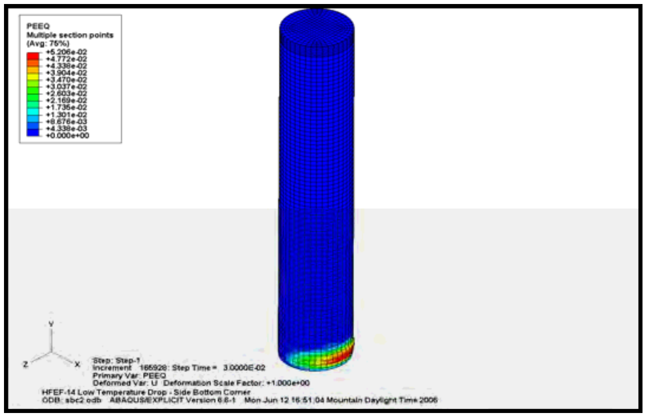

Figure 7. Plastic strain in the outer can from the bottom corner drop.

Other Results

Results from the side impact (Fig. 8) show that the top lid bolts fail, allowing the lid to separate from the cask. Also, the remnants of the door structure are shown after their brittle failure. Figure 9 shows the indentation of the side drop on a rigid post. The lead is not punctured by this drop and the cask integrity is maintained.

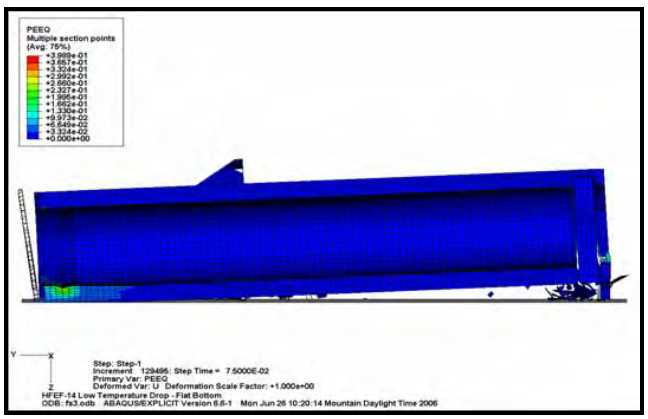

Figure 8. Flat side drop showing the lid separated from the cask and the shattered door structure elements.

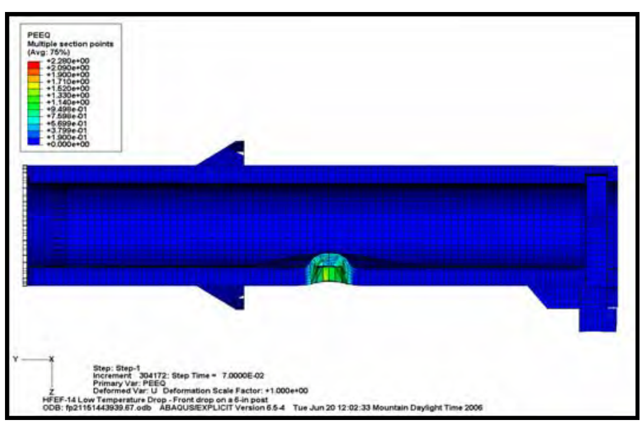

Figure 9. Results of a side impact on a post.

Figure 10 shows the indentation of the outer can by the side post drop. This distortion may make it difficult to remove the outer can from the cask, but it is not breached and maintains it seal.

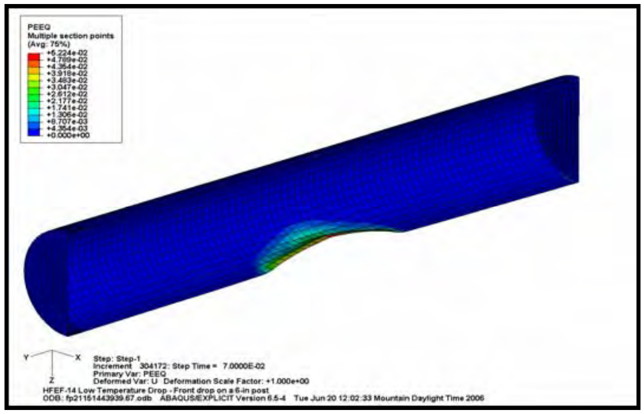

Figure 10. Indentation of the inner can from the side impact on a rigid post.

CONCLUSIONS

These drop scenarios show that the cask outer shell and other support structures are damaged and may shatter during the various drops, but the outer can is still shielded in the cask. The door always remains in place during the drops and does not show any indication of coming out of the cask. The damaged structures surrounding the door may assist in keeping the door in place. The top lid does come loose during the front drop and separates from the cask. The outer can experiences plastic deformation and strain during the drops, but does not strain enough during any drop to indicate that a breach occurs in the outer can. The outer can always stays within the confines of the cask.

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