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SPENT FUEL TRANSPORTATION RISK ASSESSMENT: CASK IMPACT ANALYSES

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ABSTRACT

The NRC has recently completed an updated Spent Fuel Transportation Risk Assessment, NUREG-2125[1]. This assessment considered the response of three certified casks to a range of impact accidents in order to determine whether or not they would lose their ability to contain the spent fuel or maintain effective shielding. The casks consisted of a lead shielded rail cask that can be transported either with or without an inner welded canister, an all-steel rail cask that is transported with an inner welded canister, and a DU shielded truck cask that is transported with directly loaded fuel. Finite element analyses were performed for impacts at speeds of 48, 97, 145, and 193 kph into a rigid target. Impacts in end-on, side-on, and CG-over-corner orientations were analyzed for each cask and impact speed. Calculations were performed to equate these impacts onto rigid targets with higher speed impacts onto the yielding targets that exist in the real world. These analyses indicated that a cask with an inner welded canister or a truck cask would not release radioactive material in any impact accident and that only very high-speed impacts onto hard rock targets could result in either release of material or significant degradation of shielding for rail casks without an inner canister.

Impacts other than those onto flat unyielding targets were also considered. Analyses show that an impact that bypasses the impact limiters on the ends of the casks does not result in seal failure and neither does an impact by a locomotive also between the impact limiters.

INTRODUCTION

Spent fuel casks are required to be accident resistant. During the NRC certification process the cask designer must demonstrate, among other things, that the cask would survive a free fall from a height of 9 meters falling onto a flat, essentially unyielding, target in the orientation most likely to damage the cask (10 CFR 71.73). The NRC's required high standards and conservative approaches for this demonstration include the use of conservative (usually minimum) material properties in analyses, allowing only small amounts of yielding, and the use of materials with high ductility. These approaches ensure that the casks not only will survive impacts at the speed created because of the 9-meter (30-foot) drop but will also survive much higher speed impacts.

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In addition to the conservative designs that the certification process ensures, two additional requirements of the 9-meter drop provide safety when compared to actual accidents. The first requirement is that the impact must be onto an essentially unyielding target. This implies that the cask will absorb all of the kinetic energy of the impact and the target will absorb none. For impacts onto real surfaces, both the cask and the target absorb the kinetic energy. The second requirement is that the vertical impact must be onto a horizontal target. This requirement ensures that at some point during the impact, the velocity of the cask will be zero, and all of the kinetic energy is converted into strain energy (i.e., absorbed by the cask). Most real accidents occur at an angle, and the kinetic energy of the cask is absorbed by multiple impacts instead of one impact. In this chapter, these three aspects are discussed.

FINITE ELEMENT ANALYSES OF CASKS

Previous risk studies have used generic casks. The Modal Study[2] assumed that any accident more severe than the regulatory hypothetical impact accident would lead to a cask release. In NUREG/CR-6672[3], the impact limiters of the generic casks were assumed to be unable to absorb more energy than the amount from the regulatory hypothetical impact accident (i.e., a 9-meter (30-foot) free fall onto an essentially rigid target). Modeling limitations at the time of the studies required both of these assumptions. In reality, casks and impact limiters have excess capacity to resist impacts. In the current study, three NRC-certified casks were used instead of generic casks, and the actual impact resistance capability of those cask designs were included in the analyses. However, for the truck cask no new FE analyses were performed. The current study relied upon analyses performed for other studies, some of which used a generic truck cask.

The response to impacts of 48 kph, 97 kph,145 kph, and 193 kph (equal to 30 mph, 60 mph, 90 mph, and 120 mph) onto an unyielding target in the end, corner, and side orientations for the Rail-Steel and Rail-Lead spent fuel transportation casks were determined using the nonlinear transient dynamics explicit FE code PRESTO[4]. PRESTO is a Lagrangian code, using a mesh that follows the deformation to analyze solids subjected to large, suddenly applied loads. The code is designed for a massively parallel computing environment and for problems with large deformations, nonlinear material behavior, and contact. PRESTO has a versatile element library that incorporates both continuum (3D) and structural elements, such as beams and shells. The results from analyses using this type of code have been compared to results from both regulatory and high-speed impact tests. A recent Safety Analysis Report Addendum for the PAT-1 air transport package compared the very large deformations seen in full-scale testing of this package to those calculated using nonlinear explicit dynamics[5]. There have also been comparisons between full-scale regulatory drop tests of two spent fuel casks in Germany with explicit dynamic finite element analyses[6,7].

In addition to the detailed analyses of rail casks performed for this study, the response of the Truck-DU spent fuel transportation cask was inferred based on the FE analyses performed for the generic casks in NUREG/CR-6672. The direction of the cask travel was perpendicular to the surface of the unyielding target in all of the analyses performed.

Figure 1 is a pictorial representation of the three impact orientations analyzed. In all of the analyses, the spent fuel basket and fuel elements were treated as a uniform homogenous material. The density of this material was adjusted to achieve the correct weight of the loaded basket. The overall behavior of the material was conservative (i.e., because it acts as a single entity that affects the cask all at once instead of many smaller parts that affect the cask over a longer period of time) for assessing the effect the cask contents of the cask had on the behavior of the cask. A sub-model of a single assembly was used to calculate the detailed response of the fuel assemblies.

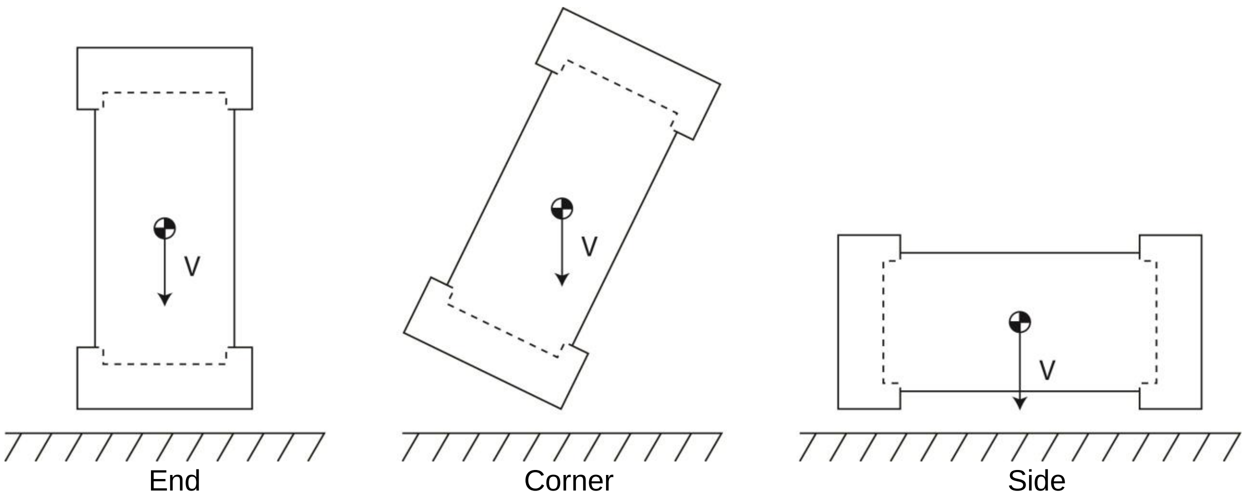

Figure 1. Impact orientations analyzed

RAIL-STEEL CASK

Finite Element Model

Figure 2 shows the overall FE model of the Rail-Steel cask. This cask has steel gamma-shielding material and transports 24 PWR assemblies in a welded multipurpose canister (MPC). The impact limiters on each end of the cask are designed to absorb the kinetic energy of the cask during the regulatory hypothetical impact accident. They are made of an interior stainless steel support structure, an aluminum honeycomb energy absorber, and a stainless steel skin. The aluminum honeycomb has direction-dependent properties. The strong direction of the honeycomb is oriented in the primary crush direction, requiring the FE model to include the individual blocks of honeycomb material, rather than a single material for the entire impact limiter. The cask has a single, solid steel lid attached with fifty-four 1-⅝-inch diameter bolts and sealed with dual metallic o-rings.

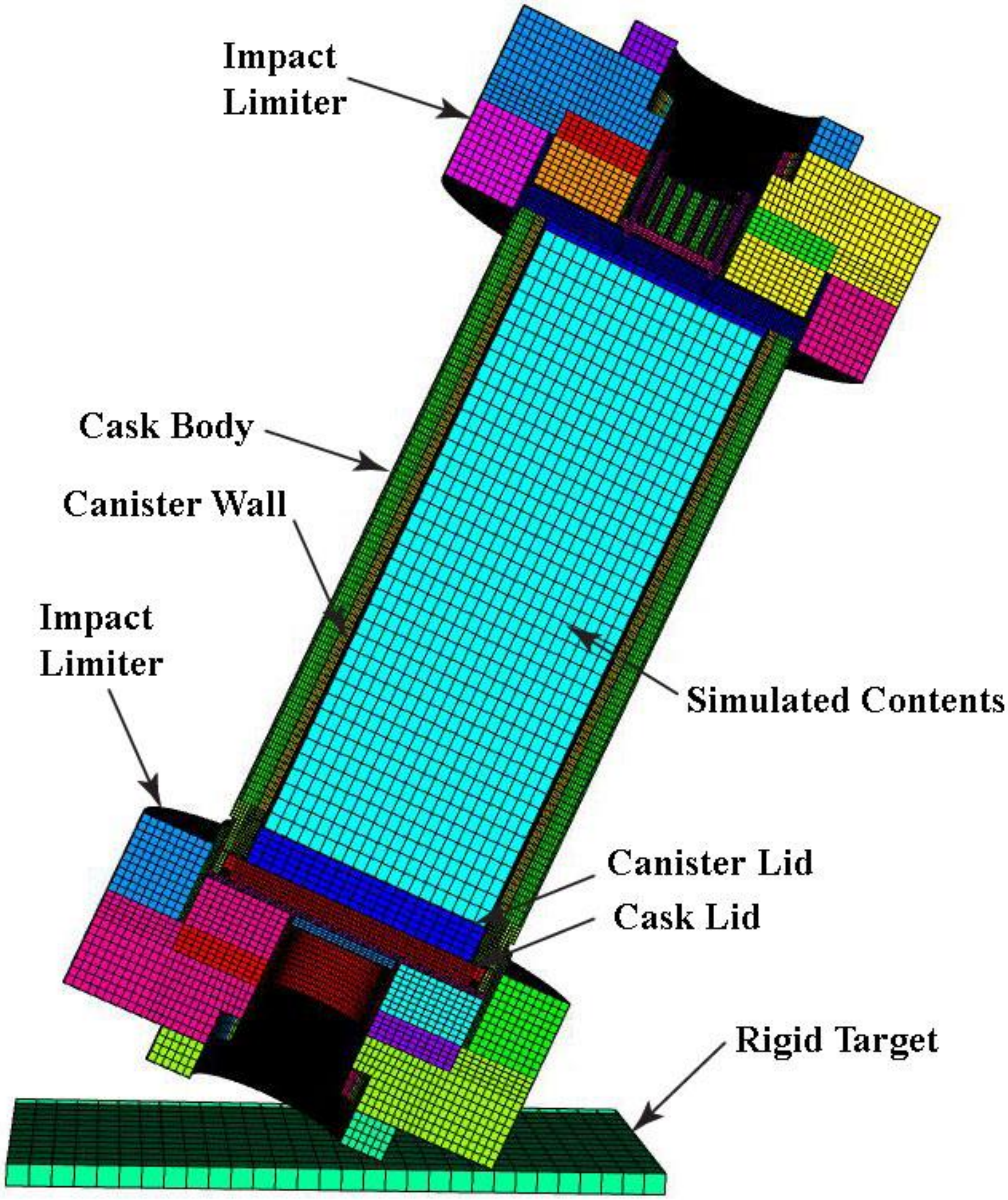

Figure 2. Finite element mesh of the Rail-Steel cask

Analysis results

As expected, for all end, corner, and side impacts of the 48 kph (30 mph) impact analyses—the impact velocity from the regulatory hypothetical impact accident—the impact limiter absorbed almost all of the cask's kinetic energy and there was no damage (i.e., permanent deformation) to the cask body or canister. As the impact velocity increases, additional damage to the impact limiter occurs for all orientations because it absorbs more kinetic energy. This shows the margin of safety in the impact limiter design. At 97 kph (60 mph) there is still no significant damage to the cask body or canister. At an impact speed of 145 kph (90 mph), damage to the cask and canister begins. The impact limiter has absorbed all the kinetic energy it can, and any additional kinetic energy must be absorbed by plastic deformation in the cask body.

For the side impact at 145 kph (90 mph), several lid bolts fail in shear but the lid remains attached. At this point, the metallic seal no longer maintains the leak-tightness of the cask, but the spent fuel remains contained within the welded canister. Even at the highest impact speed of 193 kph (120 mph), the welded canister remains intact for all orientations. Figure 3 shows the deformed shape and plastic strain in the canister for the 193 kph (120 mph) impact in a side orientation. This case has the most plastic strain in the canister. The peak value of plastic strain in this case is 0.7. This value is specified by the equivalent plastic strain (EQPS), which is a representation of the magnitude of local permanent deformation. The canister's stainless steel material can easily withstand plastic strains greater than 1[8]. These results demonstrate that no impact accident will lead to release of material from the Rail-Steel canister.

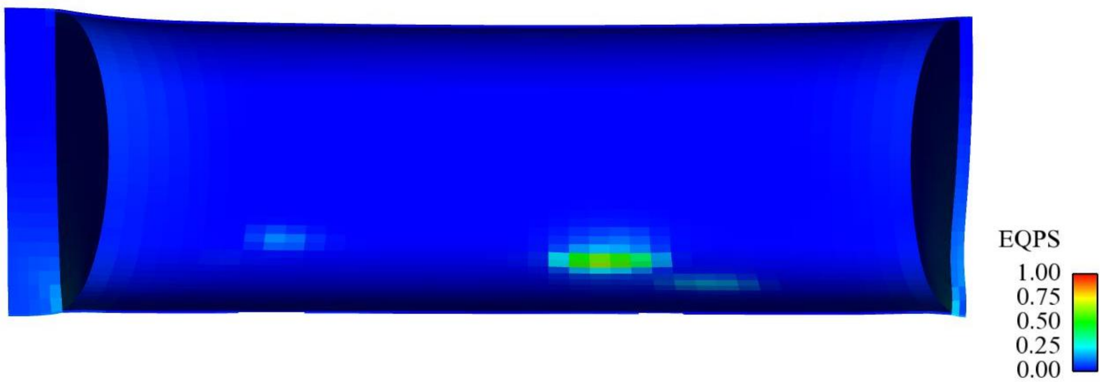

Figure 3. Plastic strain in the welded canister of the Rail-Steel for the 193 kph (120 mph) side impact case

RAIL-LEAD CASK

Finite Element Model

Figure 4 shows the overall FE model of the Rail-Lead cask. This cask has lead gamma-shielding material and transports either 26 directly-loaded PWR assemblies or 24 PWR assemblies in a welded MPC. The impact limiters at each end of the cask are designed to absorb the cask's kinetic energy during the regulatory hypothetical impact accident. The impact limiters are made of redwood and balsa wood energy-absorbing material and a stainless steel skin. The cask has a dual lid system. The inner lid is attached with 42 38 mm (1.5-inch) diameter bolts and sealed with dual elastomeric o-rings if the cask is only used for transportation and metallic o-rings if the cask is used for storage before transportation. The outer lid is attached with 36 25 mm (1-inch) diameter bolts and sealed with a single elastomeric o-ring if the cask is only used for transportation and a metallic o-ring if the cask is used for storage before transportation.

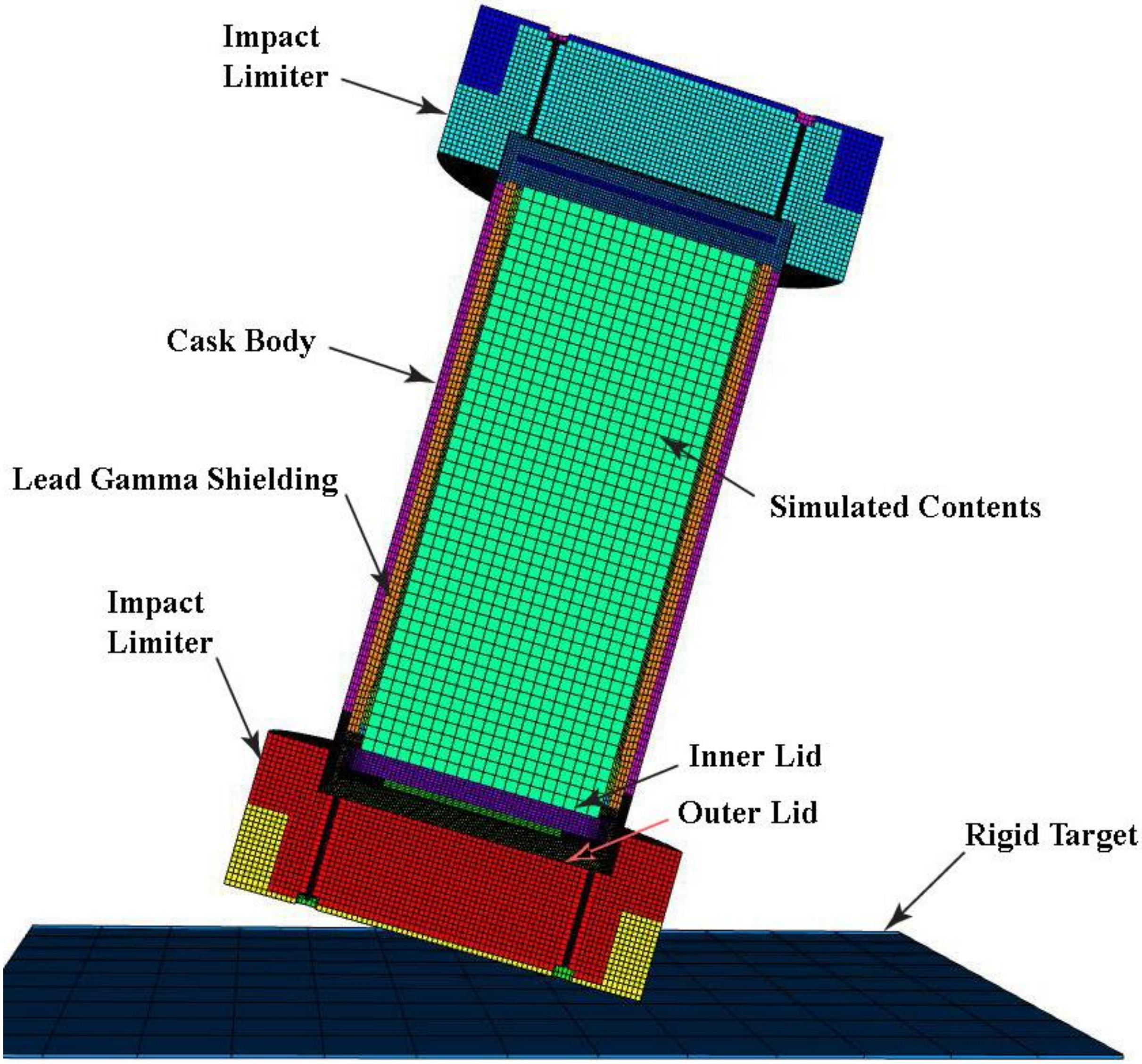

Figure 4. Finite element mesh of the Rail-Lead cask

Analysis Results

The impact limiter absorbed almost all of the kinetic energy of the cask for the 48 kph impact analyses—the impact velocity from the regulatory hypothetical impact accident—and no damage to the cask body occurred. For the end orientation, as the impact velocity increased, initially there was additional damage to the impact limiter because it was absorbing more kinetic energy, which shows the margin of safety in the impact limiter design. There is no significant damage to the cask body at 97 kph (60 mph). At an impact speed of 145 kph (90 mph), damage to the cask begins. The impact limiter has absorbed all the kinetic energy it can and any additional kinetic energy is absorbed by plastic deformation in the cask body. At this speed there is significant slumping of the lead gamma shielding material, resulting in a loss of lead shielding near the end of the cask away from the impact point. As the impact velocity is increased to 193 kph (120 mph), the lead slump becomes more pronounced and there is enough plasticity in the lids and closure bolts to result in a loss of sealing capability. For the directly loaded cask (without a welded MPC) there could be some loss of radioactive contents if the cask has metallic seals. This would not be the case if the cask has elastomeric seals. Figure 5 shows the deformed shape of the Rail-Lead cask following the 193 kph (120 mph) impact in the end-on orientation. The amount of lead slump from this impact is 35.5 cm (14.0 in) and the area without lead shielding is visible in the figure.

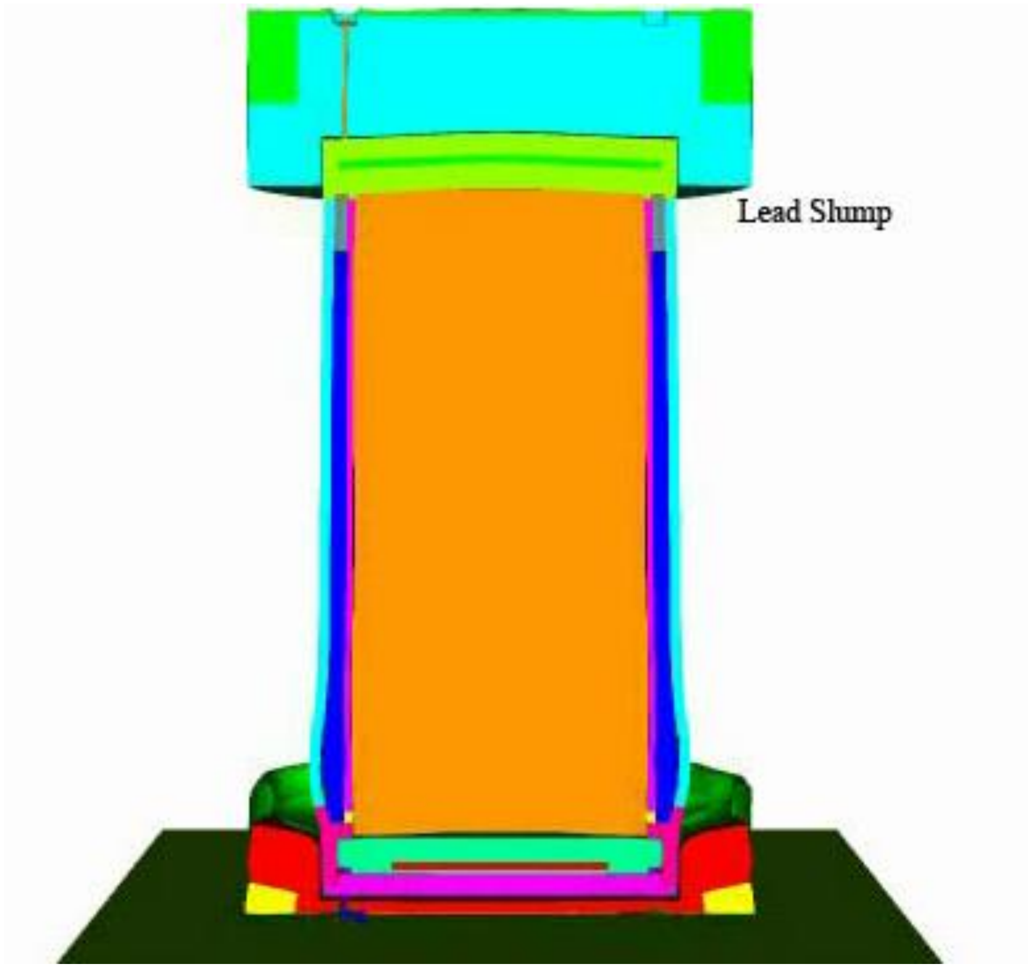

Figure 5. Deformed shape of the Rail-Lead cask following the 193-kph (120 mph) impact onto an unyielding target in the end-on orientation

In the side impact, as the impact velocity increases from 48 kph (30 mph) to 97 kph (60 mph), the impact limiter ceases to absorb additional energy and there is permanent deformation of the cask and closure bolts. The resulting gap in between the lids and the cask body is sufficient to allow leakage if there is a metallic seal, but not if there is an elastomeric seal. This gap calculation between the cask body and lid is conservative because the clamping force applied by bolt preload was neglected in the analysis (i.e., the clamping force acts to keep the lid and cask body together). When the impact speed is increased to 145 kph (90 mph), the amount of damage to the cask increases significantly. In this case, many bolts from the inner and outer lid fail in shear and there is a gap between each of the lids and the cask. This gap is sufficient to allow leakage if the cask is sealed with either elastomeric or metallic o-rings.

Figure 6 shows the deformed shape of the cask following this impact. The response of the cask to the 193 kph (120 mph) impact is similar to that from the 145 kph (90 mph) impact, except that the gaps between the lids and the cask are larger.

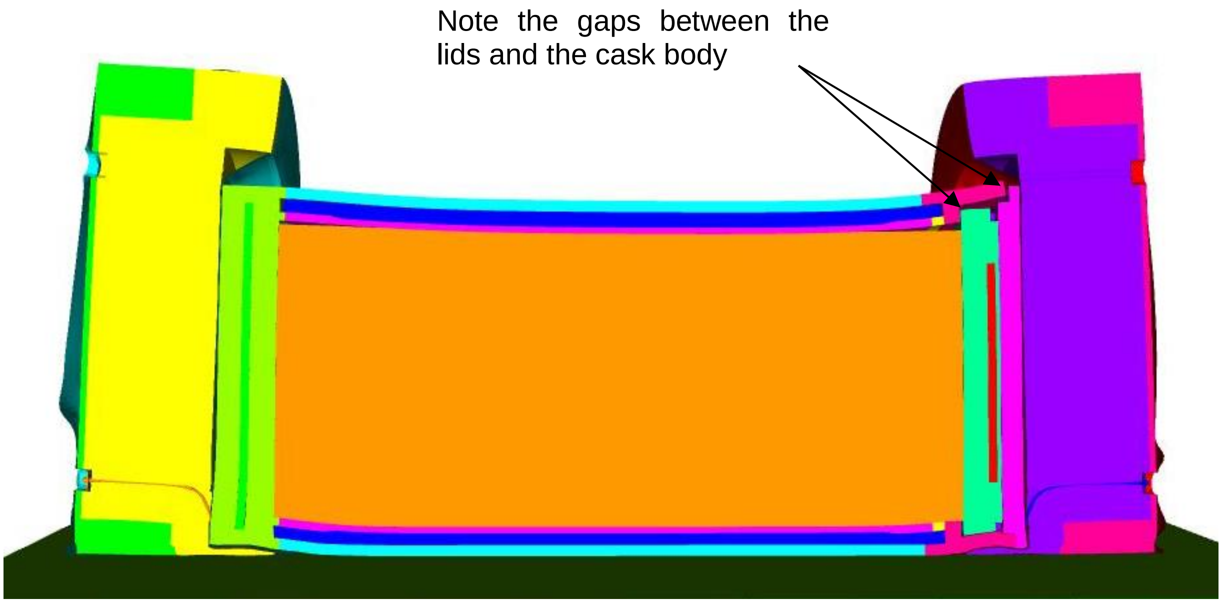

Figure 6. Deformed shape of the Rail-Lead cask following the 145 kph (90 mph) impact onto an unyielding target in the side orientation

IMPACTS ONTO YIELDING TARGETS

The analysis results discussed above were for impacts onto an unyielding, essentially rigid, target. All real impact accidents involve targets that yield to some extent. When a cask impacts a real target, the amount of impact energy the target and cask absorb depends on the relative strength and stiffness of the two objects. For an impact onto a real target to produce the same amount of damage as the impact onto an unyielding target, the force applied to the cask has to be the same. If the target is not capable of sustaining that level of force, it cannot produce the corresponding level of cask damage.

For the Rail-Lead cask (the only one of the three investigated in this study with any release), the peak force associated with each impact analysis performed is supplied in Table 1. In this table, the cases with possible release have bold text. It can be seen that in order to produce sufficient damage for the cask to release any material, the yielding target has to be able to apply a force to the cask greater than 146 million Newtons (MN), or 33 million pounds. Very few real targets are capable of applying this amount of force. A hard rock is the closest thing to an unyielding target. In this study, hard rock is defined as rock that requires blasting operations to remove. While not all classes of this type of rock are equally strong, all of them are assumed to absorb negligible energy during an impact; therefore, they are treated as rigid.

If the cask hits a flat target, such as the ground, roadway, or railway, it will penetrate into the surface. The greater the contact force between the cask and the ground, the greater the penetration depth. As the cask penetrates the surface, some of its kinetic energy is absorbed by the surface. For example, the end impact at 97 kph (60 mph) onto an unyielding target requires a contact force of 124 MN (27.9 x 106 pounds). A penetration depth of approximately 2.2 meters (7.2 feet) will cause a hard desert soil to exert this amount of force. The soil absorbs 142 million Joules (MJ) (105 x 10^6 foot pounds) of energy when penetrated to this depth. Adding the energy absorbed by the soil to the 41 MJ (30 x 10^6 foot pounds) of energy absorbed by the cask yields a total absorbed energy of 183 MJ (135 x 10^6 foot pounds). For the cask to have this amount of kinetic energy, it would have to be traveling at 205 kph (127 mph). Therefore, a 205 kph (127 mph) impact onto hard desert soil causes the same amount of damage as a 97 kph (60 mph) impact onto an unyielding target. A similar calculation can be performed for other impact speeds, orientations, and target types. The resulting equivalent velocities are given in Table 2.

Table 1. Peak Contact Force for the Rail-Lead Cask Impacts onto an Unyielding Target
Table note: (bold numbers are for the cases where there may be seal leaks)

Orientation	Speed, kph (mph)	Accel. (g)	Contact Force (Millions of Pounds)	Contact Force (MN)
End	48 (30)	58.5	14.6	65.0
	97 (60)	111.6	27.9	123.9
	145 (90)	357.6	89.3	397.1
	193 (120)	**555.5**	**138.7**	**616.8**
Corner	48 (30)	36.8	9.2	40.9
	97 (60)	**132.2**	**33.0**	**146.8**
	145 (90)	**256.7**	**64.1**	**285.1**
	193 (120)	**375.7**	**93.8**	**417.2**
Side	48 (30)	76.1	19.0	84.5
	97 (60)	**178.1**	**44.5**	**197.8**
	145 (90)	**411.3**	**102.7**	**456.7**
	193 (120)	**601.1**	**150.0**	**667.4**

Table 2. Equivalent Velocities for Impacts onto Various Targets with the Rail-Lead Cask, kph (mph)

Orientation	Rigid (or hard rock)	Soil	Concrete
End	48 (30)	102 (63)	71 (44)
	97 (60)	205 (127)	136 (85)
	145 (90)	>250 (>155)	>250 (>155)
	193 (120)	**>250 (>155)**	**>250 (>155)**
Corner	48 (30)	73 (45)	70 (43)
	97 (60)	**236 (147)**	**161 (100)**
	145 (90)	**>250 (>155)**	**>250 (>155)**
	193 (120)	**>250 (>155)**	**>250 (>155)**
Side	48 (30)	103 (64)	79 (49)
	97 (60)	**246 (153)**	**185 (115)**
	145 (90)	**>250 (>155)**	**>250 (>155)**
	193 (120)	**>250 (>155)**	**>250 (>155)**

IMPACTS WITH OBJECTS

The preceding sections dealt with impacts onto flat surfaces, but a large number of impacts occur on surfaces that are not flat. These include impacts into columns and other structures, impacts by other vehicles, and, more rarely, impacts by collapsing structures. These types of impacts were not explicitly included in this study, but recent work by Sandia National Laboratories[9,10,11] have shown the GA-4 cask response to some of these impacts. The result of an impact into a large, semi-circular, rigid column is shown in Figure 7[9]. While this impact led to significant permanent deformation of the cask, the level of strain was not high enough to cause tearing of the containment boundary and there was no permanent deformation in the closure region and no loss of containment. Collision by a railroad locomotive could potentially cause cask damage and is probably the most severe type of collision with another vehicle that could occur. Ammerman et al.[11] investigated several different scenarios of this type of collision. None of the analyses led to deformations that would cause a release of radioactive material from the cask or resulted in cask accelerations high enough for the fuel rod cladding to fail. Figure 8 shows a sequence from one of the impacts. The front of the locomotive is severely damaged and the trailer is totally destroyed, but there is very little deformation of the cask—only minor denting where the collision posts of the locomotive hit the cask.

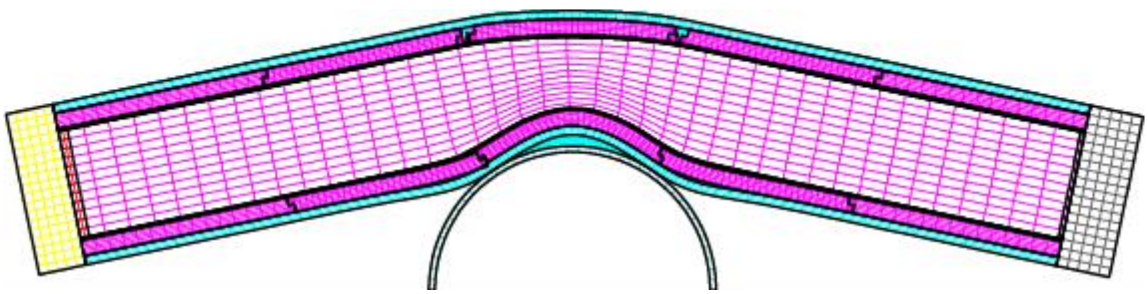

Figure 7. Deformations to the GA-4 truck cask after a 97 kph (60 mph) side impact onto a rigid semi-circular column

CONCLUSIONS

Detailed FE analyses performed for two spent fuel transportation rail casks indicate that casks are very robust structures capable of withstanding almost all impact accidents without release of radioactive material. In fact, when spent fuel is transported within an inner welded canister or in a truck cask, no impacts result in release. Even the rail cask without an inner welded canister can withstand impacts much more severe than the regulatory impact without releasing any material.

In the worst orientation (i.e., side impact), an impact speed onto a rigid target at more than 97 kph is required to cause seal failure in a rail cask. If the cask has an inner welded canister, even this impact will not lead to a release of radioactive material. A 97 kph (60 mph) side impact onto a rigid target produces a force of approximately 200 MN (45 million pounds) and is equivalent to a 185 kph (115 mph) impact onto a concrete roadway or abutment, or a 246 kph (153 mph) impact onto hard soil. For impacts onto hard rock, which may be able to resist these large forces, impacts at angles less than 30 degrees require a speed of more than 193 kph (120 mph) to be equivalent.

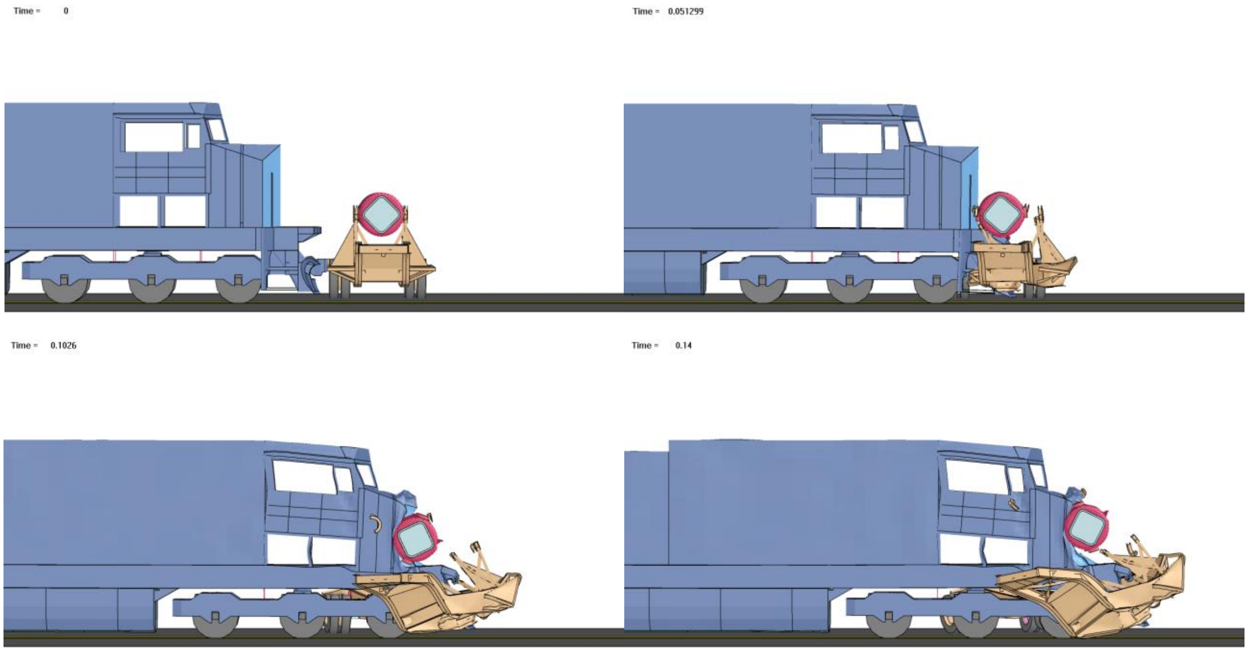

Figure 8. Sequential views of a 129 kph (80 mph) impact of a locomotive into a GA-4 truck cask

Assessment of previous analyses performed for spent fuel truck transportation casks, including impacts onto flat rigid targets, into cylindrical rigid targets, by locomotives, and by falling bridge structures, indicate that truck casks will not release their contents in any impact accidents.

In summary, the sequence of events necessary for there to be the possibility of any release is a rail transport cask with no welded canister travelling at an impact velocity greater than 97 kph (60 mph). This cask would have to impact in a side orientation and the surface would have to be hard rock with an impact angle greater than 30 degrees.

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