# CHAPTER 3

# CASK RESPONSE TO IMPACT ACCIDENTS

## 3.1 Introduction

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

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Comment [XXX1]: A little awkward in that this sentence mixes units of height and speed

In addition to the robust designs assured by the certification process, there are two additional aspects of the nine-meter drop that provide safety when compared to actual accidents. The first of these is the requirement that the impact be onto an essentially unyielding target. This implies that all of the kinetic energy of the impact will be absorbed by the cask and none by the target. For impacts onto real surfaces, the kinetic energy is absorbed by both the cask and the target. The second aspect is the requirement that the vertical impact is onto a horizontal target. This requirement assures 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 (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 all in one impact. In this chapter, all three of these aspects will be discussed.

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## 3.2 Finite Element Analyses of Casks

Previous risk studies have been carried out using generic casks. In the case of the Modal Study (Fischer et al, 1987) it was assumed any accident that was more severe than the regulatory hypothetical impact accident would lead to a release from the cask. In NUREG/CR-6672 (Sprung et al., 2000) 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 (a nine-meter 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 each have excess capacity to resist impacts. In this study, three NRC certified casks were used instead of generic casks, and the actual impact resistance capacity of those cask designs was included in the analyses.

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Comment [MF2]: Is this true? I thought the truck cask structural analysis was of a generic cask?

The response to impacts of 48, 97,145, and 193 kilometers per hour (kph)—equal to 30, 60, 90, 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 non-linear transient dynamics explicit finite element code PRESTO (SIERRA, 2009). 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



H-3

has a versatile element library that incorporates both continuum elements and structural elements, such as beams and shells.

Comment [XXX3]: Please briefly explain this concept as it is not common (as the beams and shells mentioned below are common).

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 upon the finite element analyses performed for the generic casks in NUREG/CR-6672. All analyses were performed with the direction of the cask travel perpendicular to the surface of the unyielding target. Figure 3-1 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 single homogenous material. The density of this material was adjusted to achieve the correct weight of the loaded basket. The overall behavior of this material was conservative (because it acts as a single entity that impacts the cask all at once instead of many smaller parts that impact the cask over a longer period of time) for assessing the effect the contents of the cask had on the behavior of the cask. Detailed response of the fuel assemblies was calculated using a sub-model of a single assembly.

Comment [XXX4]: Not sure I agree this is the main focus. I thought the main focus was to perform a risk assessment of SF transport

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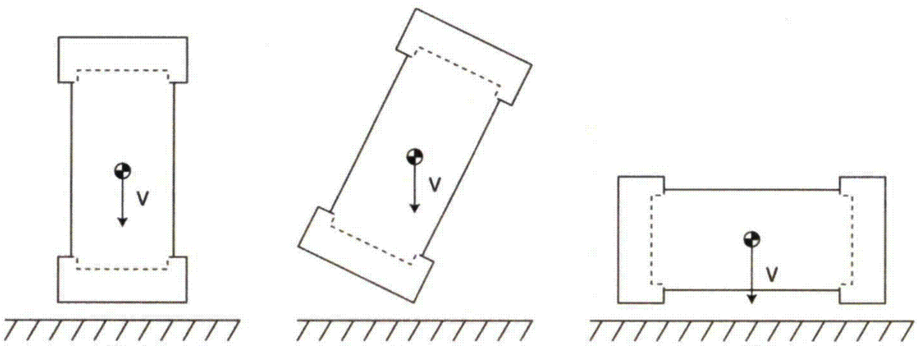



**Figure 3-1. Impact orientations analyzed**

### 3.2.1 Rail-Steel Cask

***Finite element model***

Figure 3-2 shows the overall finite element model of the Rail-Steel cask. This cask uses steel for its gamma-shielding material and transports 24 PWR assemblies in a welded multi-purpose canister. 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, aluminum honeycomb energy absorber, and a stainless steel skin. Figure 3-3 shows the finite element mesh of the closure end impact limiter (the one on the other end of the cask differs only in how it is attached to the cask). The cask has a single solid steel lid that is attached with 54 1-5/8 inch diameter bolts and sealed with dual metallic o-rings. Figure 3-4 shows the finite element mesh of the closure bolts (also shown are the bolts used to attach the closure end impact limiter) and the level of mesh refinement included in these important parts. Details of the finite element models, including material properties, contact surfaces, gaps, and material failure, are included in Appendix III.

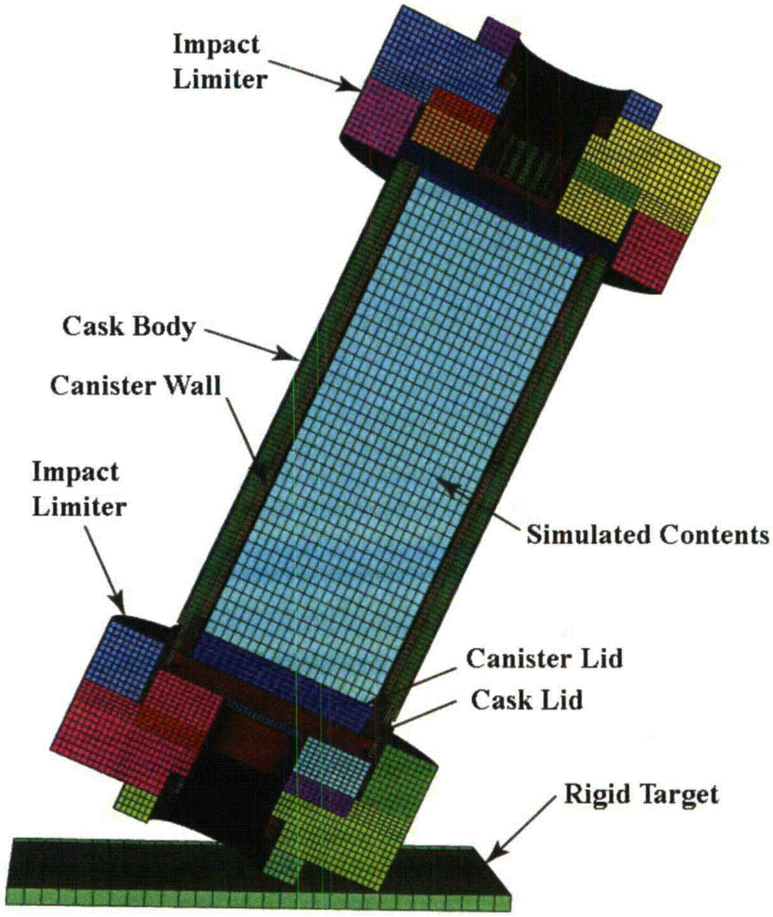
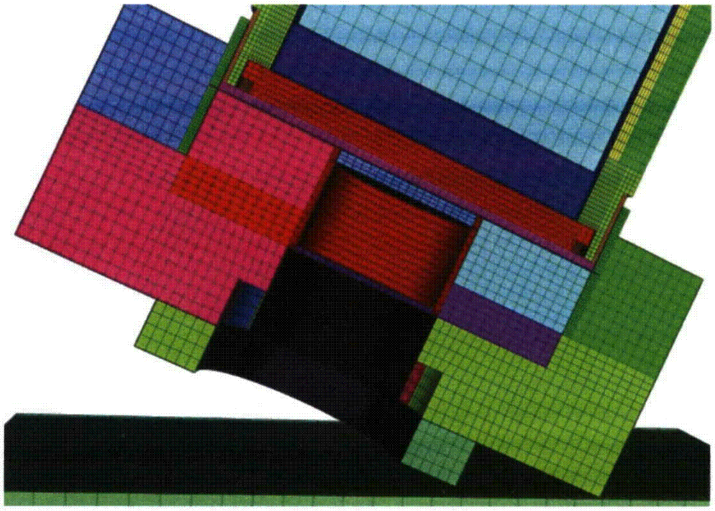
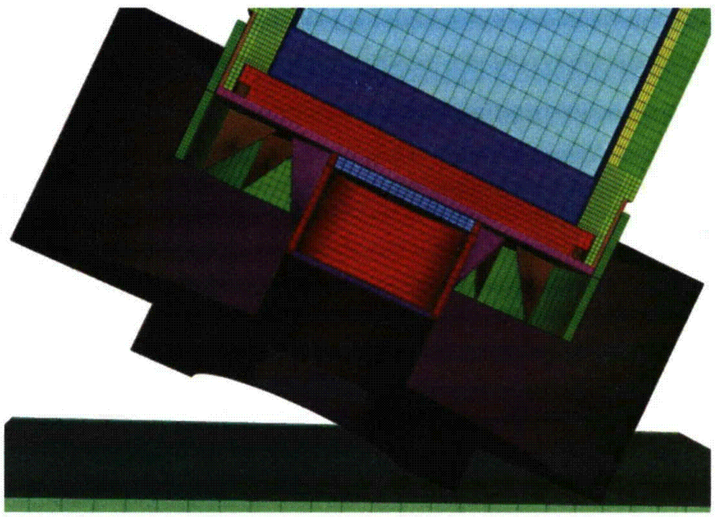



**Figure 3-2. Finite element mesh of the Rail-Steel cask**

**Comment [XXX5]:** Suggest discussing the different colors in the text. This is much more complicated impact limiter than is usually found on such packages. The various colors make it appear non-symmetric, so some discussion is warranted.



**Impact limiter showing the various blocks of honeycomb**



**Impact limiter with the honeycomb removed to reveal the inner support structure**

**Figure 3-3. Details of the finite element mesh for the impact limiters of the Rail-Steel cask**

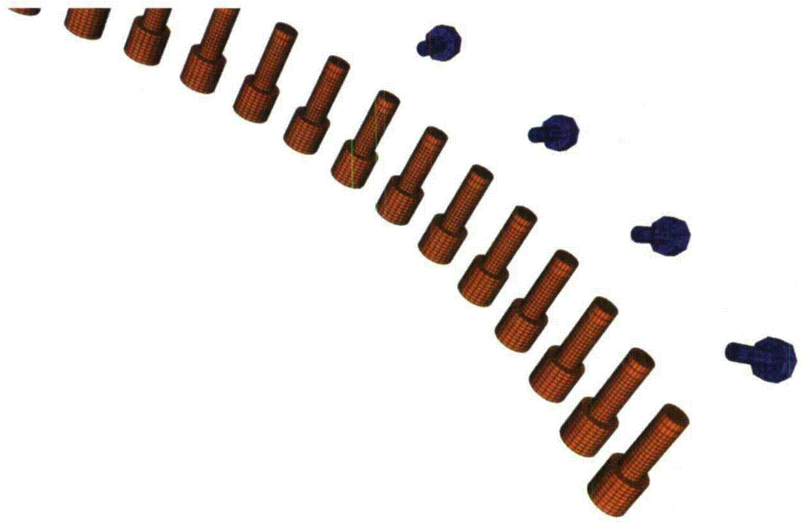


**Figure 3-4. Finite element mesh of the Rail-Steel closure bolts and the closure end impact limiter attachment bolts. The highly refined mesh in these critical parts assures an accurate assessment of the closure response.**

***Analysis results***

As expected, for all of the 48 kph impact analyses (the impact velocity from the regulatory hypothetical impact accident) the impact limiter absorbed almost all of the kinetic energy of the cask and there was no damage (permanent deformation) to the cask body or canister. As the impact velocity increases there is first additional damage to the impact limiter because it is absorbing more kinetic energy (this shows the margin of safety in the impact limiter design). At 97 kph there is still no significant damage to the cask body or canister. At an impact speed of 145 kph damage to the cask and canister appears to begin. 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 several of the lid bolts fail in shear (discussion of the failure model is included in Appendix III), 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, 193 kph, the welded canister remains intact. Figure 3-5 shows the deformed shape and plastic strain in the canister for the 193 kph impact in a side orientation. This is the case that has the most plastic strain in the canister. The peak value of plastic strain (EQPS=Equivalent Plastic Strain, a representation of the magnitude of local permanent deformation) in this case is 0.7. The stainless steel material of the canister can easily withstand plastic strains greater than one. These results demonstrate that no impact accident will lead to release of material from the Rail-Steel canister. Similar figures for the other orientations and speeds are included in Appendix III.

**Comment [XXX6]:** Please provide a reference. Typical stainless failure strain is ~0.56.

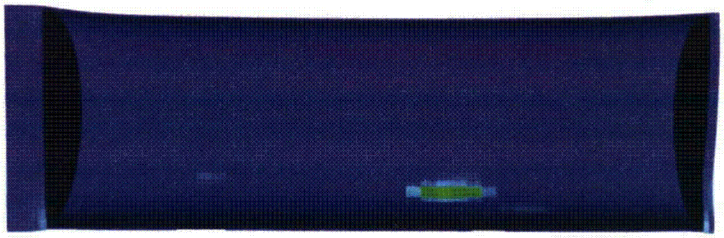



**Figure 3-5. Plastic strain in the welded canister of the Rail-Steel for the 193 kph side impact case**

### 3.2.2 Rail-Lead Cask

***Finite Element Model***

Figure 3-6 shows the overall finite element model of the Rail-Lead cask. This cask uses lead for its gamma-shielding material and transports either 26 directly loaded PWR assemblies or 24 PWR assemblies in a welded multi-purpose canister. 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 up of redwood and balsa wood (energy absorbing materials) and a stainless steel skin. Figure 3-7 shows the finite element mesh of the closure end impact limiter (the impact limiter on the other end of the cask is identical). The cask has a dual lid system. The inner lid is attached with 42 1-1/2 inch diameter bolts and sealed with dual o-rings that are elastomeric if the cask is used only for transportation and metallic if the cask is used for storage before transportation. The outer lid is attached with 36 1-inch diameter bolts and sealed with a single o-ring that is elastomeric if the cask is used only for transportation and metallic if the cask is used for storage before transportation. Figure 3-8 shows the finite element mesh of the closure bolts and the level of mesh refinement included in these important parts. Details of the finite element models are included in Appendix III.

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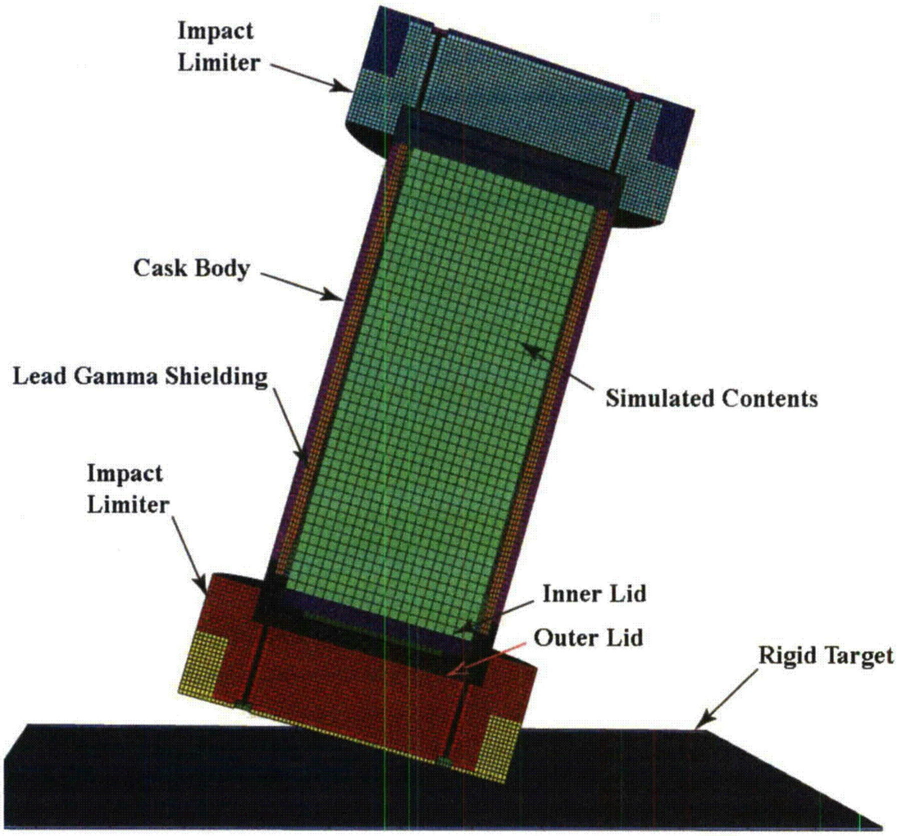
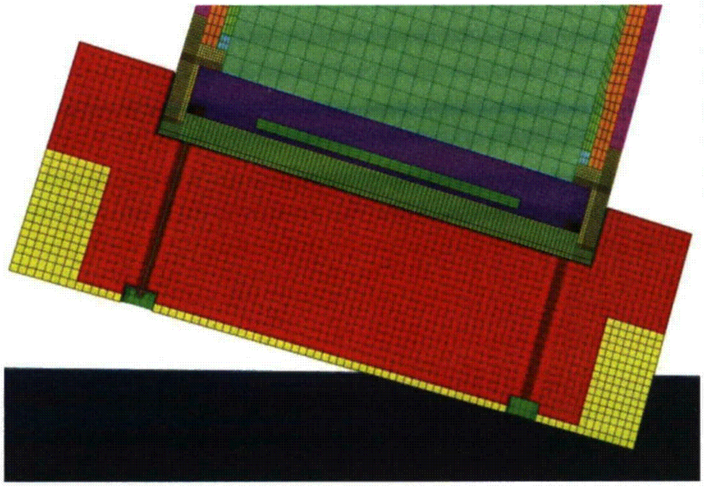
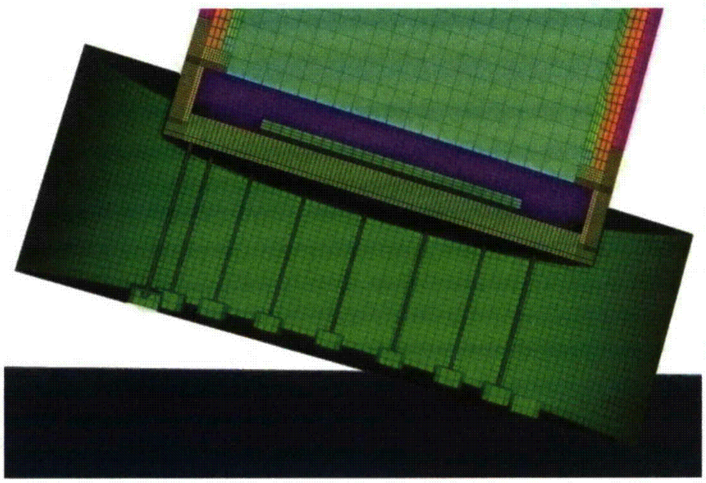



**Figure 3-6. Finite element mesh of the Rail-Lead cask**



**Impact limiter showing the two different types of wood. The yellow is balsa and the red is redwood.**



**Impact limiter with the wood removed to reveal the inner attachment bolts**

**Figure 3-7. Details of the finite element mesh for the impact limiters of the Rail-Lead**

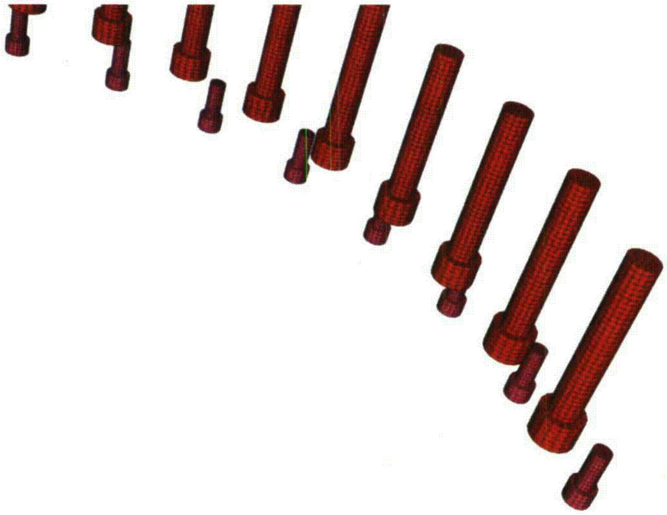


**Figure 3-8. Finite element mesh of the Rail-Lead closure bolts for both the inner and outer lids. The longer bolts are for the inner lid and the shorter ones for the outer lid.**

***Analysis results***

For the 48 kph impact analyses (the impact velocity from the regulatory hypothetical impact accident) the impact limiter absorbed almost all of the kinetic energy of the cask and there was no damage to the cask body. The response of the Rail-Lead cask is more complicated than that of the Rail-Steel cask. As the impact velocity increases for the end orientation, there is first additional damage to the impact limiter because it is absorbing more kinetic energy (this shows the margin of safety in the impact limiter design). At 97 kph there is no significant damage to the cask body or canister. At an impact speed of 145 kph damage to the cask and canister appears to begin. 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 shielding near the end of the cask away from the impact point (this is discussed in Chapter 5 and Appendix V). As the impact velocity is increased to 193 kph, 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 multi-purpose canister) there could be some loss of radioactive contents if the cask has metallic seals but not for the case with elastomeric seals. A more detailed discussion of leakage is provided later in this section. Figure 3-9 shows the deformed shape of the Rail-Lead following the 193 kph impact in the end-on orientation. The amount of lead slump from this impact is 35.5 cm, and the area without lead shielding is visible in Figure 3-9. Table 3-1 gives the amount of lead slump in each of the analysis cases.

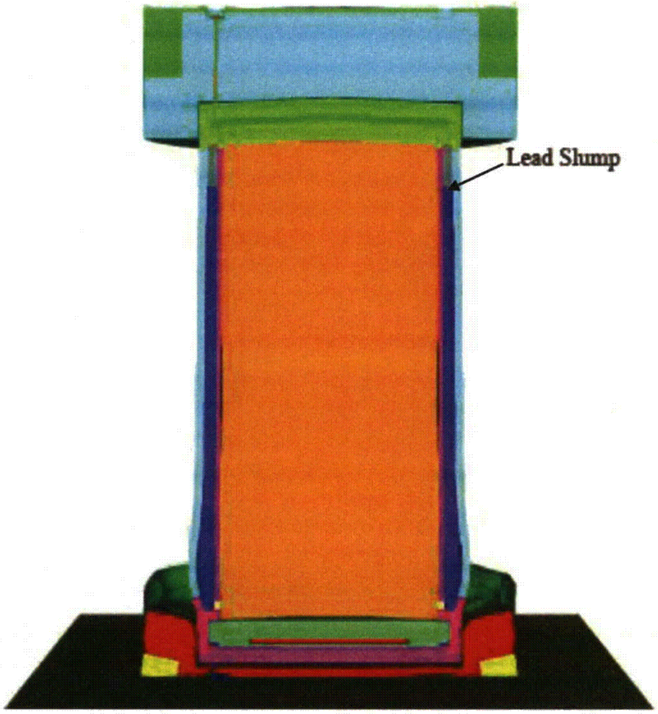



**Figure 3-9. Deformed shape of the Rail-Lead cask following the 193 kph impact onto an unyielding target in the end-on orientation**

**Table 3-1. Maximum lead slump for the Rail-Lead from each analysis case***

| Speed (kph) | Max. Slump End (cm) | Max. Slump Corner (cm) | Max. Slump Side (cm) |
|---|---|---|---|
| 48 | 0.64 | 0.17 | 0.01 |
| 97 | 1.83 | 2.51 | 0.14 |
| 145 | 8.32 | 11.45 | 2.09 |
| 193 | 35.55 | 31.05 | 1.55 |

*The measurement locations for each impact orientation are given in Appendix III.

For the corner impacts at 97 and 145 kph there is some damage to the cask body, in addition to deformation of the impact limiter, that results in lead slump and closure bolt deformation. The amount of deformation to the closure in these two cases is not sufficient to cause a leak if the cask is sealed with elastomeric o-rings, but is enough to cause a leak if the cask is sealed with metallic o-rings. For a corner impact at 193 kph there is more significant deformation to the cask, more lead slump, and a larger gap between the lid and the cask body. Figure 3-10 shows the deformed shape of the cask for this impact analysis. The deformation in the seal region is sufficient to cause a leak if the cask has metallic o-rings but not if it has elastomeric o-rings. The maximum amount of lead slump is 31 cm.

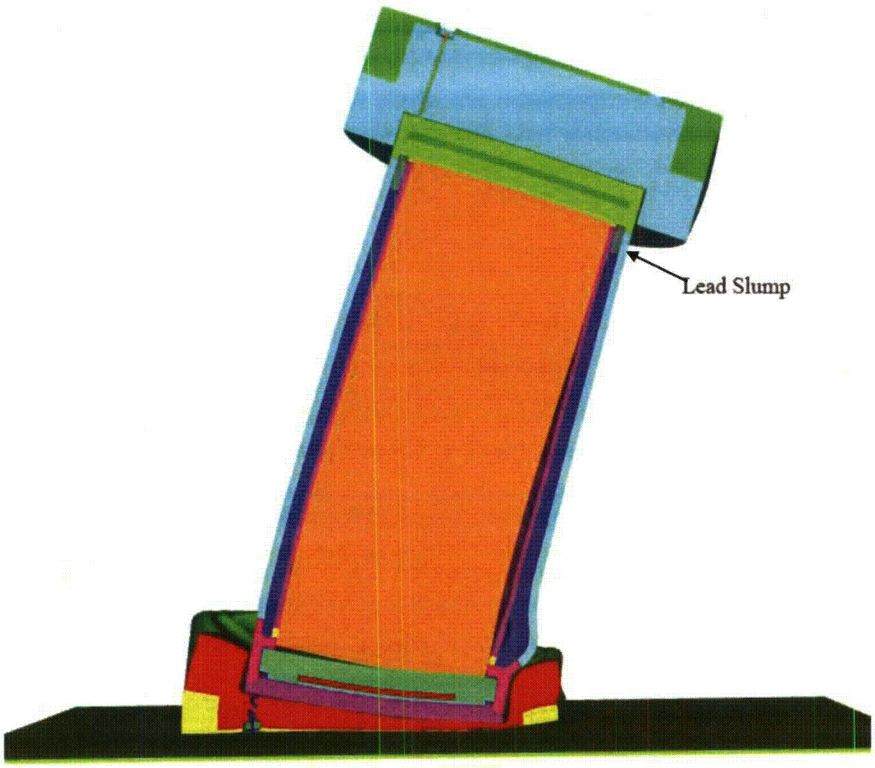



**Figure 3-10. Deformed shape of the Rail-Lead following the 193 kph impact onto an unyielding target in the corner orientation**

In the side impact as the impact velocity increases from 48 kph to 97 kph, 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 enough to leak if there is an elastomeric seal. When the impact speed is increased to 145 kph the amount of damage to the cask increases significantly. In this case many of the bolts from both 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 3-11 shows the deformed shape of the cask following this impact. The response of the cask to the 193 kph impact is similar to that from the 145 kph impact, only the gaps between the lids and the cask are larger. Deformed shapes for all of the analysis cases are shown in Appendix III.

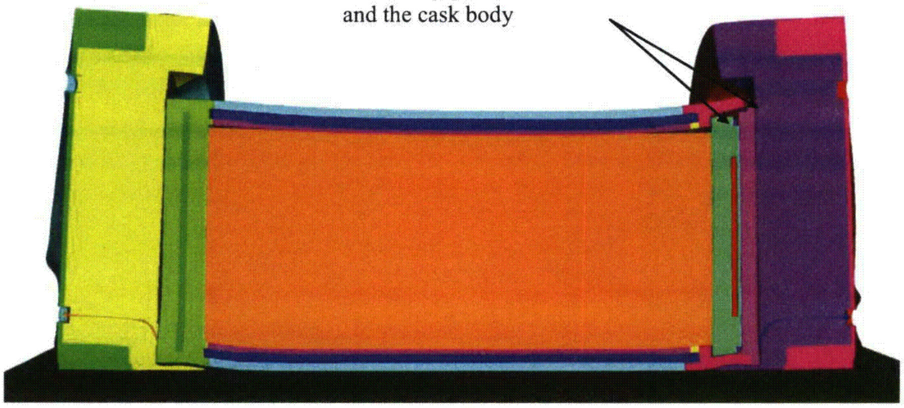



**Figure 3-11. Deformed shape of the Rail-Lead following the 145 kph impact onto an unyielding target in the side orientation**

***Leak area***

The Certificate of Compliance for the Rail-Lead cask allows transportation of spent fuel in three different configurations. The analyses conducted for this study were all for the direct-loaded fuel case, but the results can be applied to the case with an internal canister. The impact limiter and cask body are the same for that case. The addition of the internal canister adds strength and stiffness to the cask in the closure region (the canister has a 203-mm thick lid) that will inhibit the rotation of the cask wall and reduce any gaps between the closure lids and the cask. None of the analyses show sufficient deformation into the interior volume of the cask to cause a failure of the internal welded canister. So for this cask, like the Rail-Steel cask, if the spent fuel is transported in an inner welded canister there would be no release from any of the impacts.

**Comment [XXX7]:** Provide strain results and failure criteria (including reference)

In the cases without an inner canister the cask can be used for dry spent fuel storage before shipment or to transport fuel that is removed from pool storage and immediately shipped. In the first of these two cases metallic o-rings provide the seal between each of the lids and the cask body. This type of seal is less tolerant to movement between the lids and the cask, and closure opening greater than 0.25 mm will cause a leak. If the cask is used for direct shipment of spent fuel, elastomeric o-rings provide the seal between each of the lids and the cask body. This type of seal can withstand closure openings of 2.5 mm without leaking (Sprung et al., 2000). Table 3-2 gives the calculated axial gap in each analysis and the corresponding leak area for both metallic and elastomeric seals.

**Table 3-2. Available areas for leakage from the Rail-Lead cask**

| Orientation | Speed (kph) | Location | Lid Gap (mm) | Seal Type | Hole Size ($mm^2$) |
|---|---|---|---|---|---|
| End | 48 | Inner | 0.226 | Metal** | none |
| | | Outer | 0 | Elastomer | none |
| | 97 | Inner | 0.056 | Metal | none |
| | | Outer | 0.003 | Elastomer | none |
| | 145 | Inner | 2.311 | Metal | none |
| | | Outer | 0.047 | Elastomer | none |
| | 193 | Inner | 5.588 | Metal | 8796 |
| | | Outer | 1.829 | Elastomer | none |
| Corner | 48 | Inner | 0.094 | Metal | none |
| | | Outer | 0.089 | Elastomer | none |
| | 97 | Inner | 0.559 | Metal | 65 |
| | | Outer | 0.381 | Elastomer | none |
| | 145 | Inner | 0.980 | Metal | 599 |
| | | Outer | 1.448 | Elastomer | none |
| | 193 | Inner | 2.464 | Metal | 1716 |
| | | Outer | 1.803 | Elastomer | none |
| Side | 48 | Inner | 0.245 | Metal | none |
| | | Outer | 0.191 | Elastomer | none |
| | 97 | Inner | 0.914 | Metal | 799 |
| | | Outer | 1.600 | Elastomer | none |
| | 145 | Inner | 8* | Metal | >10000 |
| | | Outer | 25* | Elastomer | >10000 |
| | 193 | Inner | 15* | Metal | >10000 |
| | | Outer | 50* | Elastomer | >10000 |

*Estimated; the method used to calculate the gaps for the other cases is explained in Appendix III.

**The metal seal for the Rail-Lead cask is only installed when the cask has been used for dry storage prior to transportation. Currently there are none of these casks being used for dry storage and there are no plans for using them in that way in the future.

**Comment [XXX8]:** How are these estimated? If the method for calculating the gaps is explained elsewhere, the method of estimation should also be explained.

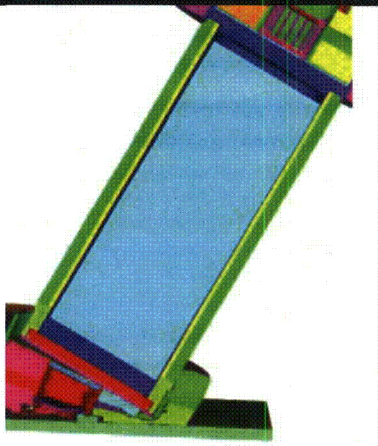
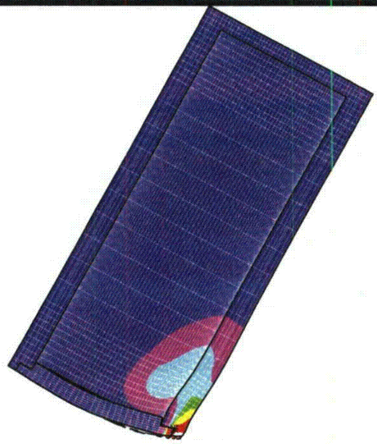
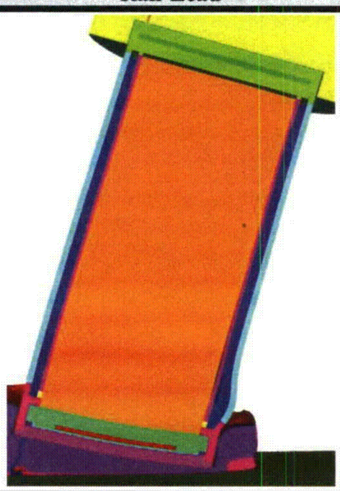
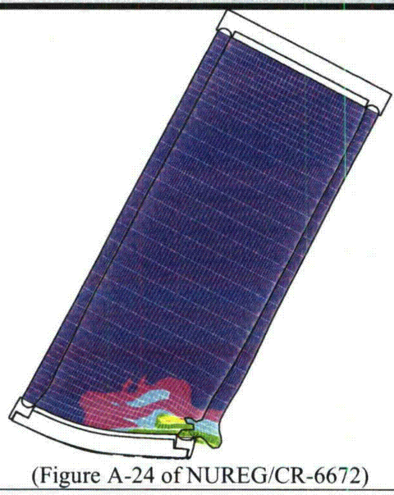
### 3.2.3 Truck-DU Cask

Detailed finite element analyses of the Truck-DU cask were not performed for this study, because the response of the truck casks in NUREG/CR-6672 indicated no gaps between the lid and the cask body at any impact speed. Therefore, the results discussed here are based upon the finite element analysis of the generic steel-DU-steel truck cask performed for NUREG/CR-6672. In general, the results from the analyses performed for this study have shown that the analyses performed for NUREG/CR-6672 were conservative (see Table 3-3), so the results discussed

**Comment [XXX9]:** This needs to be made clear throughout the document. Other places it is written as though a structural analysis of the truck was performed specifically for this study.

below are likely to be an overestimate of the damage to the Truck-DU cask from severe impacts. Figure 3-12 shows the deformed shape and plastic strain contours for the generic steel-DU-truck cask from Appendix A of NUREG/CR-6672 (Figures A-15, A-19, and A-22). None of the impacts caused strains that are great enough to fail the cask wall, and in all cases the deformation in the closure region was insufficient to cause seal failure. Table 3-4 (extracted from Table 5.6 of NUREG/CR-6672) provides the deformation in the seal region for each case. For all of these cases there would be no release of radioactive contents.

**Table 3-3. Comparison of analyses between this study and NUREG/CR-6672**

| Item/Cask | Rail-Steel | 6672 Monolithic Steel |
|---|---|---|
| **Deformed Shape 145 kph** |  |  (Figure A-35 of NUREG/CR-6672) |
| **Failed Bolts** | No | Yes |
| **Item/Cask** | **Rail-Lead** | **6672 SLS Rail** |
| **Deformed Shape 145 kph** |  |  (Figure A-24 of NUREG/CR-6672) |
| **Gap Size** | Inner Lid - 0.980 mm<br>Outer Lid – 1.448 mm | 6.096 mm |
| **Failed Bolts** | No | Yes |

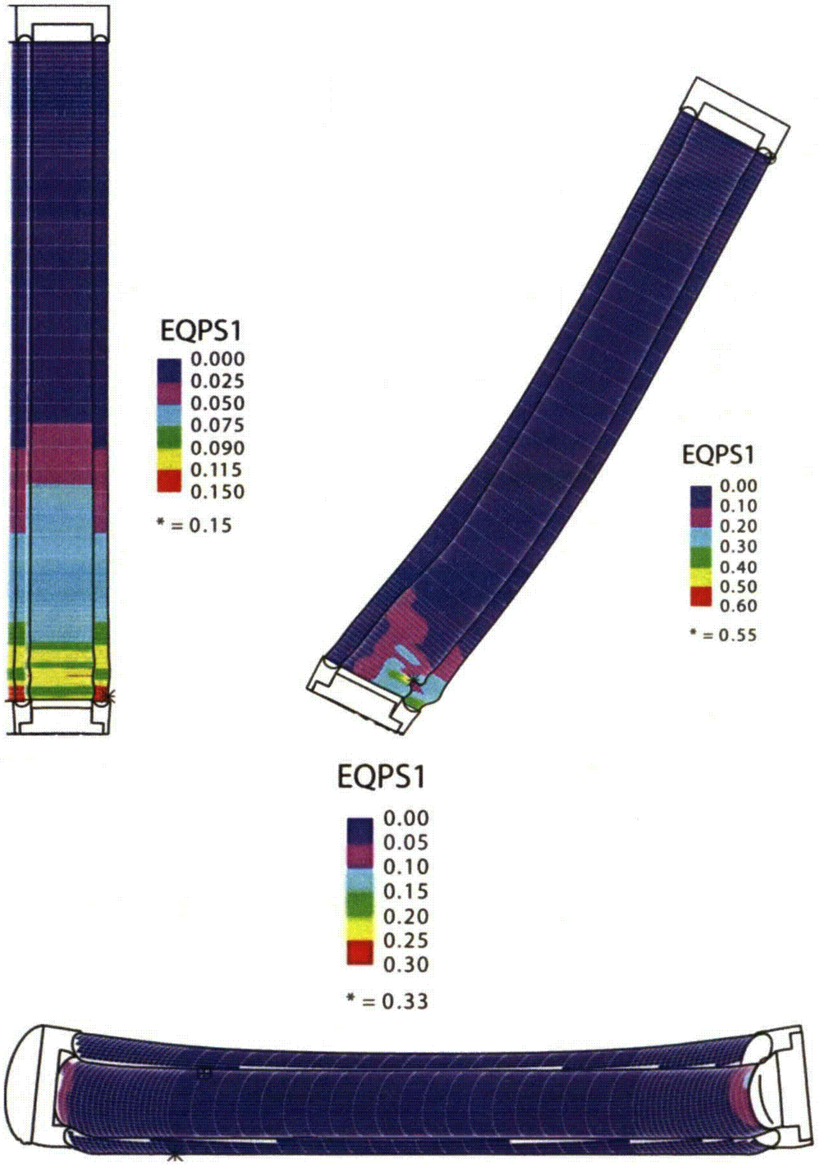



**Figure 3-12. Deformed shapes and plastic strains in the generic steel-DU-steel truck cask from NUREG/CR-6672 (impact limiter removed)** after ??-ft drop test in various orientations (clock wise from top left top down, CGOC??, ??° slap down)

**Table 3-4. Deformation of the closure region of the steel-DU-steel truck cask from NUREG/CR-6672, in mm**

| Cask | Analysis Velocity | Corner Impact | | End Impact | | Side Impact | |
|---|---|---|---|---|---|---|---|
| | | Opening | Sliding | Opening | Sliding | Opening | Sliding |
| Steel-DU-Steel Truck | 48 kph | 0.508 | 1.778 | 0.127-0.305 | 0.025-0.127 | 0.254 | 0.508 |
| | 97 kph | 2.032 | 1.778 | 0.254-0.508 | 0.076-0.152 | 0.254 | 0.254 |
| | 145 kph | 0.508 | 2.540 | - | - | 0.254 | 0.508 |
| | 193 kph | 0.762 | 3.810 | 0.330 | 0.762 | 0.102 | 0.508 |

## 3.3 Impacts onto Yielding Targets

All of the analysis results discussed in Section 3.2 were for impacts onto an unyielding essentially rigid target. All real impact accidents involve targets that are to some extent yielding. When a cask impacts a real target the amount of the impact energy that is absorbed by the target and the amount that is absorbed by the cask depend 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 damage in the cask.

**Comment [XXX10]:** This section describes impacts with "rigid" surfaces. The conclusions section describes impacts with "hard rock". I think these are one in the same, but the concept of hard rock needs to be introduced and explained in this section.

For the Rail-Lead cask (the only one of the three investigated in this study that has any release) the peak force associated with each of the impact analyses performed is given in Table 3-5. In this table the cases that have non-zero hole sizes from Table 3-4 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 MN (33 million pounds). Very few real targets are capable of applying this amount of force.

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. Figure 3-13 shows the relationship between penetration depth and force for the Rail-Lead cask impacting onto hard desert soil. As the cask penetrates the surface, some of its kinetic energy is absorbed by the surface. The amount of energy absorbed by the target is equal to the area underneath the force vs. penetration curve of Figure 3-13. As an example, the end impact at 97 kph onto an unyielding target requires a contact force of 123.9 MN. A penetration depth of approximately 2.2 meters will cause the soil to exert this amount of force. The soil absorbs 142 MJ of energy in being penetrated this distance. Adding the energy absorbed by the soil to the 41 MJ of energy absorbed by the cask gives a total absorbed energy of 183 MJ. For the cask to have this amount of kinetic energy it would have to be traveling at 205 kph. Therefore, a 205 kph impact onto hard desert soil causes the same amount of damage as a 97 kph impact onto an unyielding target. A similar calculation can be performed for other impact speeds, orientations and target types. Table 3-6 provides the resulting equivalent velocities. Where the calculated velocity is more than 250 kph the value in the table is listed as greater than 250. No accident velocities are more than this. The concrete target used is a 23 cm thick slab on engineered fill. This is typical of many concrete roadways and concrete retaining walls adjacent to highways. Details on the calculation of equivalent velocities are included in Appendix III.

**Comment [XXX11]:** Don't understand this statement. Please explain.

**Table 3-5. Peak contact force for the Rail-Lead cask impacts onto an unyielding target (bold numbers are for the cases where there may be seal leaks)**

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

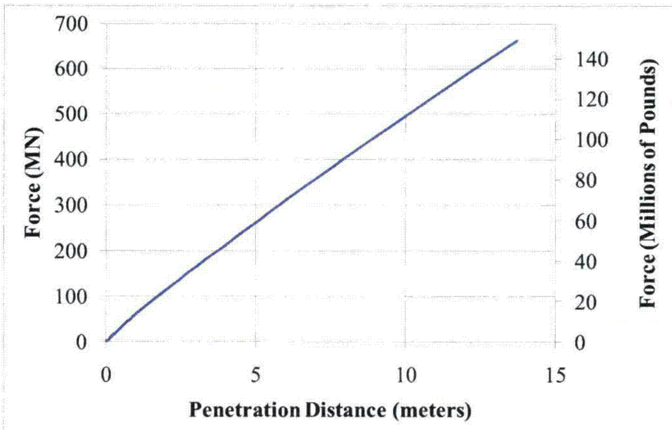



**Figure 3-13. Force generated by the Rail-Lead cask penetrating hard desert soil**

**Table 3-6. Equivalent velocities for impacts onto various targets with the Rail-Lead cask, kph**

| Orientation | Rigid | Soil | Concrete |
|---|---|---|---|
| End | 48 | 102 | 71 |
| | 97 | 205 | 136 |
| | 145 | >250 | >250 |
| | 193 | >250 | >250 |
| Corner | 48 | 73 | 70 |
| | 97 | 236 | 161 |
| | 145 | >250 | >250 |
| | 193 | >250 | >250 |
| Side | 48 | 103 | 79 |
| | 97 | 246 | 185 |
| | 145 | >250 | >250 |
| | 193 | >250 | >250 |

## 3.4 Effect of Impact Angle

The regulatory hypothetical impact accident requires the cask's velocity to be perpendicular to the impact target. All of the analyses were also conducted with this type of impact. During transport the usual scenario is that the velocity is parallel to the nearby surfaces, and therefore, most accidents that involve impact with surfaces occur at a shallow angle (this is not necessarily true for impacts with structures or other vehicles).

Accident databases do not include impact angle as one of their parameters, so there is no information on the relative frequency of impacts at various angles. Given that vehicles usually travel parallel to the nearby surfaces, for this study a triangular distribution of impact angles was used. Figure 3-14 shows the assumed step-wise distribution of impact angle probabilities. For impacts onto hard targets, which are necessary to damage the cask, the component of the velocity that is parallel to the impact surface has very little effect on the amount of damage to the cask. This requires the accident speed to be higher for a shallow angle impact then a perpendicular one in order to achieve the same amount of damage. Figure 3-15 depicts an example of an impact at a shallow angle and the components of the velocity parallel and perpendicular to the surface. Table 3-7 provides the cumulative probability of exceeding an impact angle range and the accident speeds that are required to have the velocity component in the direction perpendicular to the target.

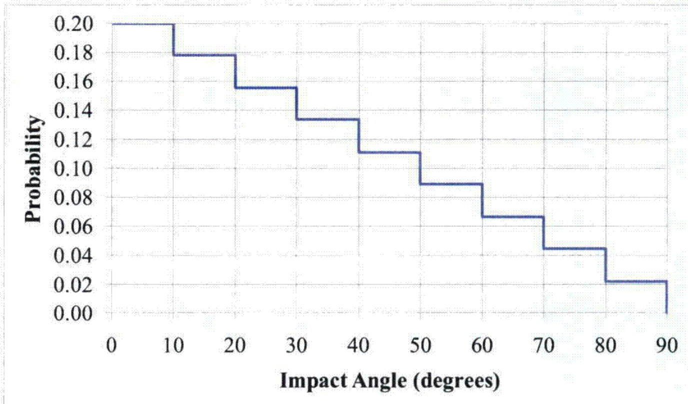



**Figure 3-14. Probability distribution for impact angles**

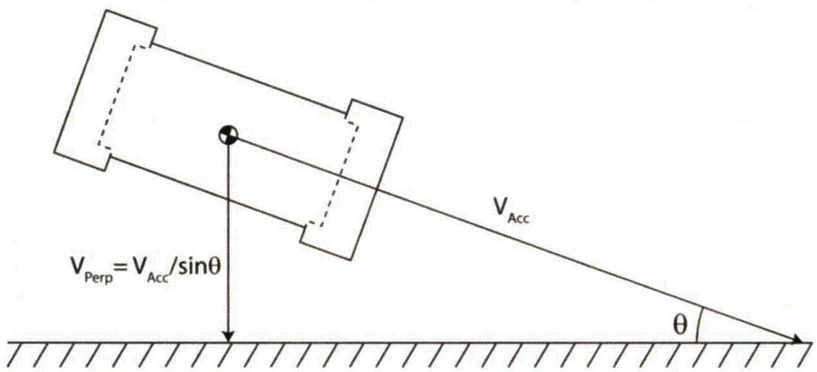



**Figure 3-15. Influence of impact angle on effective velocity**

**Table 3-7. Accident speeds that result in the same damage as a perpendicular impact, kph**

| Angle | Prob. | Cum. Prob. | $V_{Acc}$ so $V_{Perp}$ = 48 kph | $V_{Acc}$ so $V_{Perp}$ = 97 kph | $V_{Acc}$ so $V_{Perp}$ = 145 kph | $V_{Acc}$ so $V_{Perp}$ = 193 kph |
|---|---|---|---|---|---|---|
| 0 - 10 | 0.2000 | 1.0000 | 278 | 556 | 834 | 1112 |
| 10 - 20 | 0.1778 | 0.8000 | 141 | 282 | 423 | 565 |
| 20 - 30 | 0.1556 | 0.6222 | 97 | 193 | 290 | 386 |
| 30 - 40 | 0.1333 | 0.4667 | 75 | 150 | 225 | 300 |
| 40 - 50 | 0.1111 | 0.3333 | 63 | 126 | 189 | 252 |
| 50 - 60 | 0.0889 | 0.2222 | 56 | 111 | 167 | 223 |
| 60 - 70 | 0.0667 | 0.1333 | 51 | 103 | 154 | 206 |
| 70 - 80 | 0.0444 | 0.0667 | 49 | 98 | 147 | 196 |
| 80 - 90 | 0.0222 | 0.0222 | 48 | 97 | 145 | 193 |

## 3.5 Impacts with Objects

The discussions in the preceding sections all dealt with impacts onto flat surfaces. A large number of impacts deal with 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 (NRC, 2003b, Ammerman and Gwinn, 2004, Ammerman et al., 2005) has shown the response of the GA-4 truck cask to some of these impacts. The result of an impact into a large, semi-circular, rigid column is shown in Figure 3-16 (NRC, 2003b). 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.

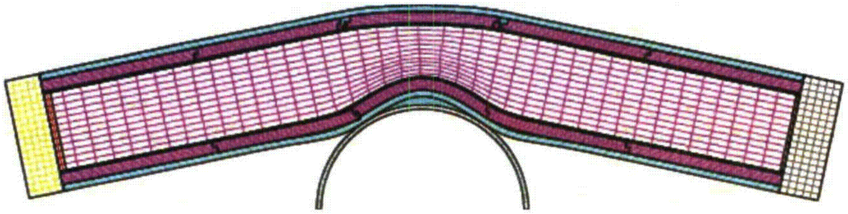


**Figure 3-16. Deformations to the GA-4 truck cask after a 96 kph side impact onto a rigid semi-circular column (NRC, 2003b).**

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Another type of accident that could potentially damage a cask is the collision by a railroad locomotive. This is probably the most severe type of collision with another vehicle that is possible. Several different scenarios of this type of collision were investigated by Ammerman et al. (2005). The overall configuration of the general analysis case is shown in Figure 3-17. Variations on the general configuration included using the two most common types of locomotives, having a level crossing (such that the tires of the truck and the wheels of the locomotive are at the same elevation), having a raised crossing where the bottom of the main beams of the trailer at the same elevation as the top of the tracks, and having a skewed crossing so the impact is at 67° instead of at 90°. For all analyses the truck was assumed to be stopped. Train velocities of 113 kph and 129 kph were considered.

**Comment [XXX12]:** Suggest provide a more detailed overview of this analysis. Figure 3-17 makes it appear as though the analysis performed only considered a train with a mass equivalent to 1 engine and 3 hopper cars when a real train would more likely contain several engines and hundreds of cars.

None of the analyses led to deformations that would cause a release of radioactive material from the cask and none of them resulted in cask accelerations that were high enough to fail the fuel rod cladding. Figure 3-18 shows a sequence of the impact. 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.

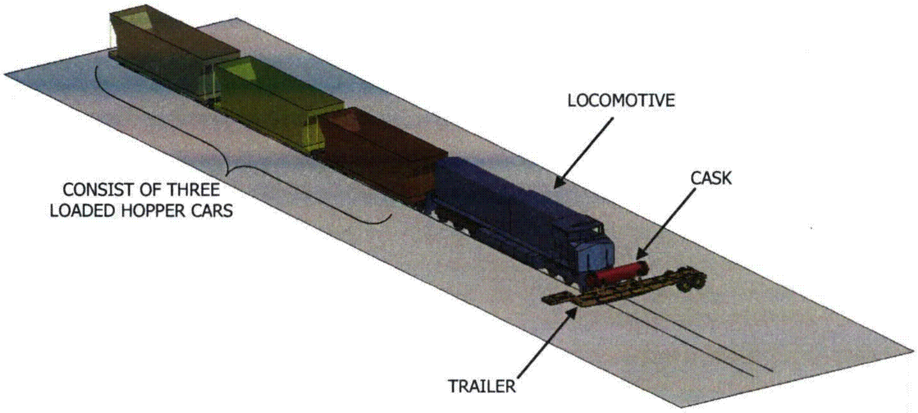


**Figure 3-17. Configuration of locomotive impact analysis (from Ammerman et al., 2005)**

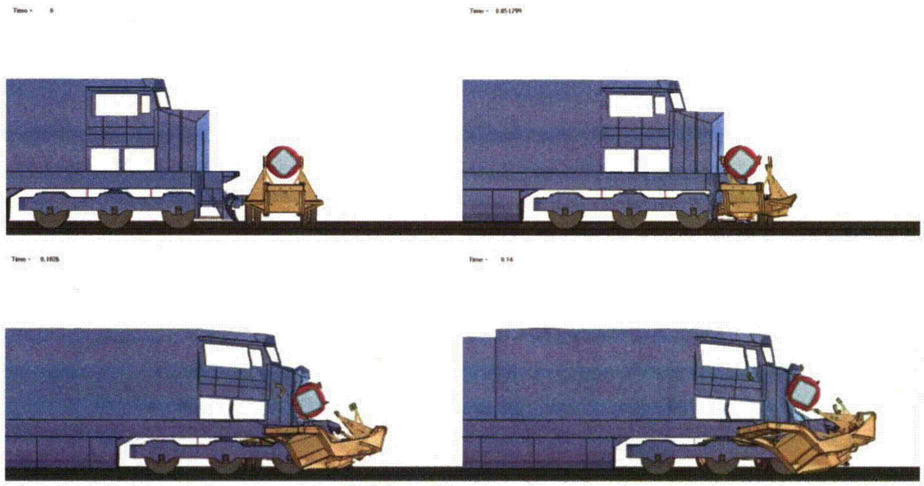

**Figure 3-18. Sequential views of a 129 kph impact of a locomotive into a GA-4 truck cask (from Ammerman et al., 2005)**

A type of accident that occurs less frequently, but also has the potential to damage a cask is the collapse of a bridge onto the cask. This type of accident occurred when an elevated portion of the Nimitz Freeway collapsed during the Loma Prieta earthquake. This accident scenario was analyzed to determine if it would cause a release of spent fuel from the GA-4 truck cask

(Ammerman and Gwinn, 2004). The analysis assumed the cask was lying directly on the roadway (neglecting the cushioning effect of the trailer and impact limiters) and one of the main beams of the elevated freeway fell and impacted the middle of the cask. The stresses in the cask and damage to the beam are shown in Figure 3-19. As in the other analyses for impacts with objects, there would be no loss of containment from this accident.

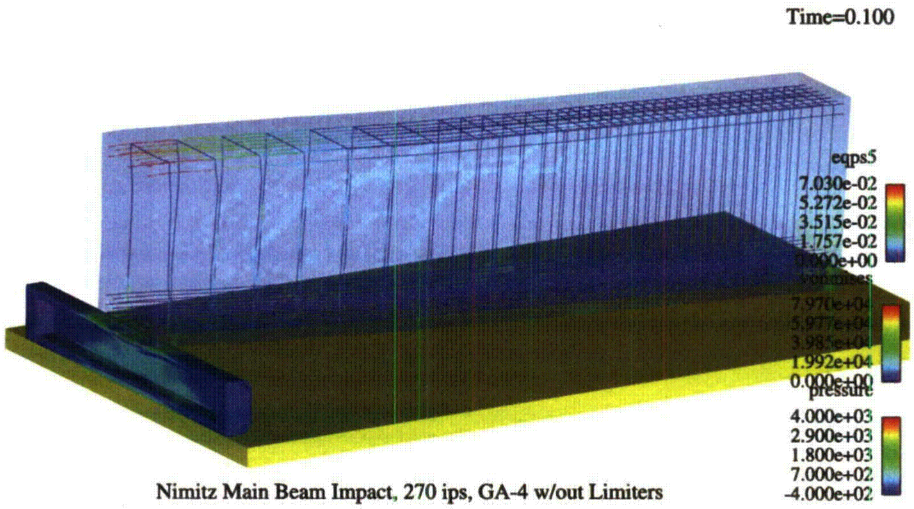


**Figure 3-19. Results of a finite element simulation of an elevated freeway collapse onto a GA-4 spent fuel cask (from Ammerman and Gwinn 2004)**

Comment [XXX13]: Key needs work so words are not on top of one another. Does the figure show all 3 properties with one set of fringe plots? What is the meaning of negative pressure?

## 3.6 Response of Spent Fuel Assemblies

The finite element analyses of the casks in this study did not include the individual components of the spent fuel assemblies. Instead, the total mass of the fuel and its support structure were combined into an average material. To determine the response of individual components, a detailed model of a spent fuel assembly was developed (Kalan et al., 2005). Figure 3-20 shows this model. The loads associated with a 100 G cask impact in a side orientation were then applied to this detailed model. Kalan et al. only analyzed side impacts of spent fuel assemblies because the strains associated with buckling of the rods during an end impact are limited by the constrained lateral deformations provided by the basket. The side impact results in forces in each fuel rod at their supports and in many of the fuel rods midway between the supports where they impact onto the rods above or below them. The response of the rod with the highest loads was determined by a detailed finite element model, shown in Figure 3-21. There is slight yielding of the rod at each support location and slightly more yielding where the rods impact each other.

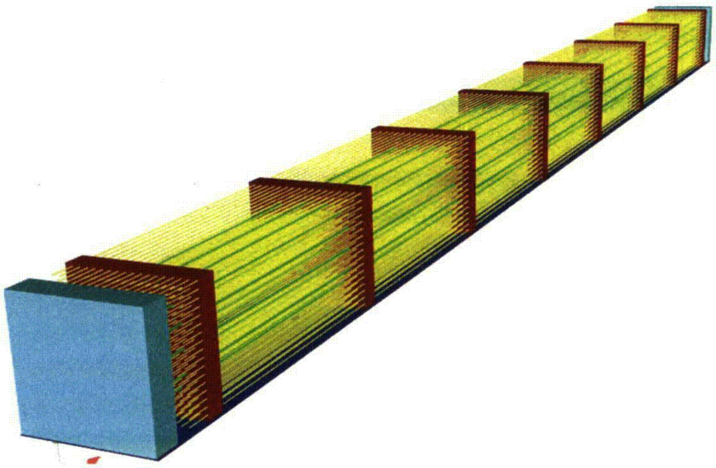

Figure 3-20. Finite element model of a PWR fuel assembly.

Comment [MF14]: Provide key to the colored objects.

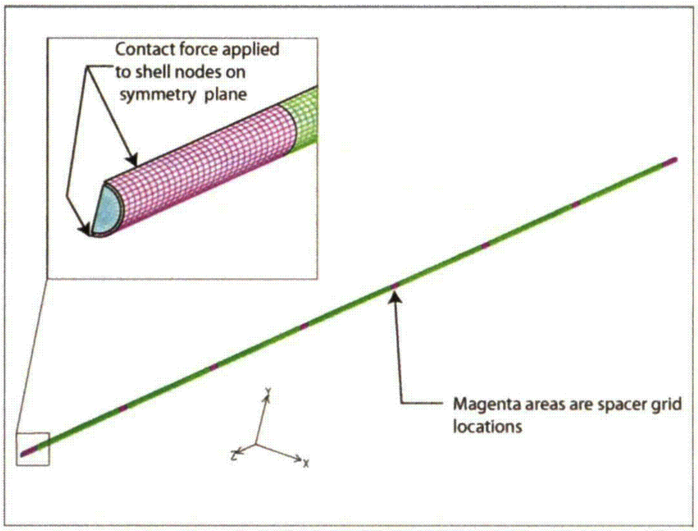


**Figure 3-21. Detailed finite element model of a single fuel rod.**

Figure 3-22 shows the maximum plastic strain at each location. The largest of these strains is slightly below 2%, which is half the plastic strain capacity of irradiated zircaloy at the maximum burn-up allowed in the Rail-Lead cask (45,000 MWD/MTU) (Sanders et al., 1992), so fuel rods will not crack. For cladding to fail, the peak acceleration of the cask would have to be above 200G. The only impacts that are severe enough to crack the rods are those with impact speeds onto an essentially unyielding target of 145 kph or higher. A detailed description of the fuel assembly modeling is included in Appendix III.

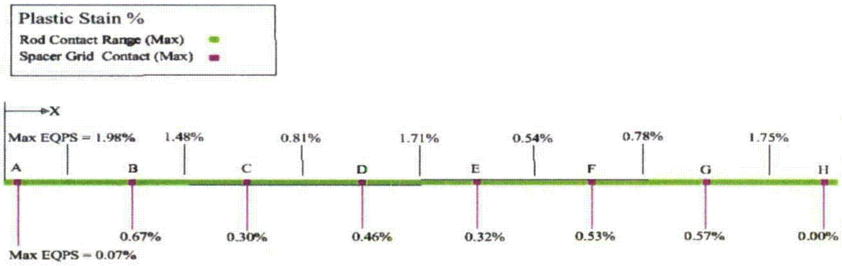


**Figure 3-22. Maximum strains in the fuel rod with the highest loads.**

## 3.7 Conclusions

The finite element analyses performed indicate that casks are very robust structures that are 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, there are no impacts that result in release. Even the rail cask without an inner welded canister can withstand impacts that are much more severe than the regulatory impact without releasing any material.

**Comment [XXX15]:** It could be construed that the document is taking credit for analysis not performed. This paragraph reads as though truck cask FEA was performed for this work. Suggest that the a brief summary paragraph of the FEA performed for the rail casks (similar to what is already here) start this section and then a second paragraph that briefly describes how the truck cask case was handled.

In the worst orientation (side impact) an impact speed onto a rigid target 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 side impact onto a rigid target produces a force of about 200 MN (45 million pounds) and is equivalent to a 185 kph impact onto a concrete roadway or abutment or a 246 kph 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 more than 193 kph in order to be equivalent.

**Comment [XXX16]:** This is the very first mention of "hard rock". New concepts should not be introduced in the conclusions section.

In summary, the sequence of events that is needed 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. This cask would need to be impacted in a side orientation and the impact surface would need to be hard rock with an impact angle greater than 30 degrees.

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