CHAPTER 4

CASK RESPONSE TO FIRE ACCIDENTS

4.1 Introduction

Certified Type B casks are designed to survive a fully-engulfing fire for thirty minutes. Certification analyses of the hypothetical accident condition (HAC) fire environment specified in 10 CFR 71.73 generally impose a thermal environment on the package that is similar to or more severe than a real fully-engulfing fire. This is more severe than the majority of the thermal environments a cask may be exposed to in an actual transportation accident that results in a fire (Fischer et al. 1988). Large open pool fires can burn at temperatures higher than the average temperature of 800°C specified in the regulations. Real fire plumes have location- and time-varying temperature distributions that vary from about 600°C to more than 1200°C (Koski, 2000; Lopez et al., 1998). Therefore, the evenly-applied 800°C fire environment used in a certification analysis could be more severe for seal and fuel rod response than the exposure to an actual fire.

For this risk study, computer codes capable of modeling fires and the thermal response of casks exposed to fires in a realistic[15] fashion are used to analyze the response of the Rail-Steel and the Rail-Lead casks to three different fire configurations. These configurations are described in this chapter and the temperature responses of the casks are presented and discussed. An analysis of the thermal performance of the Truck-DU cask when exposed to a severe fire scenario is also presented.

The thermal response of each cask is compared to two characteristic temperature limits. These are the seal failure temperature (350°C for elastomeric seals used in the Rail-Lead cask and the Truck-DU and 649°C for the metallic seal used in the Rail-Steel cask) and the fuel rod burst rupture temperature (750°C for all casks). The values selected for these temperature limits are the same as those used in NUREG/CR-6672 for the elastomeric seal and fuel rod burst temperature. The Rail-Steel cask seal temperature limit is obtained from Table 2.1.2 and Table 4.1.1 in the HI-STAR 100 SAR (Holtec International, 2004). Section 7.2.5.2 in NUREG/CR-6672 explains that 350°C is a conservative temperature limit for elastomeric seals typically used in the SNF transportation industry. Section 7.2.5.2 of NUREG/CR-6672 also provides the rationale for the use of 750°C as the fuel rod burst rupture temperature. These temperature limits are used in this study to determine if the cask seals or fuel rods would be compromised, allowing release of radioactive material under any of the accident scenarios analyzed.

4.2 Description of Accident Scenarios

4.2.1 Pool size

Three fire accident scenarios are analyzed for each rail cask and one for the truck cask. A hydrocarbon fuel pool that conforms to the HAC fire described in 10 CFR 71.73 is used as the basis for each scenario. This regulation specifies a hydrocarbon fuel pool that extends between

[15] Computational fluid dynamics fire codes are capable of modeling flame behavior, soot formation, flow of hot gasses, and other physical phenomena found in fires.

one and three meters horizontally beyond the external surface of a cask. To ensure the casks analyzed in this study are fully engulfed by the fire, all fuel pools were assumed to extend three meters from the sides of the cask (a pool fire that extends less than three meters can be sufficient to ensure full engulfment of smaller packages).

4.2.2 Fire Duration

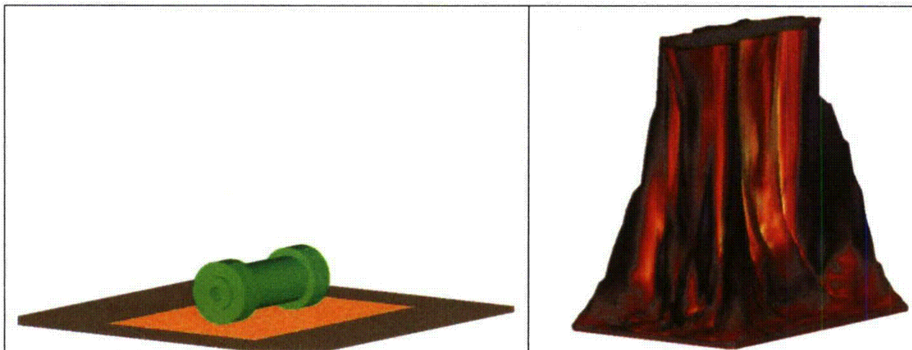
The duration of the fires postulated for the rail cask analyses is based on the capacity of a large rail tank car. Typical large rail tank cars can carry about 30,000 gallons (113,562 liters) of liquid (hydrocarbon) fuel. To estimate the duration of the fires, all the fuel in the tank car is released and assumed to form a pool with the dimensions of a regulatory pool fire for the rail casks that were analyzed. That is, fuel pools that extend horizontally three meters (ten feet) beyond the surfaces of the casks are used in the fire models. Provided that there are relatively small differences between the overall dimensions of the Rail-Steel cask and the Rail-Lead cask, these fuel pools are similar in size and are nominally 14 m × 9 m (46 ft × 29.5 ft). A pool of this size would need to be 0.9 m (3 ft) deep to pool 30,000 gallons (113,562 liters) of liquid fuel, a condition that is extremely unlikely to be met in any accident scenario. If all of the fuel in such a pool were to ignite and burn (i.e., none of the fuel runs off or soaks into the ground), this pool fire would burn for about 3 hours. This fire duration is estimated using a nominal hydrocarbon fuel recession (evaporation) rate of 5 mm (0.2 in) per minute, typical of large pool fires (SFPE, 2002; Lopez et al., 1998; Quintiere, 1998). Another way this large pool area could burn for up to three hours would be the even less likely case in which liquid fuel flows at exactly the right rate to feed and maintain the pool area for the duration of the fire. Provided that both of these pooling conditions are very difficult to obtain, the fire duration presented here is considered to be conservative. Nevertheless, a three-hour fire that is not moving over time and is capable of engulfing a rail cask over the duration of the fire is conservatively used for the analysis of the two rail casks considered in this study.

In the case of the Truck-DU cask, the fire duration is based on the fuel capacity of a typical petroleum tank truck. About 9,000 gallons (34,070 liters) of gasoline can be transported on the road by one of these tank trucks. Provided that the overall dimensions of the Truck-DU cask are 2.3 m × 6 m (7.5 ft × 19.7 ft), a regulatory pool that extends horizontally 3 meters (10 feet) beyond the outer surface of the cask would be 8.3 m × 12 m (27.2 ft × 39.4 ft). To pool 9,000 gallons (34,070 liters) of gasoline in a pool of this area, the pool would need to be 0.3 m (1 ft) deep, a configuration that is difficult to obtain in an accident scenario and therefore unlikely to occur. Such a pool fire would burn for a little more than an hour. As discussed for the rail cask pool fire, the other possibility of maintaining a fire that can be engulfing and that can burn for that duration is if, for example, gasoline were to flow at the right rate to maintain the necessary fuel pool conditions. This scenario is also very unlikely. Nevertheless, one hour is used as the duration of a fire that is not moving over time for the conservative analysis of the Truck-DU cask.

4.2.3 Hypothetical Accident Configurations for the Rail Casks

Three fire accident scenarios that differ from the regulatory HAC fire configuration are analyzed in this study for the rail casks. These are:

1. Cask lying on the ground in the middle of (concentric with) a pool of flammable liquid (such as gasoline) as depicted in Figure 4-1. This scenario represents the case in which the liquid fuel spilled because of an accident flows to the location where the cask comes to rest following the accident and forms a large pool under (and concentric with) the cask.



Cask in the middle of flammable liquid fuel pool region(shown in orange)

Fire engulfing the cask

Figure 4-1. Cask lying on ground concentric with fuel pool.

2. Cask lying on the ground three meters (10 feet) away from the pool of flammable liquid (with the side of the cask aligned with the side of fuel pool) as depicted in Figure 4-2. This scenario represents the hypothetical case in which the fuel pool and the cask are separated by the width of one rail car. This could be the case in an accident in which the rail cars derail in an "accordion" fashion.

Figure 4-2. Cask lying on ground 3 meters from pool fire.

3. Cask lying on the ground 18 meters (60 feet) from the pool of flammable liquid (with the side of the package aligned with the side of fuel pool) as depicted in Figure 4-3. This scenario represents the hypothetical case in which the pool of flammable liquid and the cask are separated by the length of one rail car. This represents an accident in which the separation between a tank car carrying flammable liquid and the railcar carrying the SNF package is maintained (the distance of a buffer rail car) after the accident. For this scenario, the most damaging cask position is assumed. That is, the side of the cask is assumed to face the fire.

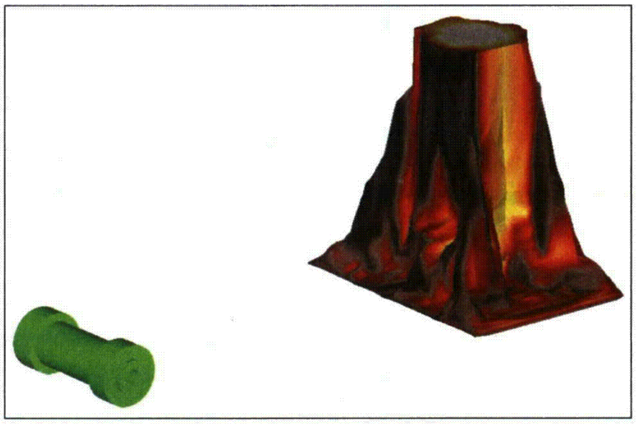
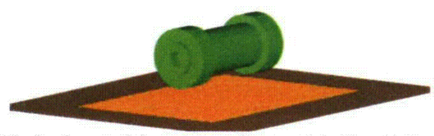


Figure 4-3. Cask lying on ground 18 meters from pool fire.

For each scenario, calm wind conditions (leading to a vertical fire) are assumed. Only the cask and the fuel pool are represented for the analysis. For conservatism, objects that would be present and could shield (protect) the cask from the fire (such as the conveyance or other rail cars) are not included. Decay heat was included for all analyses.

Before these accident scenarios are analyzed, two additional 30-minute regulatory HAC fire analyses are performed for each rail cask based on the conditions described in 10 CFR 71.73. In the first analysis, a commercially-available FE heat transfer code is used to apply an 800°C (1475°F) uniform-heating fire condition to the casks. In the second analysis, a benchmarked computational fluid dynamics (CFD) computer model with radiation heat transfer is used. In this model, each cask is positioned one meter above the fuel pool (as described in 10 CFR 71.73) and a realistic fire fully engulfs the cask as shown in Figure 4-4. The results from FE uniform heating analyses were compared to those in the safety analysis reports for the respective casks to ensure that the cask models used in these analyses are representative. The results from the CFD fire analyses are compared to the results obtained from the uniform-heating FE analyses to demonstrate that the realistic CFD fire does impose conditions that are similar to the uniform heating.



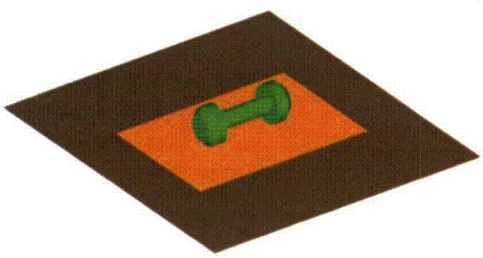
Cask elevated 1m above flammable liquid fuel pool region (shown in orange)

Regulatory fire engulfing the cask

Figure 4-4. Regulatory pool fire configuration.

4.2.4 Hypothetical Accident Configuration for the Truck Cask

In the case of the truck cask, solely the hypothetical accident configuration in which the cask is assumed to be concentric with a flammable fuel pool and is fully engulfed by a fire is analyzed. This hypothetical accident configuration is presented in Figure 4-5.



Cask in the middle of flammable liquid fuel pool region (shown in orange)

Fire engulfing the cask

Figure 4-5. Truck-DU cask lying on ground concentric with fuel pool.

4.3 Analysis of Fire Scenarios Involving Rail Casks

Advanced computational tools are employed to generate the data necessary for this risk study. For the hypothetical fire accidents, heat transfer from the fire to the cask body was simulated. To accomplish this, two computer codes including all the relevant heat transfer and fire physics are used in a coupled manner. This allows for the simultaneous detailed modeling of realistic external fire environments and heat transfer within the complex geometry of the cask. Brief descriptions of the models are presented in this section. Detailed information about the computer models including material properties, geometry, boundary conditions, and the assumptions used for model generation and subsequent analyses are presented in Appendix IV.

Results from the fire and heat transfer analyses that are performed on the Rail-Steel and the Rail-Lead casks are presented in this section. The scale in the temperature distribution plots of all the Rail-Steel cask analysis results are the same to make comparisons easier. The same is done for the Rail-Lead cask plots.

Results are presented in the following order:

1. 800°C (1475°F) uniform heating exposure for 30 minutes (based on 10 CFR 71.73)
2. CFD fire analysis using CAFE exposure for 30 minutes (based on 10 CFR 71.73)
3. 3-hour pool fire (cask on ground concentric with pool)
4. 3-hour pool fire (cask on ground 3 meters from pool)
5. 3-hour pool fire (cask on ground 18 meters from pool)

4.3.1 Simulations of the Fires

Fire simulations are performed with the Container Analysis Fire Environment (CAFE) code (Suo-Anttila et al., 2005). CAFE is a CFD and radiation heat transfer computer code that is capable of modeling fires realistically and is coupled to a commercially-available finite-element analysis computer code to examine the effects of fires on objects. CAFE has been benchmarked against large-scale fire tests specifically designed to obtain data for the calibration of fire codes (del Valle, 2009; del Valle et al., 2007; Are et al., 2005; Lopez et al., 2003). Appendix IV contains details of the benchmark exercises that were performed to ensure that proper input parameters are used to realistically represent the engulfing and offset fires assumed for this study.

4.3.2 Simulations of the Rail Casks

The heat transfer within the Rail-Steel and the Rail-Lead casks is modeled with the computer code MSC PATRAN-Thermal (P-Thermal) (MSC, 2008). This code is commercially available and may be used to solve a wide variety of heat transfer problems. P-Thermal has been coupled with CAFE, allowing for a refined heat transfer calculation within complex objects, such as spent fuel casks, with realistic external fire boundary conditions.

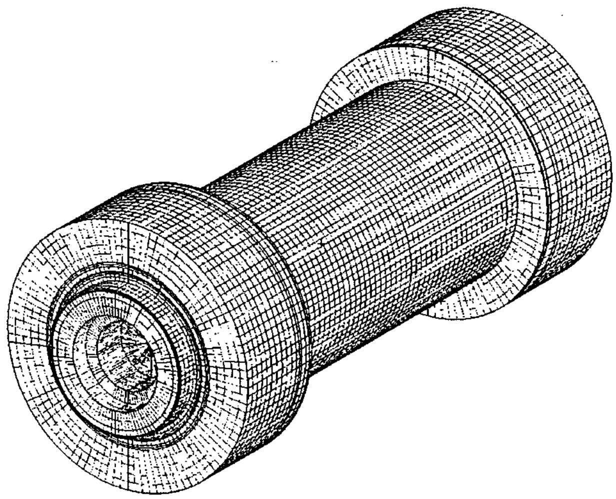
Both the Rail-Steel and the Rail-Lead casks have a polymeric neutron shield that is assumed to melt completely and be replaced by air at its operational temperature limit (see Appendix IV).

The Rail-Lead cask has a lead gamma shield that is allowed to change phase in the analyses upon reaching its melting temperature. Unlike the neutron shield, the thermal energy absorbed in the process of melting the gamma shield is included in the analyses. The effects of the thermal expansion of the lead are not included in the heat transfer calculations but are considered in the estimation of the reduction of the gamma shielding. Gamma shielding in the Rail-Steel cask is provided by the thick multi-layered carbon steel wall. Therefore, melting is not a consideration for this cask under any of the conditions to which it is exposed.

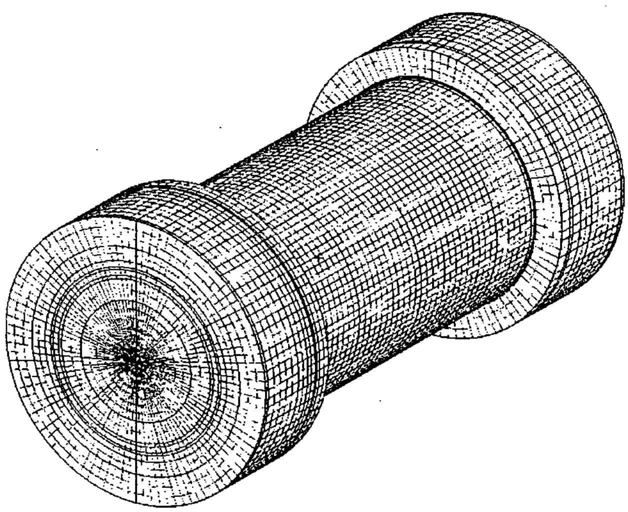
Impact limiters are modeled as undamaged (not deformed). The Rail-Steel cask has aluminum honeycomb impact limiters and the Rail-Lead cask has wood impact limiters. Spaces between components are explicitly modeled in both casks as these could have a significant effect on the thermal response of the cask. The finite element models of the two casks are shown in Figure 4-6. Cask modeling details are presented in Appendix IV.

4.3.3 Simulation of the Spent Nuclear Fuel Region

The interior of the package comprising the fuel basket and the SNF fuel assemblies is not modeled explicitly. A homogenized region, comprised of all materials and geometric features of the fuel basket of the casks that are analyzed, is represented as a solid cylinder inside the cask. The thermal response of the homogenized basket and fuel region is similar to the overall response of the results for the more detailed model of the basket and fuel region reported in NUREG/CR-6886 (NRC, 2006) and provides enough information for the purpose of this study. The details of how the effective properties of the homogenized fuel region are determined and applied to the models are presented in Appendix IV.



Rail-Steel cask



Rail-Lead cask

Figure 4-6. Finite element models of the two rail casks analyzed.

4.3.4 Rail-Steel Cask Results

The results for the Rail-Steel cask are presented in the order specified at the beginning of Section 4.3 in Figure 4-7 through Figure 4-21. Figure 4-7 through Figure 4-10 contain the temperature distribution and transient temperature response of key cask regions for the regulatory 800°C uniform heating and the regulatory CAFE fire.

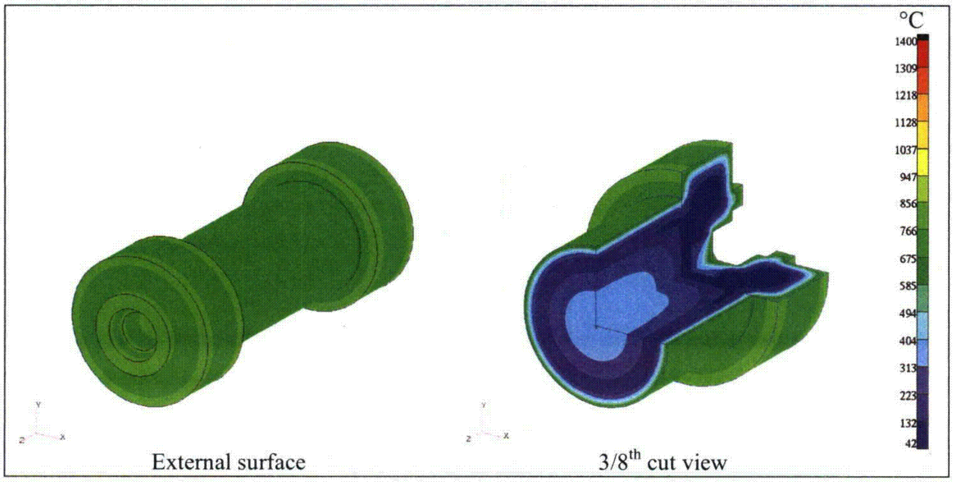


Figure 4-7. Temperature distribution of the Rail-Steel cask at the end of the 30-minute 800°C regulatory uniform heating.

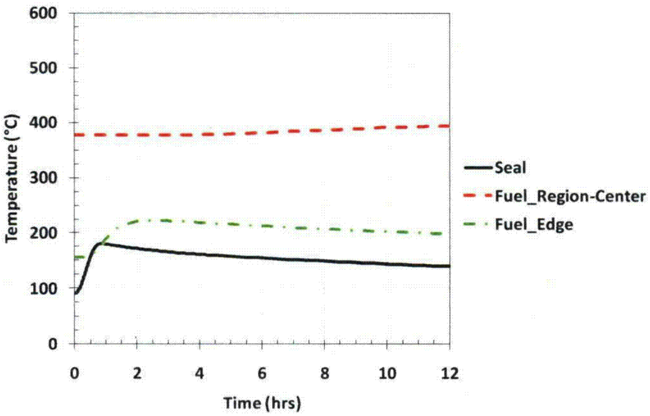


Figure 4-8. Temperature of key cask regions, Rail-Steel cask undergoing regulatory uniform heating.

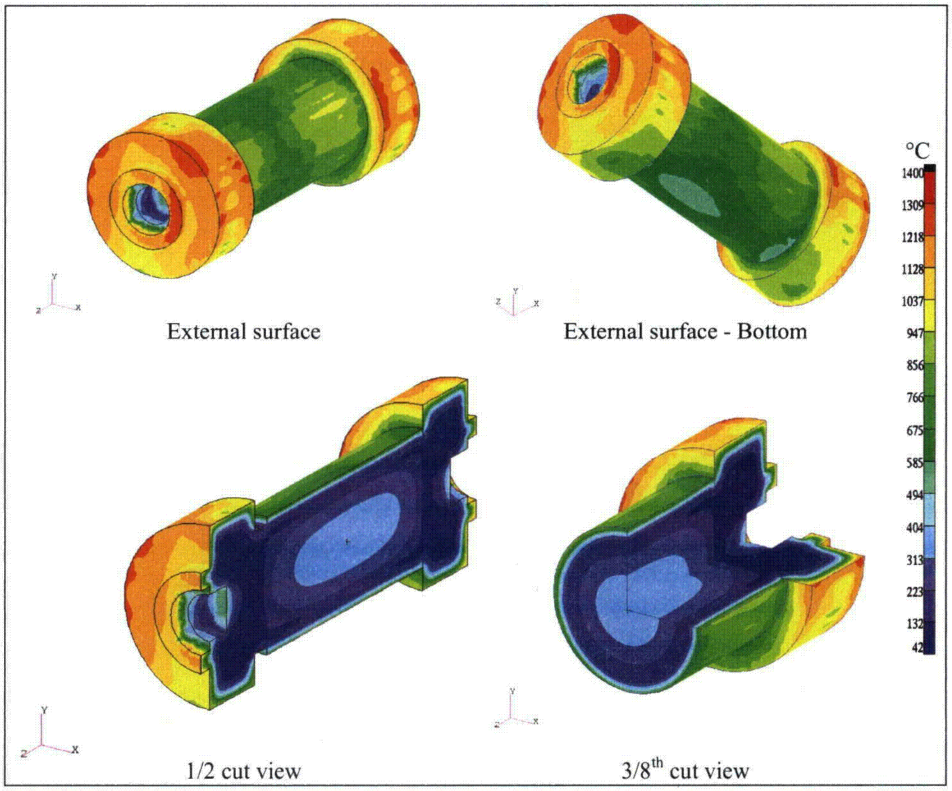


Figure 4-9. Temperature distribution of the Rail-Steel cask at the end of the 30-minute regulatory CAFE fire.

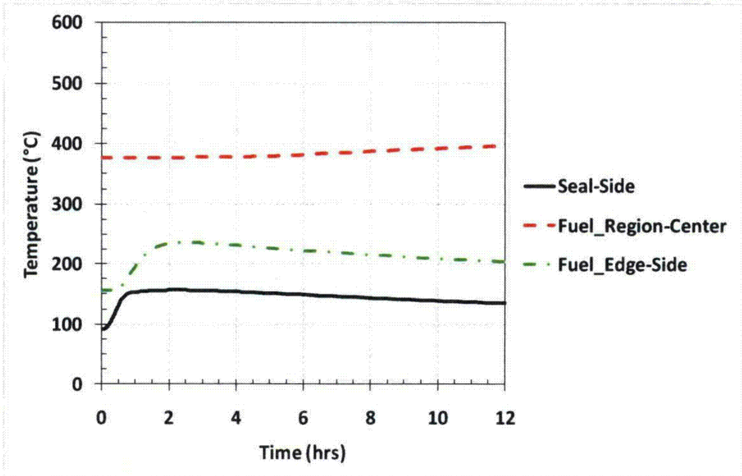


Figure 4-10. Temperature of key cask regions, Rail-Steel cask undergoing REGULATORY CAFE fire.

The uniform external heating produces an even temperature response around the circumference of the cask. However, the realistic uneven fire heating of the exterior produces temperatures that vary around the circumference. For comparison, the results obtained from the uniform regulatory fire simulation are plotted against the hottest regional temperatures obtained from the regulatory CAFE (non-uniform) fire simulation. This thermal response comparison is presented in Figure 4-11.

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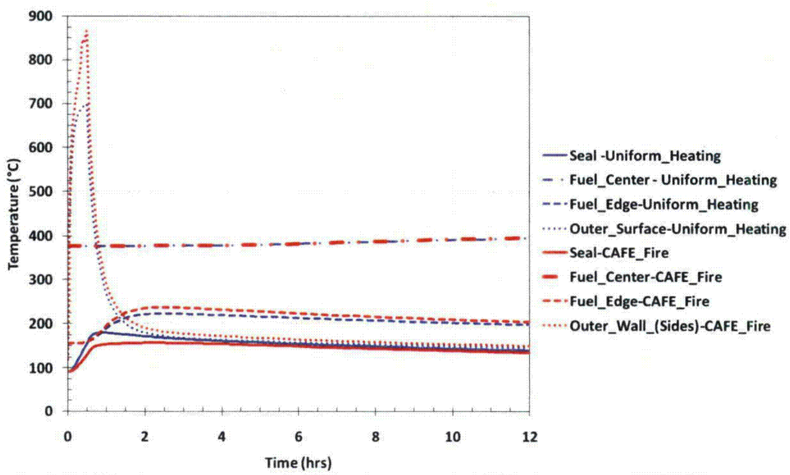
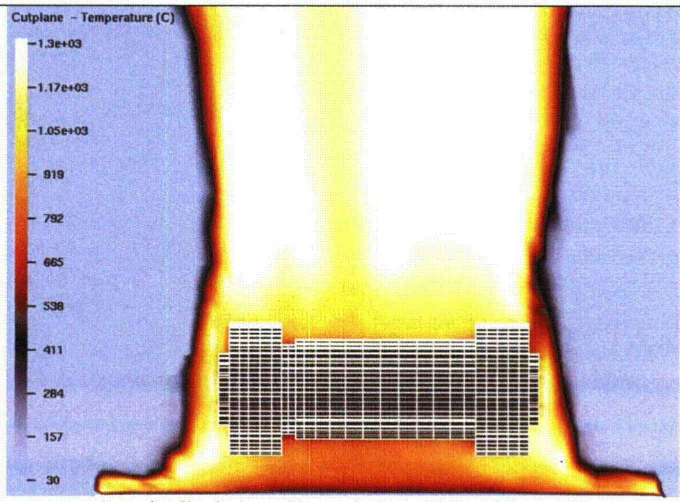


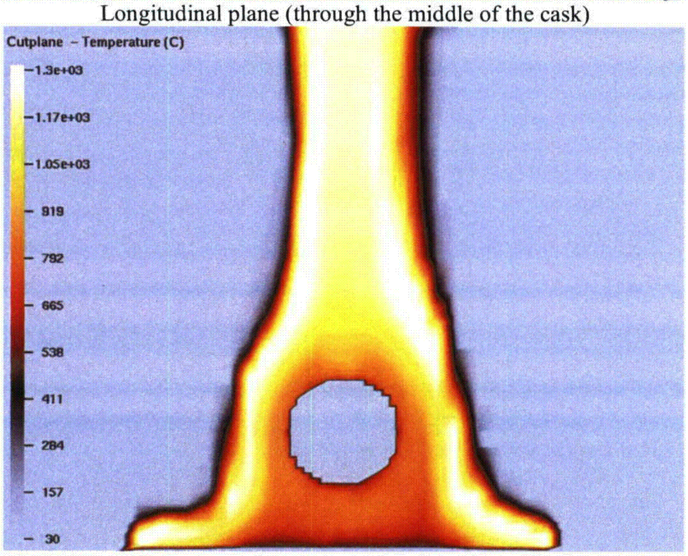
Figure 4-11. Comparison of regulatory fire analysis for Rail-Steel cask: Uniform heating vs. CAFE fire.

Figure 4-11 illustrates that the uniform heating thermal environment described in 10 CFR 71.73 heats up the seal region of the Rail-Steel cask more than a real fire may, even though a real fire can impart to the cask a temporary and localized thermal environment that is hotter than 800°C. A real fire applies a time- and space-varying thermal load to an object engulfed by it. In particular, large fires have an internal region where fuel in the form of gas exists but sufficient oxygen for that fuel to burn is not available. This region is typically called the "vapor dome." The lack of oxygen in the vapor dome is attributed to poor air entrainment in larger diameter pool fires, where much of the oxygen is consumed in the perimeter of the plume region. Since combustion is inefficient inside the vapor dome, this region stays cooler than the rest of the fire envelop. Thus, the presence of regions that are cooler than 800°C within a real fire makes it possible for fires with peak flame temperatures above 800°C to have an overall effect on internal temperatures of a thermally massive object that is similar to those obtained by applying a simpler heating condition such as the one specified in 10 CFR 71.73.

The effects of the vapor dome on the temperature distribution within a fire and the concentration of unburned fuel available in the vapor dome for the CAFE regulatory analysis can be seen in Figure 4-12 and Figure 4-13.



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

Figure 4-12. Gas temperature plots from the regulatory CAFE fire analysis.

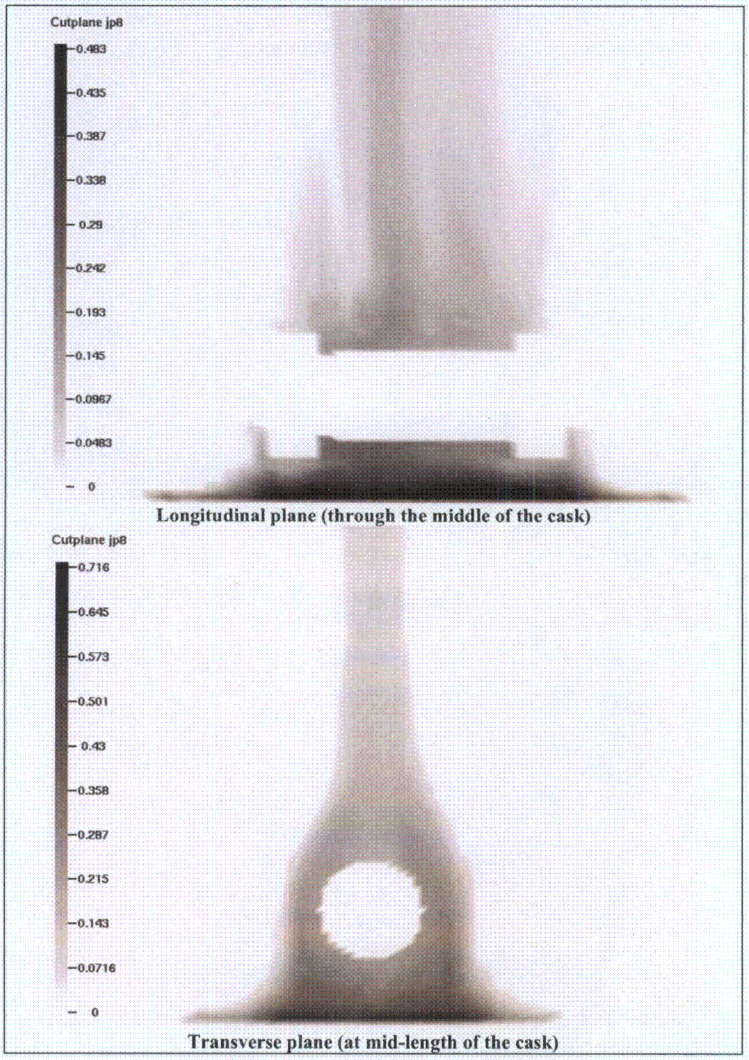


Figure 4-13. Fuel concentration plots from the regulatory CAFE fire analysis.

Note that the plots in Figure 4-12 and Figure 4-13 are snapshots of the distributions at an arbitrary time during the fire simulation. In reality, the fire moves slightly throughout the simulation causing these distributions to vary over time. Nevertheless, these plots show representative distributions for the cask and fire configuration shown.

Additional plots with more information about temperature distributions at different locations in the cask are shown in Appendix IV.

The results from the analysis of the cask lying on the ground and concentric with a pool fire that burns for three hours are presented in Figure 4-14 and Figure 4-15. As in the regulatory configuration, in which the cask is elevated 1 meter above the hydrocarbon fuel pool, the vapor dome had an effect on the temperature distribution of the cask in this case. This is evident by the cooler temperatures observed at the bottom of the cask. In this scenario, even after three hours in the fire, the temperatures at the bottom of the package are cooler than the temperatures observed in the regulatory configuration. However, the top of the cask in this configuration heats up more than the rest of the cask. This differs from what is observed in the regulatory configuration, in which the hotter regions are found on the sides of the cask.

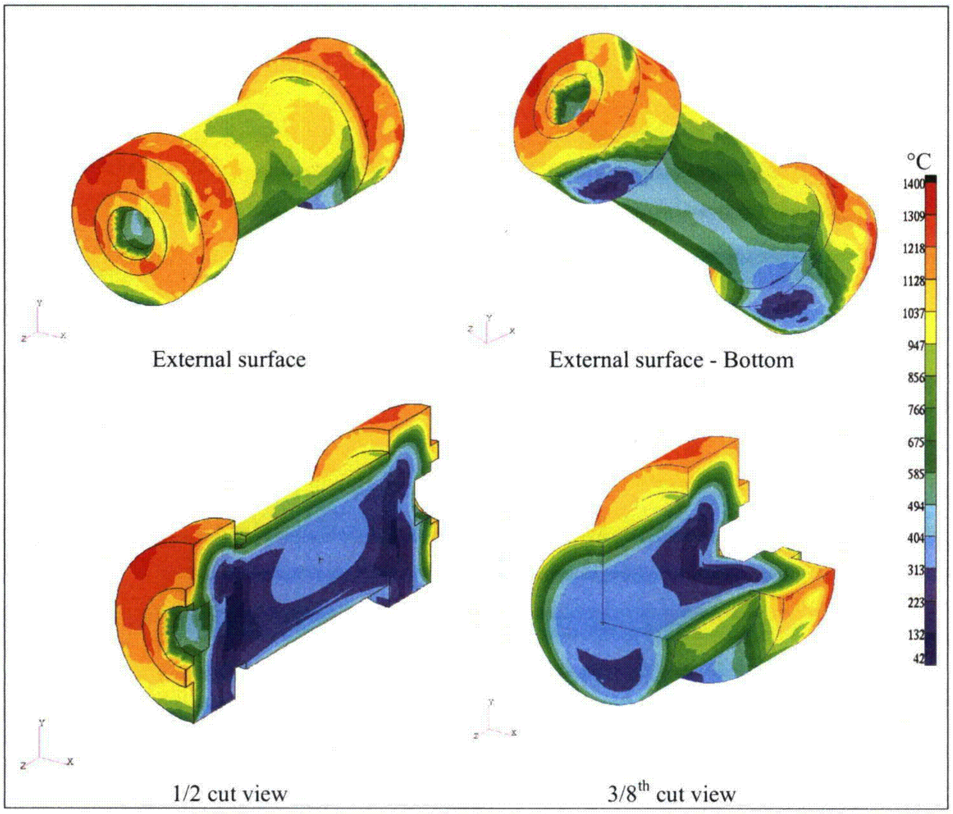


Figure 4-14. Temperature distribution of the Rail-Steel cask at the end of the 3-hour concentric CAFE fire with cask on ground.

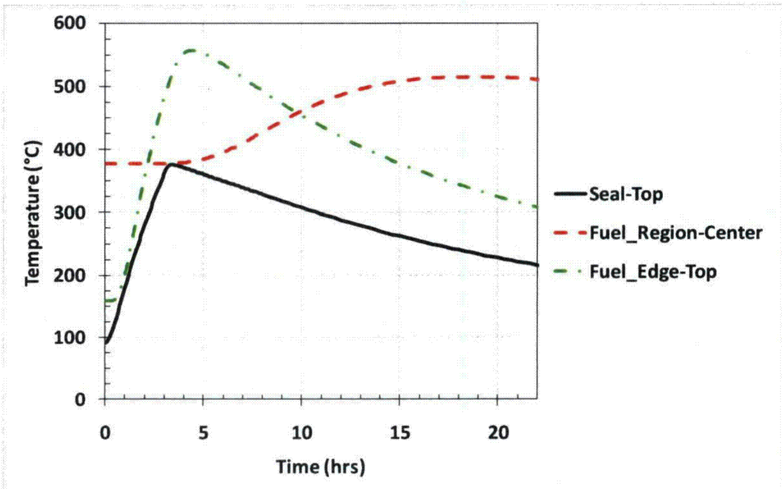
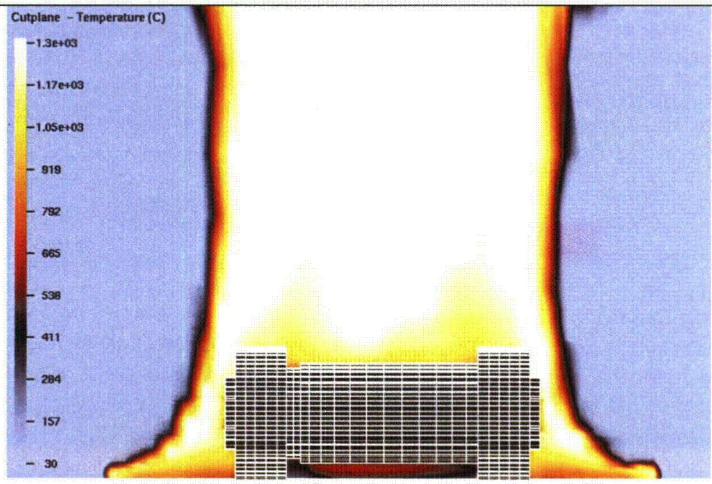
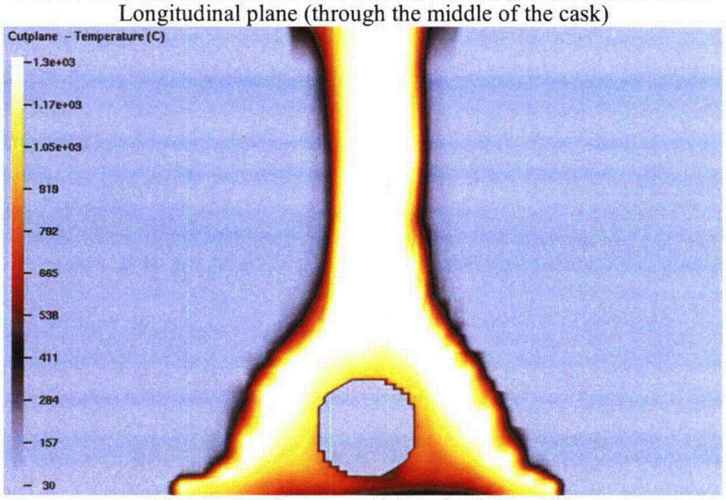


Figure 4-15. Temperature of key cask regions, Rail-Steel cask with cask on ground, concentric fire.

Figure 4-16 and Figure 4-17 are the fire temperature distribution and fuel concentration plots at an arbitrary time during the CAFE fire simulation of this scenario. In this case, the concentration of unburned fuel under the cask is high and therefore the temperature of the fire under the cask is lower than what is observed in the regulatory configuration.



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

Figure 4-16. Gas temperature plots from the CAFE fire analysis of the cask on ground.

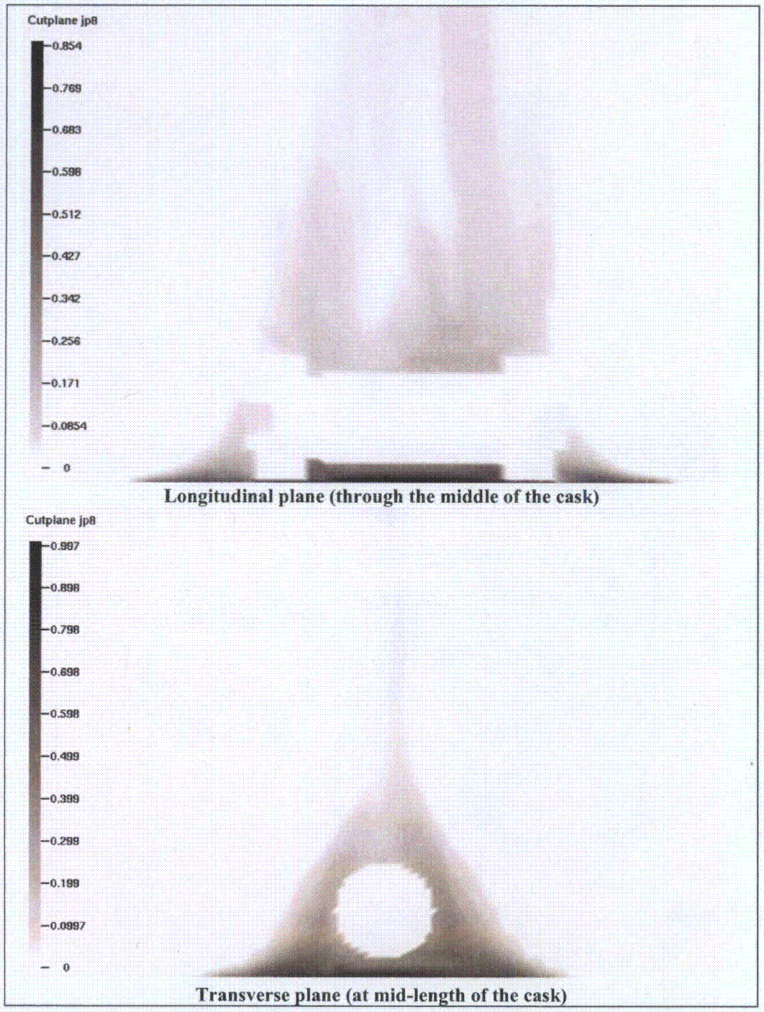


Figure 4-17. Fuel concentration plots from the CAFE fire analysis of the cask on ground.

The results of the offset fire analyses are summarized in Figure 4-18 through Figure 4-21. In the case of the 3-meter offset, the side of the cask facing the fire received heat by thermal radiation. The heat absorbed by the cask during the 3-hour exposure caused the temperature of the cask to rise as depicted in Figure 4-18 and Figure 4-19. Similarly, the 18-meter offset fire caused the cask temperature to rise as illustrated in Figure 4-20 and Figure 4-21. These results show that offset fires, even as close to the cask as three meters, do not represent a threat to this thermally massive SNF transportation cask. The maximum temperatures observed in the seal and fuel SNF region did not reach their temperature limits. Therefore, offset fire scenarios will not cause this package to release radioactive material.

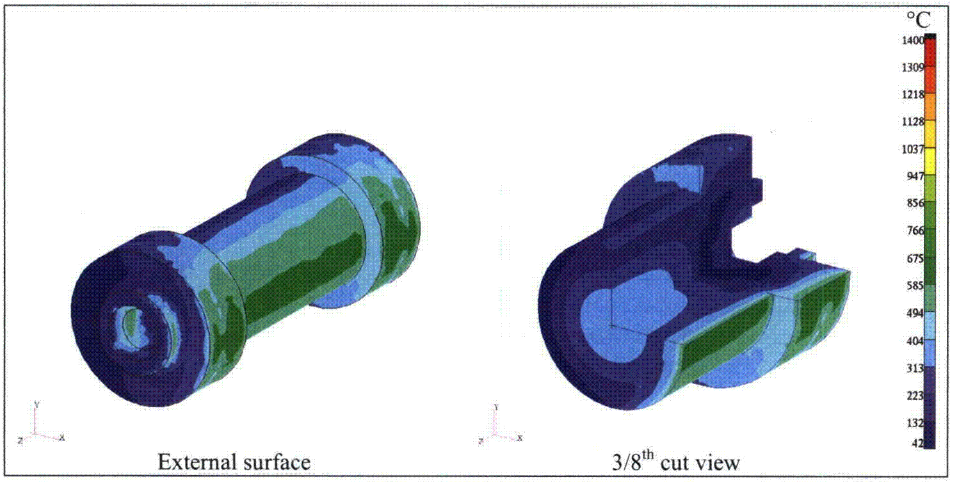


Figure 4-18. Temperature distribution of the Rail-Steel cask at the end of the 3-hour, 3m offset CAFE fire with cask on ground.

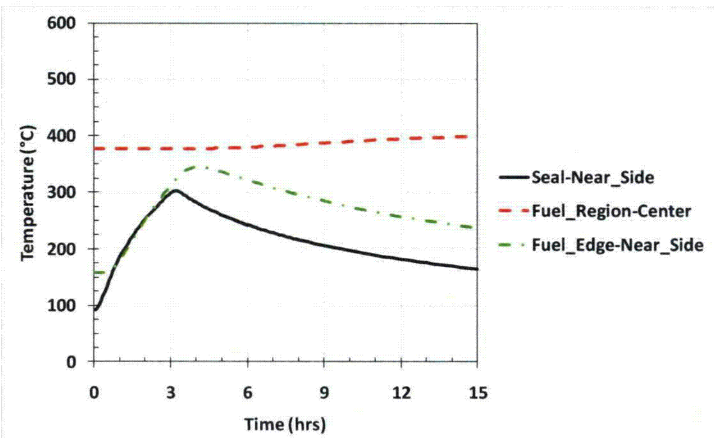


Figure 4-19. Temperature of key cask regions, Rail-Steel cask with Cask on ground, 3m offset fire.

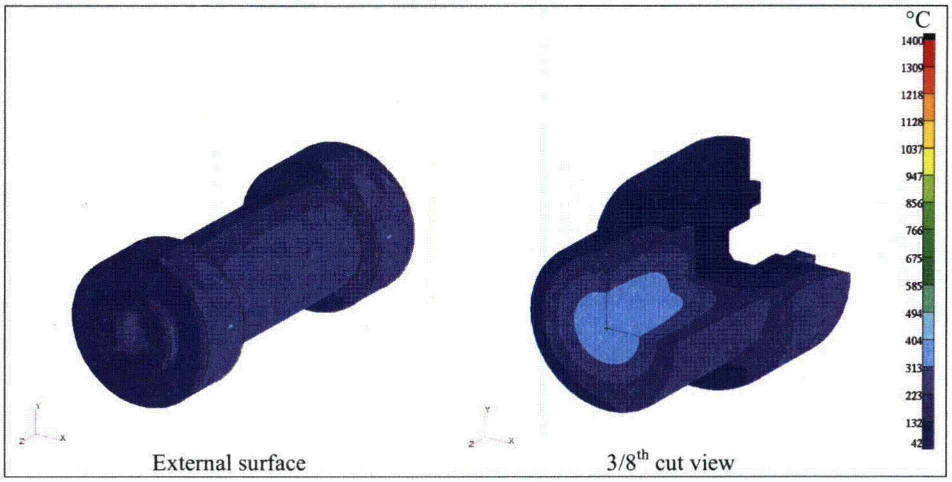


Figure 4-20. Temperature distribution of the Rail-Steel cask at the end of the 3-hour 18m offset CAFE fire with cask on ground.

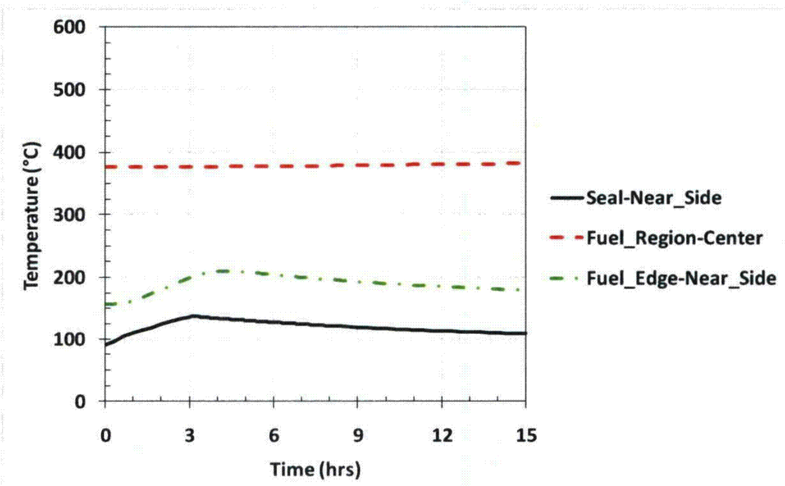


Figure 4-21. Temperature of key cask regions, Rail-Steel cask with cask on ground, 18m offset fire.

Summary of Rail-Steel Cask Analysis Results

The results presented here show that the Rail-Steel cask is capable of protecting the fuel rods from burst rupture and is also capable of maintaining containment when exposed to the severe fire environments that are analyzed as part of this study. That is, while the neutron shield material is conservatively assumed to be absent during the fire accident, the SNF region stays below 750°C (1382°F) and the seal region stayed under 649°C (1200°F) for all the scenarios that are considered. Furthermore, this cask uses a welded canister that will not be compromised under these thermal loads. This cask will not experience loss of gamma shielding because in this cask shielding is provided by the thick multi-layered carbon steel wall, which is not affected in a way that could reduce its ability to provide shielding.

4.3.5 Rail-Lead Cask Results

The thermal response of the Rail-Lead cask to the same fire environments discussed above for the Rail-Steel cask is presented in this section. The 30-minute regulatory fire results are summarized in Figure 4-22 through Figure 4-26.

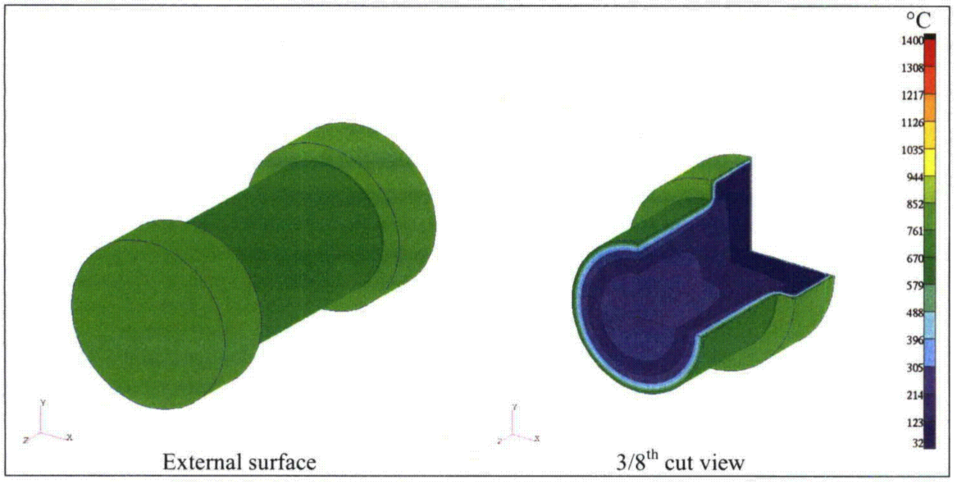


Figure 4-22. Temperature distribution of the Rail-Lead cask at the end of the 30-minute 800°C regulatory uniform heating.

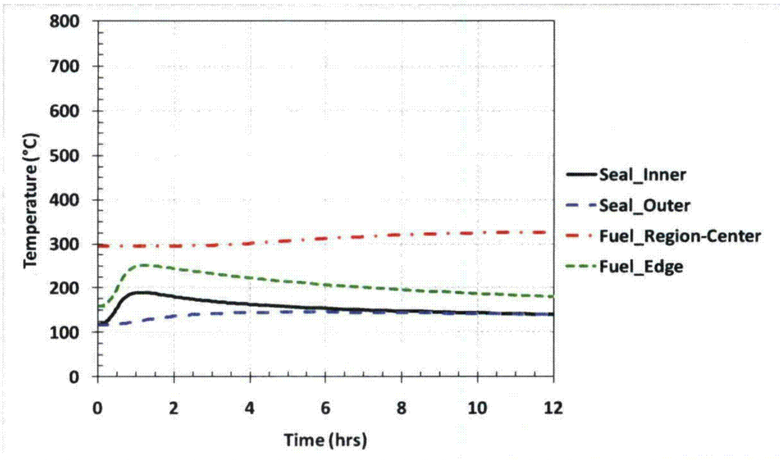


Figure 4-23. Temperature of key cask regions, Rail-Lead cask undergoing regulatory uniform heating.

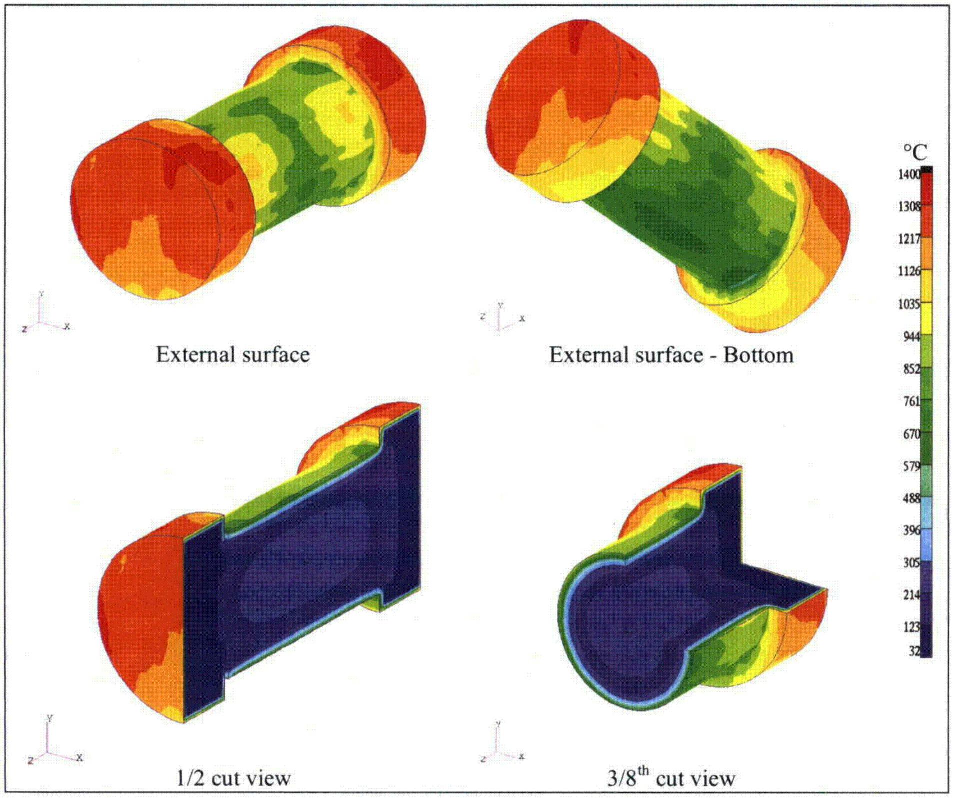


Figure 4-24. Temperature distribution of the Rail-Lead cask at the end of the 30-minute regulatory CAFE fire.

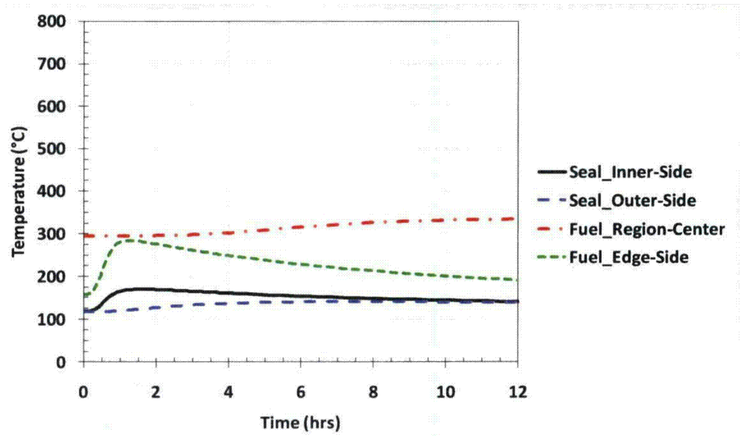


Figure 4-25. Temperature of key cask regions, Rail-Lead cask in regulatory CAFE fire.

The results obtained from the uniform regulatory fire simulation are plotted against the hottest regional temperatures obtained from the CAFE (non-uniform) regulatory fire simulation. This plot is shown in Figure 4-26. As with the Rail-Steel cask, this figure illustrates that the uniform heating thermal environment described in 10 CFR 71.73 heats the seal region of the Rail-Lead cask more than a non-uniform real fire may, even though a real fire may impart to the cask a localized thermal environment that is hotter than 800°C (1472°F).

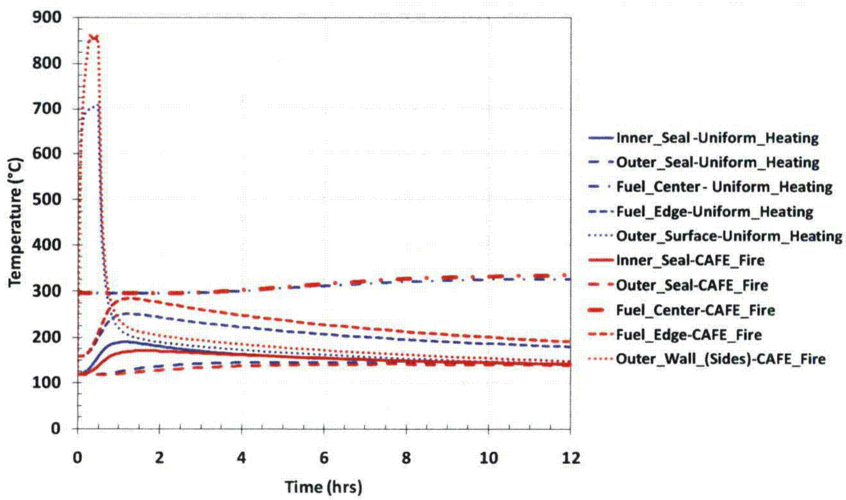


Figure 4-26. Comparison of regulatory fire analysis, Rail-Lead cask: Uniform heating vs. CAFE fire.

The results of the analyses of the cask lying on the ground heated by the concentric and offset fires are summarized in Figure 4-27 through Figure 4-32. These plots show similar trends to those observed in the Rail-Steel cask for the same configurations.

Two of the scenarios that are analyzed show melting of the lead gamma shield in the Rail-Lead cask. Lead melts at 328°C (622°F) and during that process, it absorbs (stores) heat while maintaining its temperature relatively constant at 328°C. As a result, the heat-up rate of portions of the cask slows down while the lead melts. That is why the curve of the region inward from the gamma shield region (i.e., the edge of the SNF region) in Figure 4-28 and Figure 4-30 show a change in slope at about 328°C. This effect is more clearly seen in the slower heating case shown in Figure 4-30. Once the lead melting process is complete, the cask resumes heating up as before if the external source is still at a higher temperature. Note that a similar effect is observed when the lead solidifies at 328°C during the post fire cooling period. In this case, the cooling rate of portions of the cask slows down while the lead solidifies. This can also be clearly seen in Figure 4-30.

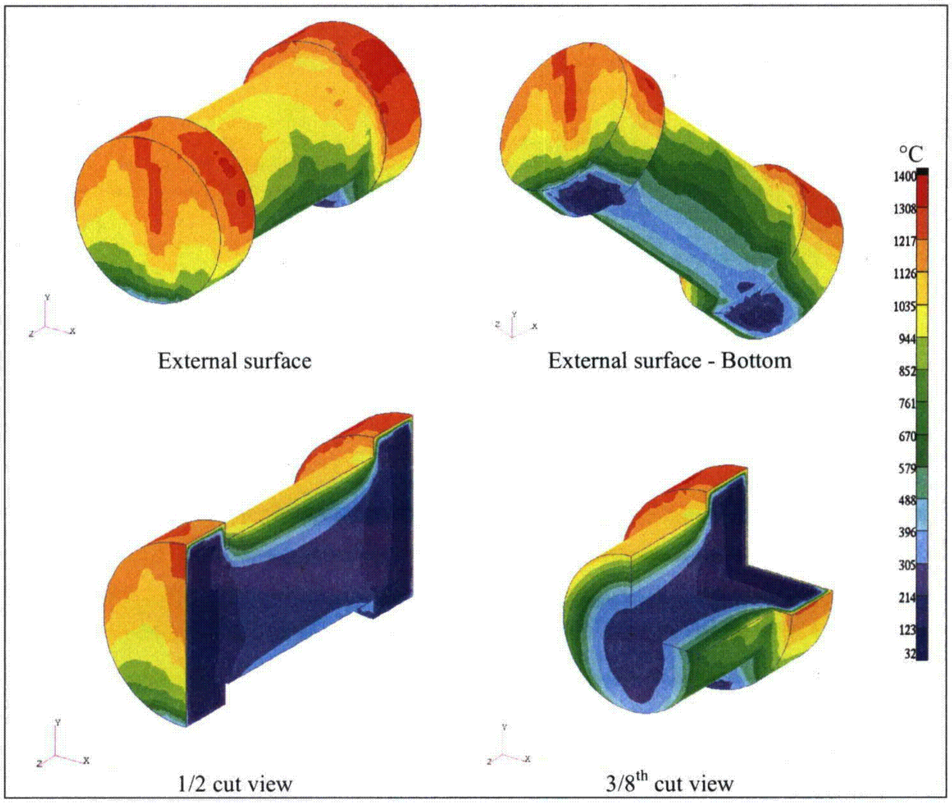


Figure 4-27. Temperature distribution of the Rail-Lead cask at the end of the 3-hour concentric CAFE fire with cask on ground.

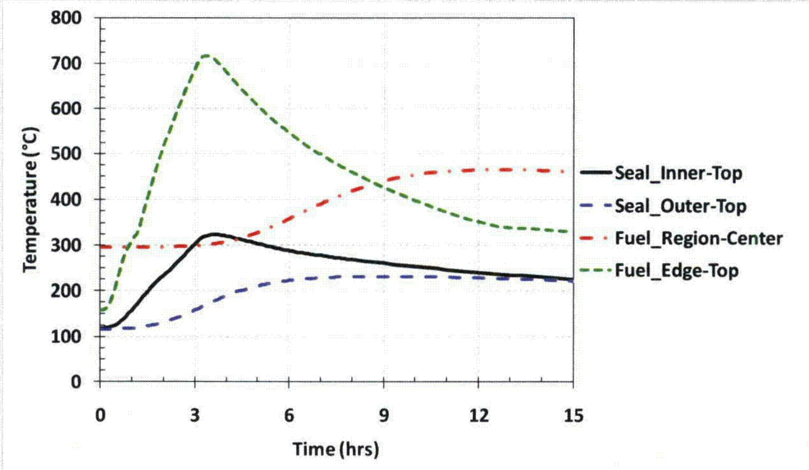


Figure 4-28. Temperature of key cask regions, Rail-Lead cask with cask on ground, concentric fire.

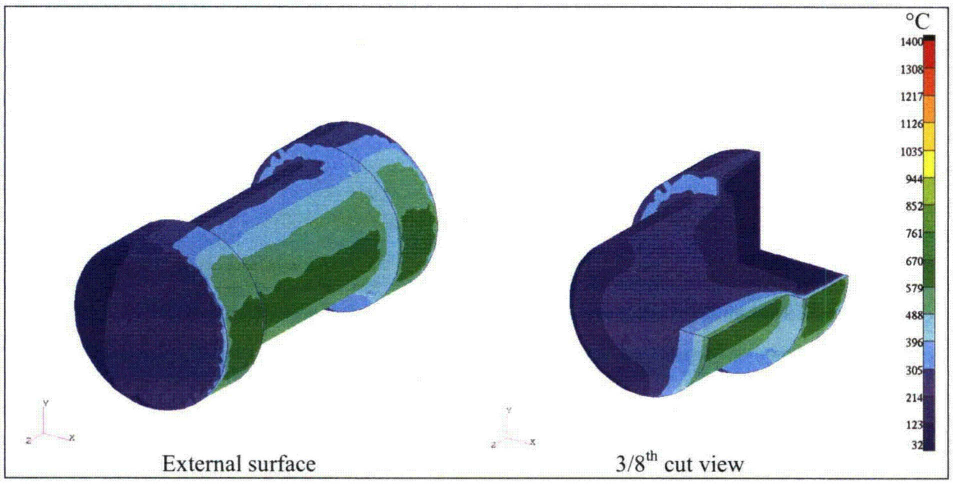


Figure 4-29. Temperature distribution of the Rail-Lead cask at the end of the 3-hour 3m offset CAFE fire with cask on ground.

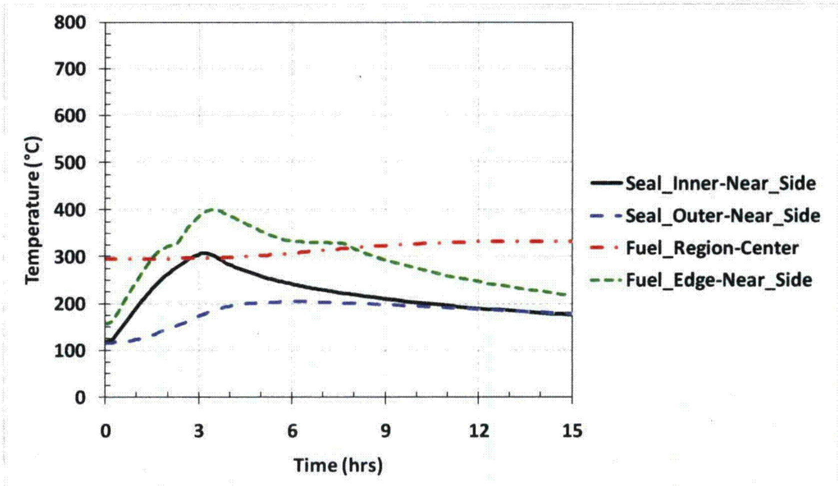


Figure 4-30. Temperature of key cask regions, Rail-Lead cask with Cask on ground, 3m offset fire.

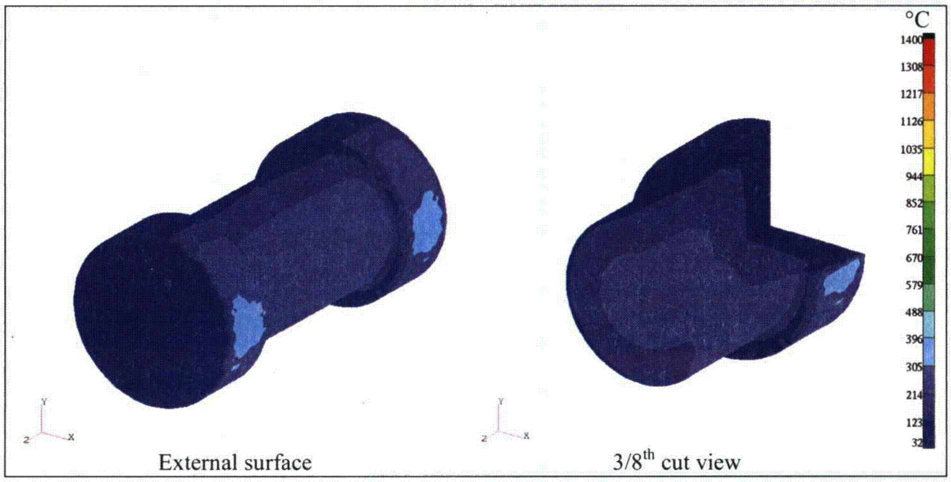


Figure 4-31. Temperature distribution of the Rail-Lead cask at the end of the 3-hour 18m offset CAFE fire with cask on ground.

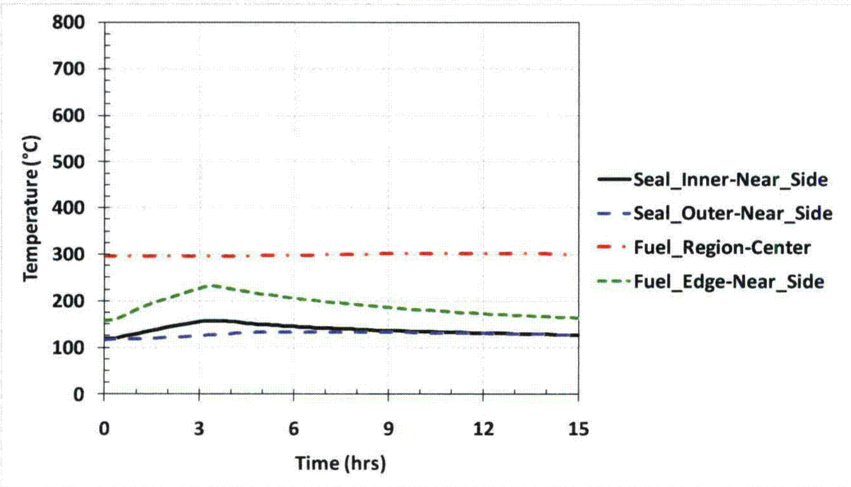


Figure 4-32. Temperature of key cask regions, Rail-Lead cask with Cask on ground, 18m offset fire.

Appendix IV contains additional plots with more information about temperature distributions at more locations in the cask. Another effect considered in the cases where lead melted is the gradual thermal expansion and contraction of the gamma shield region during the heating and cooling of the cask. This effect is discussed in the next subsection.

Melting of the Lead Gamma Shield

There are two cases in which a portion of the lead gamma shield melts. These are the three-hour concentric fire and the three-hour three-meter offset fire. The region of the lead gamma shield that melted for each case is shown in red in Figure 4-33 and Figure 4-34. Note that these two figures only show the portion of the cask wall that has lead. As shown in these figures, approximately 88% of the lead melts in the case of the three-hour concentric fire, whereas only about 30% of the lead melts in the case of the three-hour three-meter offset fire. Due to melting and thermal expansion of some of the lead gamma shield, some loss of shielding is observed, which translates to an increase in gamma radiation exposure. The width of the streaming path (gap created due to lead melt, expansion, and subsequent contraction as it solidifies) is estimated. For this estimate, the assumption is made that the thermal expansion of the lead permanently deforms (buckles) the interior wall of the cask, enabling the calculation of the gap in the lead gamma shield.

The gap in the lead region caused by the concentric fire case is assumed to appear on the top portion of the cask. That is, after the lead melts and buckles the interior wall of the cask due to its thermal expansion, molten lead is assumed to flow to the lower portions of the gamma shield region of the cask, which allows a gap to be formed on the top portion of the cask. From a geometric analysis that considered the expansion and contraction of the lead and a conservative cask wall deformation, this gap is estimated to be about 0.5 m (20 inches), which translates to an

8.1% loss of shielding. In the case of the three-meter offset fire, the gap is assumed to form on the top portion of the molten lead region shown in Figure 4-34. For this case, the gap is estimated to be about 0.127 m (5 inches), which translates to a 2% loss of shielding. These gaps are estimated using geometric information and temperature-dependent density values of lead [*i.e.*, 11.35 g/cm^3 (0.41 lb/in^3) for solid lead and 10.6 and 10.3 g/cm^3 (0.38 lb/in^3 and 0.37 lb/in^3) for molten lead at temperatures of 384°C and 577°C (723°F and 1071°F), respectively]. The loss-of-shielding fractions reported in this section are used as part of the work presented in Chapter 5 to estimate the consequences.

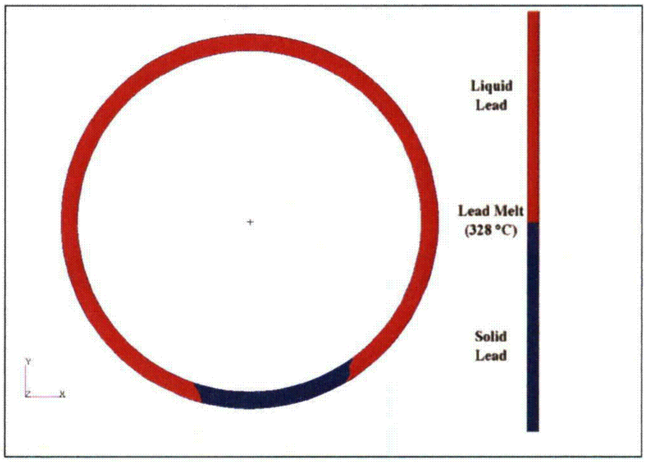


Figure 4-33. Rail-Lead cask lead gamma shield region – maximum lead melt at the middle of the cask. – Scenario: Cask on ground, 3-hour concentric pool fire.

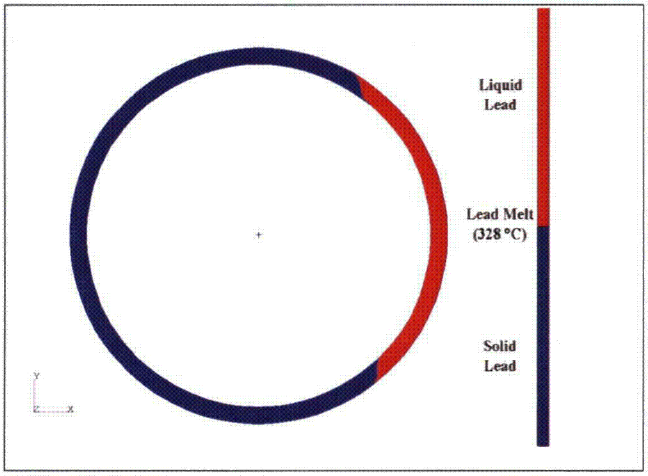


Figure 4-34. Rail-Lead cask lead gamma shield region – maximum lead melt at the middle of the cask. – Scenario: Cask lying on ground, 3-hour 3m offset pool fire.

Summary of Rail-Lead Cask Analysis Results

The results presented here show that the Rail-Lead cask is also capable of protecting the fuel rods from burst rupture and capable of maintaining containment when exposed to the severe fire environments that are analyzed as part of this study, even when the neutron shield material is conservatively assumed to be absent during the fire accident. However, some reduction of gamma shielding is estimated to occur in two cases. Partial loss of shielding is expected for the case in which the cask is exposed to an engulfing fire that burns for longer than 65 minutes and for the case in which the cask receives heat from a fire that is offset by three meters and burns for longer than two hours and 15 minutes. Nevertheless, no release of radioactive material is expected if this cask were to be exposed to any of these severe thermal environments, as the elastomeric seals did not reach their temperature limit. This ensures that the cask is capable of maintaining containment (*i.e.*, preventing any radioactive material from getting out of the package) under any of the fire environments that are analyzed.

4.4 Truck Cask Analysis

A three-dimensional analysis of the Truck-DU cask engulfed in a large fire is performed for this study. The cask is assumed to lie on the ground concentric with the hydrocarbon fuel pool fire. As explained in Section 4.2.2, the fire is assumed to last one hour. Results from the fire and heat transfer analyses that are performed on the Truck-DU cask is presented in this section.

4.4.1. Simulation of the Truck Cask

The heat transfer to and within the Truck-DU cask is modeled using P-Thermal/CAFE. The cask has a polymeric neutron shield that is assumed to melt completely and be replaced by air at its operational temperature limit (see Appendix IV). In this cask, gamma shielding is provided by a layer of DU found within the cask wall. Melting of the DU is not a concern for this cask under any of the conditions to which it is exposed. The aluminum honeycomb Impact limiters are modeled as undamaged (not deformed). Decay heat was included in the analysis. The finite element model of the cask is shown in Figure 4-35. Cask modeling details are presented in Appendix IV.

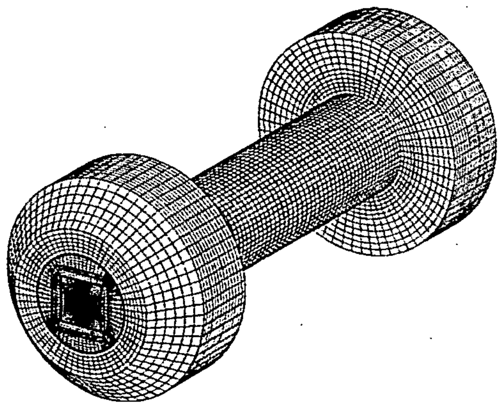


Figure 4-35. Finite element model of the Truck-DU cask.

4.4.2. Simulation of the Spent Nuclear Fuel Region

As with the rail casks, the fuel region comprising the fuel basket and the SNF assemblies is not modeled explicitly for the Truck-DU cask. Instead, a homogenized fuel region is used. All materials and geometric features of the fuel basket of the casks that are analyzed are represented as a single solid inside the cask. The effective properties of the homogenized SNF region are presented in Appendix IV.

4.4.3. Truck-DU Cask Results

The results from the analysis of the cask lying on the ground and concentric with a pool fire that burns for one hour are presented in Figure 4-36 and Figure 4-37.

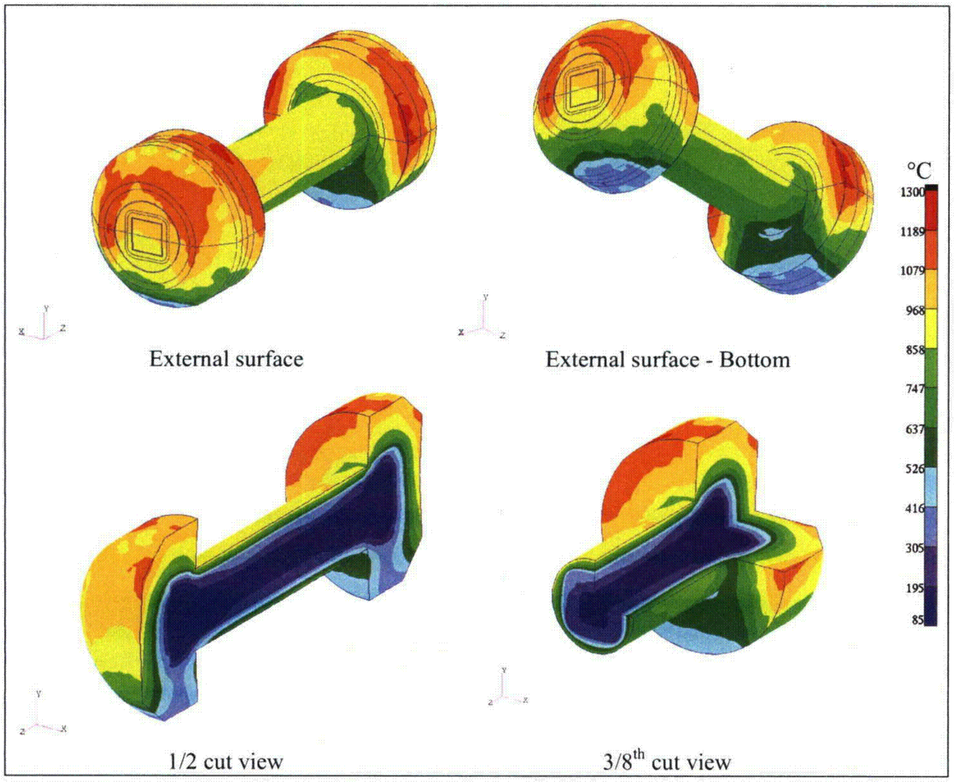


Figure 4-36. Temperature distribution of the Truck-DU cask at the end of the 1-hour concentric CAFE fire with cask on ground.

As observed with the rail casks, the vapor dome had an effect on the temperature distribution of the truck cask. This is evident by the cooler temperatures observed at the bottom of the cask. Even after one hour in the fire, the temperatures at the bottom of the cask are lowest and the temperatures at the top are highest.

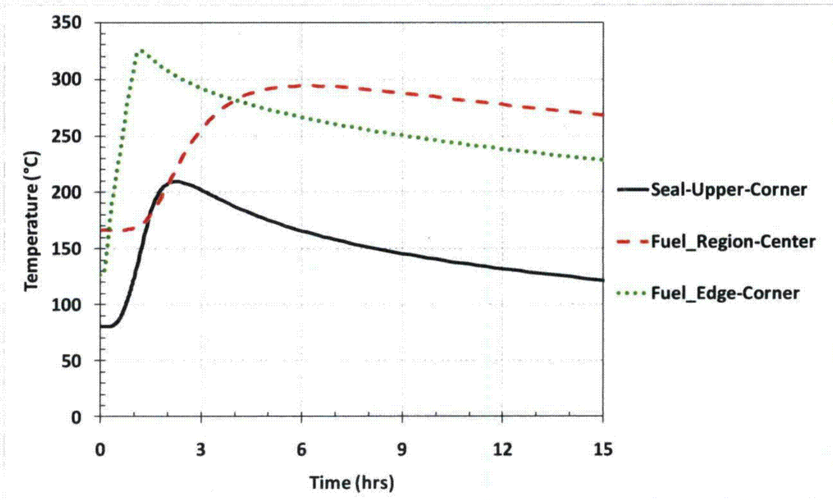


Figure 4-37. Temperature of key cask regions, Truck-DU cask with cask on ground, concentric fire.

Figure 4-38 and Figure 4-39 are the fire temperature distribution and fuel concentration plots at an arbitrary time during the CAFE fire simulation. Note that the concentration of unburned fuel under the cask is high. This means that poor combustion is occurring in that zone, leading to cooler temperatures of the lower region of the cask.

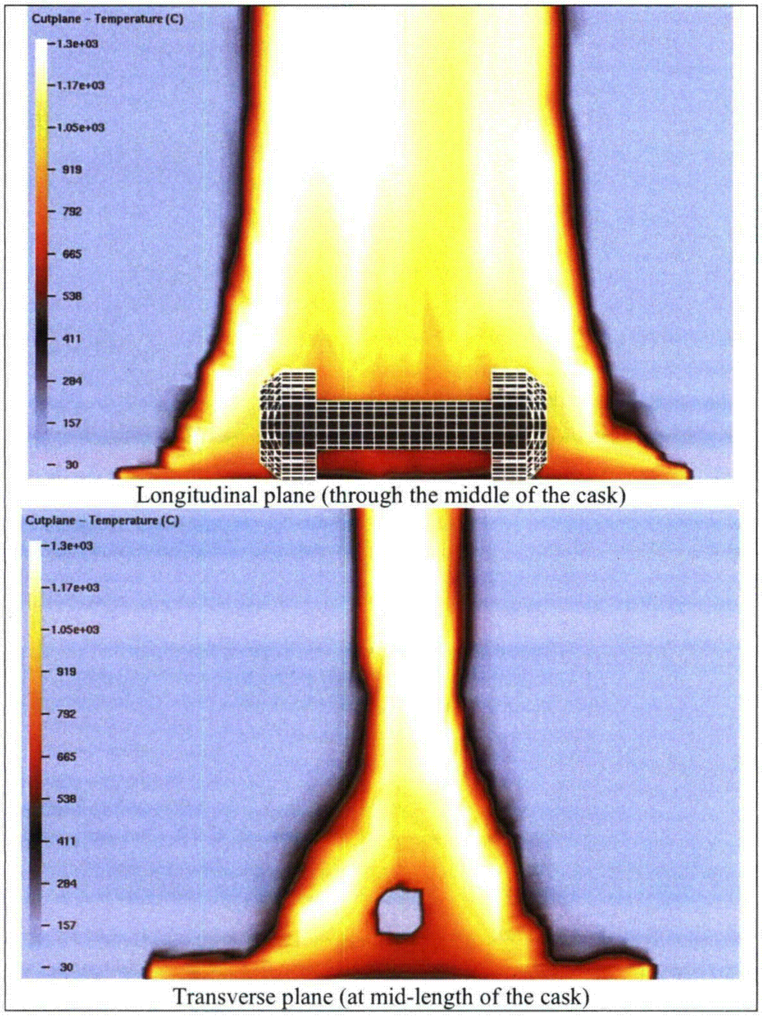


Figure 4-38. Gas temperature plots. CAFE fire analysis of the truck cask on ground.

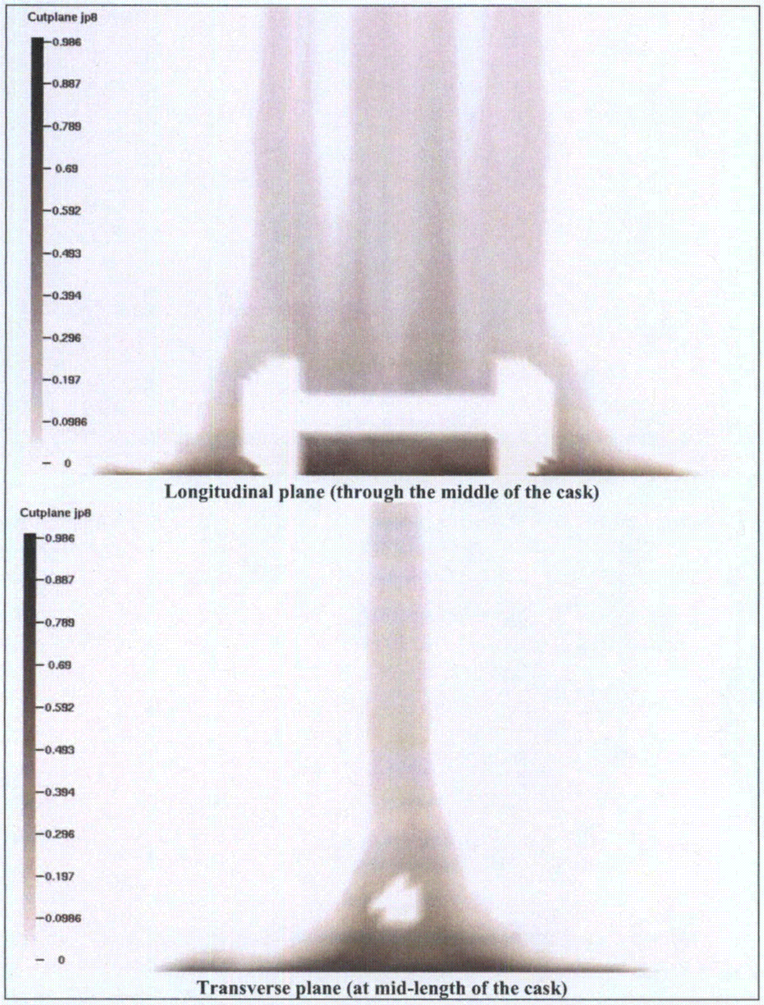


Figure 4-39. Fuel concentration plots. CAFE fire analysis of the Truck-DU cask lying on ground.

Summary of Truck-DU Cask Analysis Results

The results presented here show that the Truck-DU cask is capable of protecting the SNF rods from burst rupture and is also capable of maintaining containment when exposed to the severe fire environment analyzed in this study. That is, while the neutron shield material is conservatively assumed to be absent during the fire accident, the SNF region stays below 750°C (1382°F) and the seal region stayed under 350°C (662°F). This cask will not experience loss of gamma shielding because in this cask shielding is provided by a thick steel-DU wall, which is not affected in a way that could reduce its ability to provide shielding.

4.5 Conclusions

This chapter presents the realistic analyses of four fire accident scenarios. These are:

- the HAC fire described in 10 CFR 71.73,
- a cask on the ground concentric with a fuel pool sufficiently large to engulf the cask,
- a cask on the ground with a pool fire offset by the width of a rail car (3 meters), and
- a cask on the ground with a pool fire offset by the length of a rail car (18 meters).

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Analyses of these four fire accident scenarios are performed for the Rail-Steel and the Rail-Lead casks. An analysis of a Truck-DU cask on the ground concentric with a hydrocarbon fuel pool sufficiently large to engulf the cask is also performed. Probable worst-case fire accident scenarios for a rail cask transported by railway and for a truck cask transported by roadway were represented within the cases analyzed.

Results show that neither the Rail-Steel cask nor the Rail-Lead cask would lose the containment boundary seal in any of the accidents considered in this study. In addition, the SNF rods did not reach burst rupture temperature. However, some loss of gamma shielding is expected with the Rail-Lead cask in the event of a three-hour engulfing fire and a three-hour, three-meter offset fire. Nevertheless, because containment is not lost in any of the cases studied, no release of radioactive material is expected as a result of these hypothetical fire accidents. In the case of the Truck-DU cask, containment would be maintained in the one-hour fire accident considered in this study. These results demonstrate the adequacy of current regulations to ensure the safe transport of spent nuclear fuel. Furthermore, the results demonstrate that SNF casks designed to meet the current regulations will prevent the loss of radioactive material in realistic severe fire accidents.

CHAPTER 5

TRANSPORTATION ACCIDENTS

5.1 Types of Accidents and Incidents

The different types of accidents that can interfere with routine transportation of spent nuclear fuel are:

- Accidents in which the spent fuel cask is not damaged or affected.
  - Minor traffic accidents ("fender-benders," flat tires) resulting in minor damage to the vehicle. These are usually called "incidents."[16]
  - Accidents that damage the vehicle or trailer enough that the vehicle cannot move from the scene of the accident under its own power, but do not result in damage to the spent fuel cask.
  - Accidents involving a death or injury, but no damage to the spent fuel cask.
- Accidents in which the spent fuel cask is affected.
  - Accidents resulting in loss of lead gamma shielding, but there is no release of radioactive material.
  - Accidents in which there is a release of radioactive material.

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Accident risk is expressed as "dose risk," a combination of the radiation dose that results from the accident and the probability of that dose. The units used for accident risk are dose units (Sv).

An accident happens at a particular spot on the route. When the accident happens, the vehicle carrying the spent fuel cask stops. Thus, there can be no more than one accident for a shipment. Accidents can result in damage to spent fuel in the cask even if no radioactive material is released. While this would not result in additional exposure of members of the public, workers engaged in accident recovery operations, including unloading or subsequently opening the cask at a facility, would be affected. Accidents damaging the fuel but not damaging the cask, and potential consequent risk to workers are not included in this study.

Comment [JRC45]: Do you mean that when the cask resumes movement, it is considered a new shipment?

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5.2 Accident Probabilities

Risk is the product of probability and consequence of a particular accident scenario. The probability, or likelihood, that a spent fuel cask will be in a particular type of accident is a combination of two factors:

- The probability that the vehicle carrying the spent fuel cask will be in an accident, and

[16] In Department of Transportation parlance, an "accident" is an event that results in a death, an injury, or enough damage to the vehicle that it cannot move under its own power. All other events that occur in non-routine transportation are "incidents." This document uses the term "accident" for both accidents and incidents.

- The conditional probability that the accident will be a certain type of accident. This is a conditional probability because it depends on the vehicle being in an accident.

The net accident probability is the product of the probability of an accident and the conditional probability of a particular type of accident. A few hypothetical examples are given in Table 5-1 to illustrate the probability calculation.

Table 5-1. Illustrations of net probability

Accident Probability for a 3000-Mile Cross-Country Trip[a]	Accident	Conditional Probability[b]	Net Probability Of Accident
0.0165	Truck collision with a gasoline tank truck	0.82×0.003 = 0.0025	0.82×0.003×0.0165 = 0.000041
0.00138	Rail/truck 50 mph collision at grade crossing	0.7355×0.985× 0.0604×0.0113 = 0.00049	0.7355×0.985×0.0604×0.0113×0.00138 = 0.0000068
0.00087	Railcar falling off bridge at 30 mph	0.7355×0.2665 ×0.9887 = 0.194	0.7355×0.2665×0.9887×0.00087 = 0.00017

[a] Calculated from DOT, 2005, Table 1-32. [b] From event trees in Appendix V.

Accident probability is calculated from the number of accidents per kilometer (accident frequency) for a particular type of vehicle as recorded by the DOT and reported by the Bureau of Transportation Statistics. Large truck accidents and freight rail accidents are the two data sets used in this analysis. The accident frequency varies somewhat from state to state. The U.S. average for large trucks for the period 1991 to 2007 is 0.0035 accidents per thousand kilometers (km). For rail accidents, the average is 0.00024 per thousand railcar-km (DOT, 2008). The DOT has compiled and validated national accident data for truck and rail from 1971 through 2007, but the accident rates declined definitively between 1971 and the 1990s. For this analysis, rates from 1996 through 2007 are used: 0.0019 accidents per thousand large truck-km and 0.00011 accidents per thousand railcar-km.

Comment [JRC46]: Confusing for Table 5-1 to use miles and this text to use km.

Figure 5-1 shows the accidents per truck-km and per railcar-km for this period. The logarithmic scale is used on the vertical axis in order to show the entire range.

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Figure 5-1

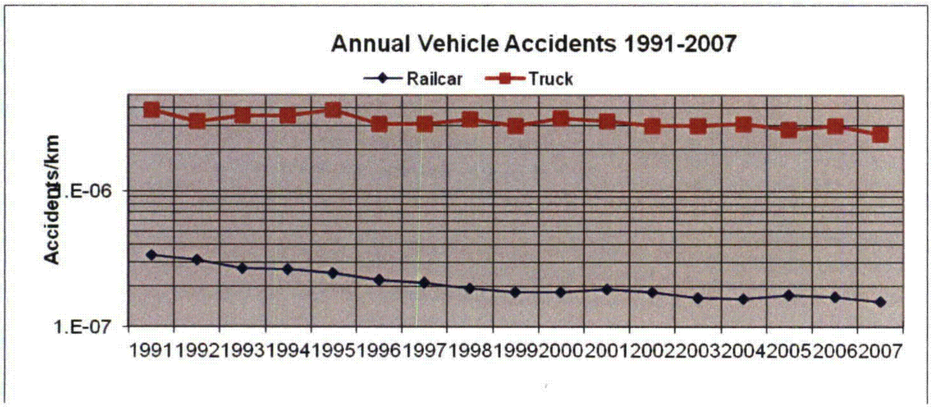

Figure 5-1. Accident frequencies in the U.S. from 1991 until 2007.

As Chapters 3 and 4 show, however, the only accidents that could result in either the loss of radiation shielding or release of radioactive material are rail accidents involving the Rail-Lead cask (when the fuel is directly loaded inside the cask, i.e, the fuel is not contained in a welded canister inside the cask). These are

- Collisions with hard rock or equivalent at impact speeds greater than 97 km/hour (60 mph) that result in some loss of lead gamma radiation shielding or damage to the cask seals. Hard rock is not necessarily an unyielding target; however, collision of a cask with hard rock is the only type of collision along a transportation route that could damage the cask (in the absence of fire) sufficiently to result in release of radioactive material or loss of lead shielding.
- Fires of long enough duration to compromise the seals.

Whether or not these accidents happen depends on the likelihood (conditional probability) of the accident scenario as well as on the accident frequency. The event trees for truck and rail, Figures V-1 and V-2 of Appendix V, show some of the elements of accident scenarios in each branch of the respective event tree. The dependence on probability is illustrated by Figure V-5, which shows the sequence of events needed for a pool fire that can burn long enough to compromise the seals and the lead shielding.

Table 5-2 shows the conditional probabilities of accidents that could result in a radiation dose to a member of the public and of accidents in which there is neither loss of lead shielding nor a release of radioactive material. The analysis that results in these conditional probabilities may be found in Appendix V, Sections V.3 to V.5.

Table 5-2. Scenarios and conditional probabilities of rail accidents involving the Rail-Lead cask

Accident Scenario for the Rail-Lead Cask	Conditional probability of gamma shield loss or radioactive material content release exceeding 10 CFR 71.51 quantities
Loss of lead shielding from impact	5.1×10^{-6}
Loss of lead shielding from fire	10^{-14} to 10^{-10}
Radioactive materials release from impact	3.6×10^{-6}
Radioactive materials release from fire	10^{-14} to 10^{-10}
No loss of lead shielding and no release of radioactive material: Truck-DU and Rail-Steel accidents	0.999991

Comment [JRC47]: Why use the other casks?

Comment [JRC48]: This value does not make sense under this column heading.

Comment [JRC49]: Probably should be a sentence that follows the table.

Loss of lead shielding or radioactive material release from a fire both depend on the same sequence of events that would result in a hot enough fire close enough to the cask to cause the damage. Therefore the conditional probabilities are the same. A more detailed discussion is in Appendix V.

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5.3 Accidents with Neither Loss of Lead Shielding nor Release of Radioactive Material

The conditional probability that an accident involving a lead-shielded cask will be this type of accident, with no release and no lead shielding loss is, as Table 5-2 shows, 99.999 percent. The only type of cask that could lose gamma shielding is a lead shielded cask like the Rail-Lead rail cask. The only type of cask that could release radioactive material in an accident is a cask carrying uncanistered spent fuel. Although the Truck-DU cask carries uncanistered fuel, this cask would not release any radioactive material under any scenario postulated in this report. The Rail-Steel cask carries canistered fuel and would not release any radioactive material. Neither Truck-DU casks nor Rail Steel casks are lead-shielded, so that shielding loss would not occur.

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The doses to emergency responders from an accident in which no material is released and there is no loss of lead gamma shield are shown in Table 5-3, and collective doses to the public from this type of accident are shown in Table 5-4 and Table 5-5. These radiation doses depend on:

- The external dose rate from the cask (Table 2-1).
- A ten-hour stop (DOE, 2002) at the scene of the accident, until the vehicle and/or cask can be moved safely. Ten hours is believed to overstate stop time.
- An average distance of five meters between the cask and the first responders and others who remain with the cask.

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- For collective doses, the average rural, urban, and suburban population densities for each route.

The radiation doses in Table 5-3, Table 5-4, and Table 5-5 are the consequences of all Truck-DU accidents, all Rail-Steel accidents, and 99.999% of the Rail-Lead accidents.

Table 5-3. Dose to an emergency responder[17] from a cask in a no-shielding loss, no-release accident

Cask	Dose in Sv	Ten-hour allowed dose in Sv derived from the one-hour dose in 10 CFR 71.51
Truck-DU	1.0 E-03	0.10
Rail-Lead	9.2E-04	0.10
Rail-Steel	6.9E-04	0.10

Table 5-4 and Table 5-5 show collective doses in Sv for the ten-hour stop that follows the accident. Doses are shown for rural, suburban, and urban segments of each route, but an accident is only going to happen at one place on any route. Each listed dose is thus the collective dose that residents on that route segment could receive if the accident happened at a spot on that type of route segment.

Table 5-4. Collective dose risk to the public from a no-shielding loss, no-release accident involving rail casks (person-Sv)

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FROM	TO	Rail-Lead			Rail-Steel		
		Rural	**Suburban**	**Urban**	**Rural**	**Suburban**	**Urban**
MAINE YANKEE	ORNL	3.1E-06	5.3E-05	6.6E-06	2.3E-06	4.0E-05	5.0E-06
	DEAF SMITH	2.3E-06	5.7E-05	6.8E-06	1.7E-06	4.3E-05	5.2E-06
	HANFORD	3.7E-06	5.3E-05	6.4E-06	2.8E-06	4.0E-05	4.8E-06
	SKULL	2.8E-06	5.1E-05	5.3E-06	2.1E-06	3.9E-05	4.0E-06
KEWAUNEE	ORNL	3.1E-06	5.7E-05	7.2E-06	2.3E-06	4.3E-05	5.4E-06
	DEAF SMITH	1.5E-06	6.1E-05	7.2E-06	1.2E-06	4.6E-05	5.4E-06
	HANFORD	1.5E-06	5.3E-05	6.6E-06	1.2E-06	4.0E-05	5.0E-06
	SKULL	2.0E-06	6.2E-05	6.0E-06	1.5E-06	4.7E-05	4.5E-06
INDIAN POINT	ORNL	2.6E-06	7.2E-05	8.7E-06	2.0E-06	5.4E-05	6.6E-06
	DEAF SMITH	1.9E-06	5.9E-05	7.5E-06	1.4E-06	4.5E-05	5.7E-06
	HANFORD	1.9E-06	5.6E-05	7.2E-06	1.4E-06	4.3E-05	5.5E-06
	SKULL	2.2E-06	6.0E-05	6.6E-06	1.7E-06	4.6E-05	5.0E-06
IDAHO NATIONAL LAB	ORNL	1.9E-06	6.0E-05	5.8E-06	1.4E-06	4.6E-05	4.4E-06
	DEAF SMITH	8.0E-07	6.0E-05	5.3E-06	6.0E-07	4.6E-05	4.0E-06
	HANFORD	1.0E-06	6.0E-05	6.7E-06	7.5E-07	4.6E-05	5.1E-06
	SKULL	2.0E-06	5.9E-05	7.1E-06	1.5E-06	4.4E-05	5.4E-06
AVERAGE		2.1E-06	5.8E-05	6.7E-06	1.6E-06	4.4E-05	5.1E-06

[17] Includes police, incident command, fire fighters, EMTs, and any other emergency responders.

Table 5-5. Collective dose risk to the public from a no-shielding loss, no-release accident involving a truck cask (person-Sv)

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FROM	TO	Truck-DU Rural	Truck-DU Suburban	Truck-DU Urban
MAINE YANKEE	ORNL	3.8E-06	6.6E-05	8.1E-06
	DEAF SMITH	2.8E-06	7.0E-05	8.4E-06
	HANFORD	4.5E-06	6.5E-05	7.9E-06
	SKULL VALLEY	3.5E-06	6.3E-05	6.6E-06
KEWAUNEE	ORNL	3.8E-06	7.1E-05	8.9E-06
	DEAF SMITH	1.9E-06	7.4E-05	8.9E-06
	HANFORD	1.9E-06	6.5E-05	8.2E-06
	SKULL VALLEY	2.4E-06	7.6E-05	7.4E-06
INDIAN POINT	ORNL	3.2E-06	8.8E-05	1.1E-05
	DEAF SMITH	2.3E-06	7.3E-05	9.2E-06
	HANFORD	2.3E-06	6.9E-05	8.9E-06
	SKULL VALLEY	2.7E-06	7.4E-05	8.2E-06
IDAHO NATIONAL LAB	ORNL	2.4E-06	7.4E-05	7.2E-06
	DEAF SMITH	9.8E-07	7.4E-05	6.6E-06
	HANFORD	1.2E-06	7.4E-05	8.3E-06
	SKULL VALLEY	2.4E-06	7.2E-05	8.8E-06
AVERAGE		2.6E-06	7.2E-05	8.3E-06

The average individual U.S. background dose for ten hours is 4.1 10^{-6} Sv. Average background doses for the 16 routes analyzed are

- Rural: 6.9×10^{-4} person-Sv
- Suburban: 0.019 person-Sv
- Urban: 0.11 person-Sv

If the Truck-DU cask, for example, is in a no-shielding loss, no-release accident, the average collective dose (the sum of the background dose and the dose due to the accident) to residents for the 10 hours following the accident would be

- Rural: 6.93×10^{-4} person-Sv
- Suburban: 0.0191 person-Sv
- Urban: 0. 110008 person-Sv

Comment [JRC50]: Why notation here and fractions below?

The background and accident suburban and urban collective doses would be indistinguishable from the collective background dose. Any dose to an individual is well below the doses allowed by 10 CFR 71.51, as one would expect.

Comment [JRC51]: Why not rural too?

5.4 Accidental Loss of Shielding

The details of the calculation of doses from shielding losses are provided in Appendix V, Section V.3.1 (loss of gamma shielding) and Section V.3.2 (loss of neutron shielding).

5.4.1 Loss of Lead Gamma Shielding

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Type B transportation packages are designed to carry very radioactive material and need shielding adequate to meet the external dose regulation of 10 CFR Part 71. Spent nuclear fuel is extremely radioactive and requires shielding that absorbs both gamma radiation and neutrons. The sum of the external radiation doses from gamma radiation and neutrons should not exceed 0.0001 Sv per hour at two meters from the cask, by regulation.

Each spent-fuel transportation cask analyzed uses a different gamma shield. Each may use different neutron shielding as well, but since no credit is taken for the neutron shield, it is not usually part of the accident analysis. The Rail-Steel cask has a stainless steel wall thick enough to attenuate gamma radiation to acceptable levels. The Truck-DU cask uses metallic DU. Neither of these shields would be damaged, or even affected by, an accident. The Rail-Lead cask has a lead gamma shield which could be damaged in an accident. Lead is relatively soft compared to DU or steel, and melts at a considerably lower temperature (330°C) than either DU or steel.

In a hard impact, the lead shield will slump, and a small section of the spent fuel in the cask be shielded only by the steel shells.

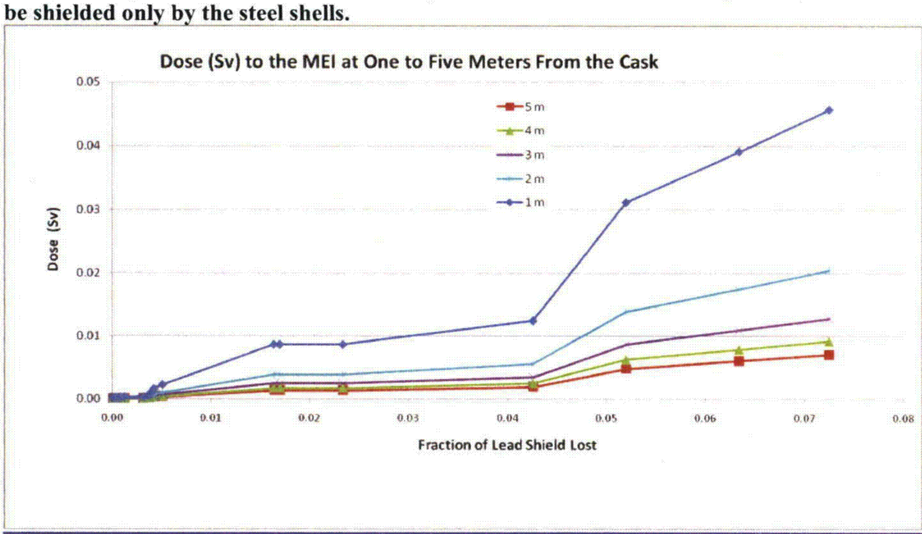


Figure 5-2 and

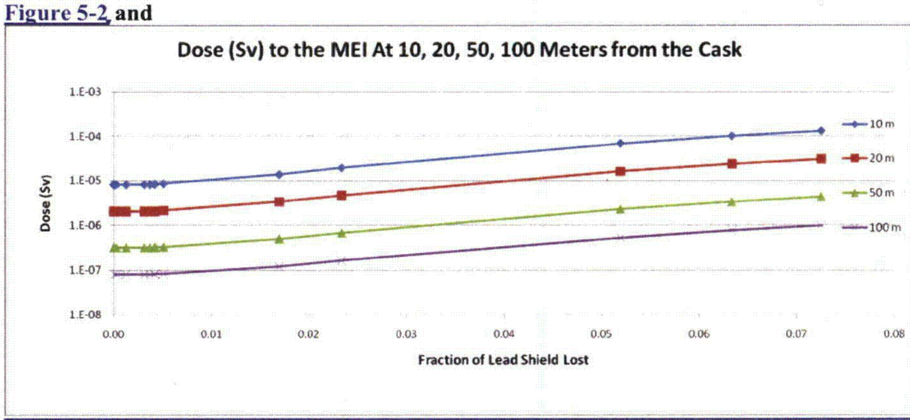
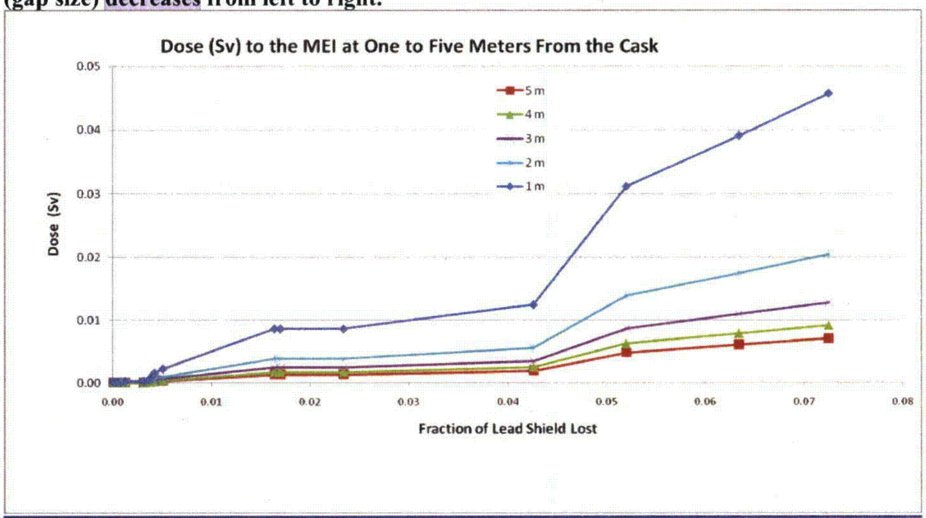


Figure 5-3 show the maximum individual radiation dose at various distances from the damaged cask for a range of gaps in the lead shield. In the figures, the dose estimates for the large gaps are depicted on the left end of the graph, and the fraction of lead shield lost (gap size) decreases from left to right.



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Comment [JRC52]: Increases?

Figure 5-2 and

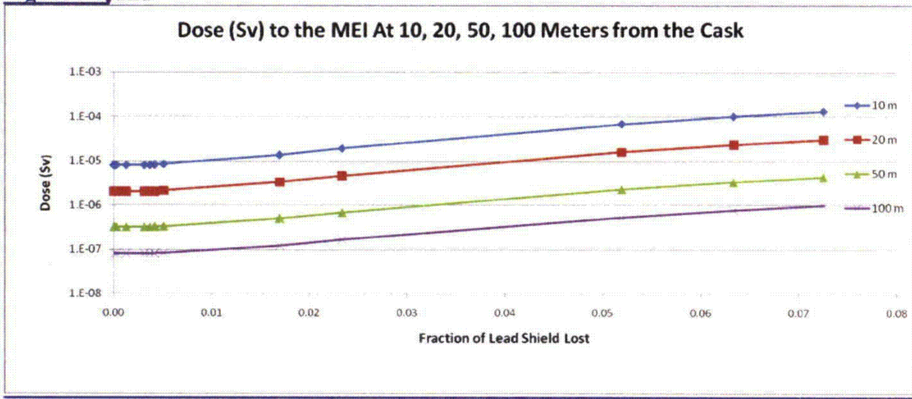

Figure 5-3 show that doses larger than the external dose that would be allowed by the regulation of 10 CFR 71.51 occur when the lead shielding gap is more than two percent of the shield.

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Deleted: Figure 5-3

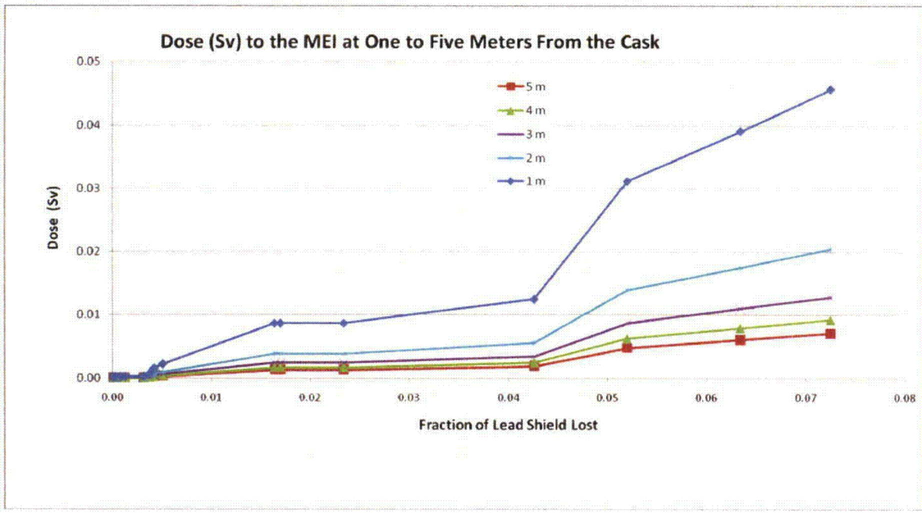

Figure 5-2. Radiation dose to the maximally exposed individual (MEI) from loss of lead gamma shielding at distances from one to five meters from the cask carrying spent fuel. The horizontal axis represents the fraction of shielding lost—the shielding gap—and is not to scale.

Comment [JRC53]: Looks to be a linear scale?

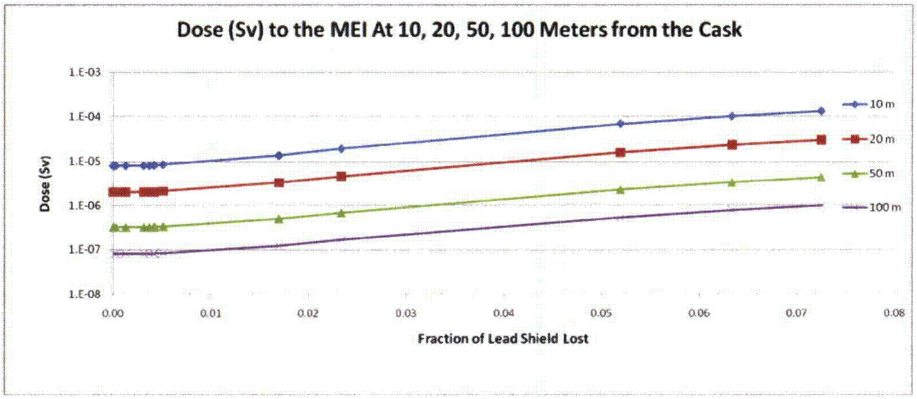

Figure 5-3. Radiation dose to the maximally exposed individual from loss of lead gamma shielding at distances from 20 to 100 meters from the cask carrying spent fuel. The vertical axis is logarithmic so that all of the doses can be shown on the same graph. The horizontal axis represents the fraction of shielding lost—the shielding gap—and is not to scale.

Comment [JRC54]: Title and legend states 10m minimum distance?

Comment [JRC55]: As above, don't follow this caveat

One of every 200,000 accidents could be an impact accident that causes loss of lead shielding; the "one in 200,000" is a conditional probability, conditional on an accident happening. The total probability of such an accident includes both this conditional probability and the probability that there will be an accident. The probability of an accident is shown in the right-hand column of

Table 5-6. For example, the probability that an accident resulting in lead shielding loss will happen on the rail route from Maine Yankee Nuclear Plant site to Hanford is:

$$(5 \times 10^{-6})*(0.00178) = 8.9 \times 10^{-9}$$

or about one in 100 million per Main Yankee to Hanford shipment.

This very small probability indicates that severe accidents, which are more traumatic to the cask than the tests shown in Figure 1-1, are not likely to happen. The conditions that can cause enough loss of lead shielding to result in radiation doses to the public are extreme conditions.

Comment [JRC56]: Right-hand column heading of Table 5-6 reads AVERAGE ACCIDENTS FOR THE TOTAL ROUTE. This is not the probability of an accident?

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Comment [JRC57]: I do not see how this is derived from the data for this route in Table 5-6.

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Table 5-6. Average railcar accident frequencies and accidents per shipment on the routes studied

ORIGIN	DESTINATION	AVERAGE ACCIDENTS PER KM	AVERAGE ACCIDENTS FOR THE TOTAL ROUTE
MAINE YANKEE	ORNL	6.5×10^{-7}	0.00139
	DEAF SMITH	5.8×10^{-7}	0.00194
	HANFORD	4.2×10^{-7}	0.00214
	SKULL VALLEY	5.1×10^{-7}	0.00218
KEWAUNEE	ORNL	4.3×10^{-7}	0.00594
	DEAF SMITH	3.3×10^{-7}	0.00487
	HANFORD	2.4×10^{-7}	0.00468
	SKULL VALLEY	3.7×10^{-7}	0.00103
INDIAN POINT	ORNL	8.8×10^{-6}	0.0112
	DEAF SMITH	6.2×10^{-7}	0.00192
	HANFORD	5.1×10^{-7}	0.00212
	SKULL VALLEY	5.5×10^{-7}	0.00217
INL	ORNL	3.6×10^{-7}	0.0012
	DEAF SMITH	3.5×10^{-7}	0.00067
	HANFORD	3.2×10^{-7}	0.00034
	SKULL VALLEY	2.8×10^{-7}	0.00013

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The overall collective dose risks to the resident population from a lead shielding loss accident on the sixteen routes studied are shown in Table 5-7. These include accidents whose resultant dose rates would be within regulatory limits. The expected dose to any member of the populations along the routes, at least 10 m. from the cask, is within the limits of 10 CFR 71.51. The Indian Point-to-ORNL collective dose risk is comparatively large because the suburban and urban populations along this route are about 20 percent larger than along the other routes, and the rail accident rate per km is an order of magnitude larger.

Table 5-7. Collective dose risks per shipment in person-Sv for a loss of lead shielding accident

SHIPMENT ORIGIN	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	4.4E-10	2.7E-10	2.4E-10	1.4E-10
KEWAUNEE	1.9E-10	9.1E-11	8.6E-11	7.7E-11
INDIAN POINT	7.4E-09	2.8E-10	2.8E-10	1.0E-10
IDAHO NATIONAL LAB	5.6E-11	9.5E-11	2.1E-11	1.3E-10

The conditional probability that a gap in lead shielding will occur after a fire involving the cask is about 10^{-19}. The conditional probability is so small because the following has to happen before a fire is close enough to the cask, and hot enough, and burns long enough, to do any damage to the lead shield.

- The train must be in an accident that results in a major derailment.
- The train carrying the spent fuel cask must also be carrying at least one tank car of flammable material.
- The derailment must result in a pileup. Railcars carrying spent fuel casks are always located between buffer cars and never located next to a railcar carrying hazardous or flammable material.
- The flammable material must leak out so that it can ignite.
- The pileup must be such that the resulting fire is no further from the cask than a railcar length.

The probability of a pileup and the probability that the cask is within a railcar length from the fire are very small. Assessing the conditional probability without these two events, and considering only the more likely events, results in a conditional probability of about 10^{-10}, or about one in ten billion.

The event trees and probabilities for fire accident are discussed in detail in Appendix V.

5.4.2 Neutron Shielding

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The type of fuel that can be transported in the three casks considered has relatively low neutron emission but does require neutron shielding. This is usually a hydrocarbon or carbohydrate polymer of some type that often contains a boron compound. All three of the casks studied have polymer neutron shields. Table 5-8 shows the neutron doses to individuals who are about five meters from a fire-damaged cask for ten hours. Neutrons are absorbed by air much better than is gamma radiation, so that external neutron radiation would impact receptors close to the cask but not members of the general public. The dose allowed by 10 CFR 71.51 is provided for comparison.

Impacts, even those that cause breaches in the seals, will not damage the neutron shield significantly. However, the neutron shielding on any of the three casks is flammable and could be destroyed in a fire.

Table 5-8. Doses to an emergency responder or other individual five meters from the cask

Cask	Dose in Sv	Ten-hour allowed dose in Sv from 10 CFR 71.51
Truck-DU	0.0073	0.1
Rail-Lead	0.0076	0.1
Rail-Steel	0.0076	0.1

The neutron doses do not exceed the dose cited in the regulation following an accident, so the loss of neutron shield is not included in the overall risk assessment. Essentially, these are not extra-regulatory accidents. The conditional probability of this neutron dose is 0.0063 for a truck fire accident and 0.0000001 for a rail fire accident. The rail fire is less probable because of the series of events needed to produce a rail fire. Details are discussed in Appendix V Section V.3.2.

5.5 Accidental Release of Radioactive Materials

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Radioactive materials released into the environment are dispersed in the air, and some deposit on the ground. If a spent fuel cask is in a severe enough accident, spent fuel rods can tear or be otherwise damaged, releasing fission products and very small particles of spent fuel into the cask. If the cask seals are damaged, these radioactive substances can be swept from the interior of the cask through the seals into the environment. Release to the environment requires that the accident be severe enough to damage the fuel rods and release the pressure in the rods, or there will be no positive pressure to sweep material from the cask to the environment.

The potential accidents that could result in such a release are discussed in Chapters 3 and 4. This chapter discusses the probability of such accidents and the consequences of releasing these radionuclides.

5.5.1 Spent Fuel Inventory

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Spent nuclear fuel contains a great many different radionuclides. The amount of each fission product nuclide in the spent fuel depends on the type of reactor fuel and how much ^{235}U was in the fuel (the enrichment) when it was loaded into the reactor. The amount of each fission product in the spent fuel also depends on how much nuclear fission has taken place in the reactor (the burnup). Finally, the amount of each radionuclide in the spent fuel depends on the time that has passed between removal of the fuel from the reactor and transportation in a cask (the cooling time) because the fission products undergo radioactive decay during this time. Plutonium, americium, curium, thorium, and other actinides produced in the reactor decay to a sequence of radioactive elements which are the progeny of the actinide. These progeny increase in concentration as the original actinide decays. However, there is never more radioactive material as a result of decay than there was initially.

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The fuel studied in this analysis is PWR fuel that has "burned" 45,000 MWD/MTU and has been cooled for nine years. The Rail-Lead cask, the only cask studied that could release radioactive material in an accident, is certified to carry more than 20 PWR assemblies. In this study, the Rail-Lead cask was loaded with 26 PWR assemblies.

Comment [JRC58]: Why the 20 vs 26 discussion?

The spent fuel inventory for accident analysis was selected by normalizing the radionuclide concentrations in the spent fuel by radiotoxicity. The resulting inventory is shown in Table 5-9.

Comment [JRC59]: Unclear; add another sentence to explain more fully.

Table 5-9. Radionuclide inventory for accident analysis of the Rail-Lead cask (TBq)

Radionuclide	Terabecquerels (TBq) 26 Assemblies
^{240}Pu	7.82E+03
^{239}Pu	1.84E+02
^{137}Cs	4.38E+04
^{238}Pu	7.18E+01
^{243}Cm	2.50E+01
^{60}Co	5.56E+01
^{154}Eu	9.01E+02
^{134}Cs	4.03E+02
^{85}Kr	2.26E+03
^{241}Am	1.58E-01
^{242}Cm	1.00E+00
^{155}Eu	2.63E+02
^{231}Pa	3.12E-02
^{106}Ru	7.50E+00
^{236}U	1.92E-01
^{63}Ni	8.99E+02
^{233}U	5.75E-01
^{241}Pu	6.13E-01
^{113m}Cd	5.24E+00

The ^{60}Co inventory listed is not part of the nuclear fuel. It is the main constituent of a corrosion product, Chalk River unidentified deposits (CRUD), which accumulates on the outside of the rods, and is formed by corrosion of hardware in the fuel pool. It is listed here with the inventory because it is released to the environment under the same conditions that spent fuel particles are released.

5.5.2 Conditional Probabilities and Release Fractions

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Seven accident scenarios involving the Rail-Lead cask, described in Chapter 3, could result in releases of material to the environment. The details of these scenarios that are important to calculating the resulting doses are shown in Table 5-10. A detailed description of the movement of radionuclide particles from fuel rods to the cask interior and from the cask interior to the environment is found in Appendix V, Sections V.5.4.1 and V.5.4.2.

Table 5-10. Parameters for determining release functions for the accidents that would result in release of radioactive material

	Cask Orientation	End	Corner	Side	Side	Side	Side	Corner
	Rigid Target Impact Speed (kph)	193	193	193	193	145	145	145
	Seal	metal	metal	elastomer	metal	elastomer	metal	metal
Cask to Environment Release Fraction	Gas	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	Particles	0.70	0.70	0.70	0.70	0.70	0.70	0.64
	Volatiles	0.50	0.50	0.50	0.50	0.50	0.50	0.45
	Crud	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Rod to Cask Release Fraction	Gas	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Particles	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	2.40E-06
	Volatiles	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	1.50E-05
	Crud	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Conditional Probability	2.68E-08	1.61E-07	8.02E-08	8.02E-08	1.52E-06	1.52E-06	5.81E-05

5.5.3 Dispersion

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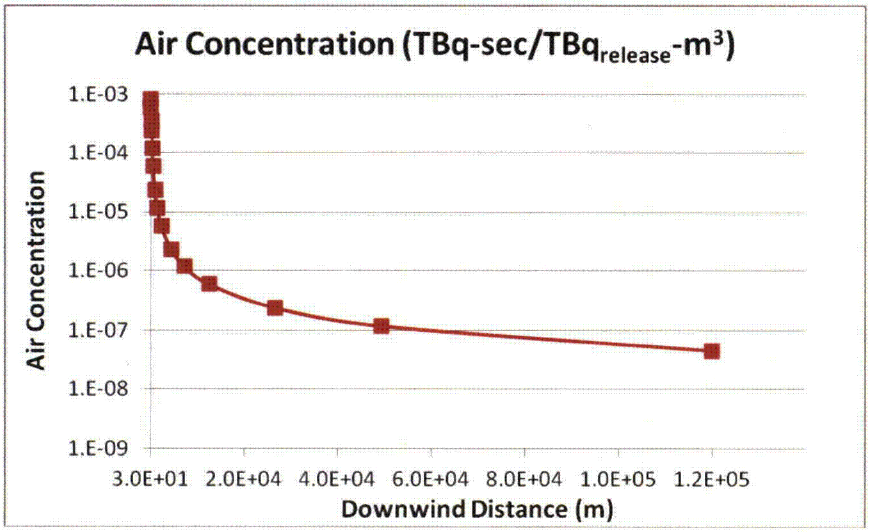
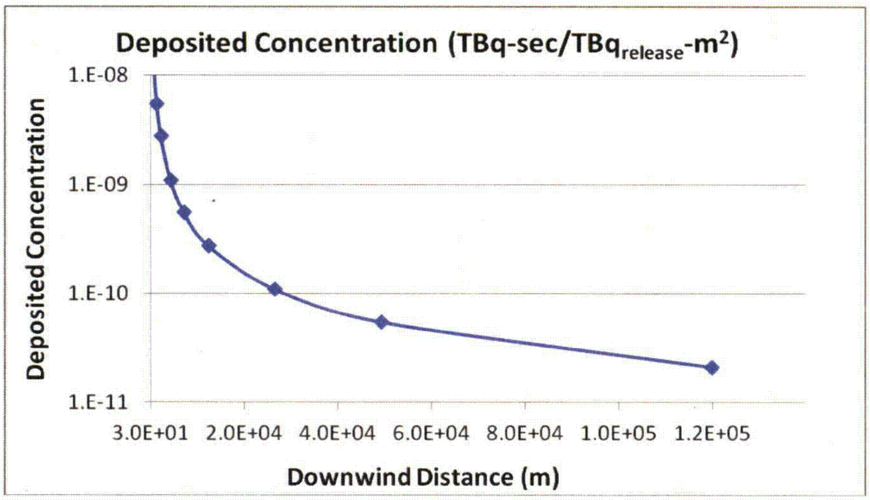
When material is swept from the cask and released into the environment, it is dispersed by wind and weather. The dispersion is modeled using the accident model in RADTRAN 6, which is a Gaussian dispersion model. The release would be at about 1.5 meters above ground level, since the cask is sitting on a railcar. The gas sweeping from the cask is warmer than ambient, so that release is elevated. Under these conditions,The maximum air concentration and ground deposition are 21 m downwind from the release. The dispersion was modeled using neutral weather conditions (Pasquill: stability D, wind speed 4.7 m/sec). It was repeated using very stable meteorology (Pasquill: stability F, wind speed 0.5 m/sec), but the difference was negligible because of the relatively low elevation of the release. The maximally exposed individual would be located directly downwind from the accident, 21 meters from the cask.

Figure 5-4 shows air and ground concentrations of released material as a function of downwind distance. The upwind side of the maximum concentration is short because the plume rise is very fast. Therefore the x-axis (downwind distance) is foreshortened so that the plume rise and gradual decay can be shown in the same graph. The concentrations shown are along the plume centerline and are the maximum concentrations in the plume. The figure shows the exponential decrease of airborne concentrations as the downwind distance increases. The ground (deposited) concentration also decreases in the downwind direction.



a. Airborne concentration of radioactive material released from the cask in an accident



b. Concentration of radioactive material deposited after release from the cask in an accident

Figure 5-4. Air and ground concentrations of radioactive material following a release.

5.5.4 Consequences and Risks from Accidents Involving Release of Radioactive Material

The dose from each of the accidents that would involve a release is shown in Table 5-11.

Table 5-11. Doses (consequences) in Sv to the maximally exposed individual from accidents that involve a release

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Re-suspension	Cloud-shine	Ground-shine	Total
End	193	metal	1.59	0.0137	0.0001	0.0009	1.60
Corner	193	metal	1.59	0.0137	0.0001	0.0009	1.60
Side	193	elastomer	1.59	0.0137	0.0001	0.0009	1.60
Side	193	metal	1.59	0.0137	0.0001	0.0009	1.60
Side	145	elastomer	1.58	0.0137	4.53E-06	3.61E-05	1.59
Side	145	metal	1.59	0.0137	8.78E-05	9.42E-04	1.60
Corner	145	metal	0.7270	0.0063	0.0001	0.0009	0.73

The doses listed in Table 5-11 are consequences, not risks. The dose to the maximally exposed individual is not the sum of the doses. Each cask orientation is a different accident scenario and results in a different set of inhalation and external doses. These are significant doses, but none would result in either acute illness or death (Shleien et al., 1998, p. 15-3). The inhalation and groundshine doses are listed separately because they have different physiological effects. External doses are exactly that, and the receptor would receive a dose only as long as he or she is exposed to the deposited or airborne material. If people near the accident are evacuated, and evacuation can take as much as a day, then they only receive an external dose for a day.

Inhaled radioactive particles lodge in the body and are eliminated slowly through physiological processes that depend on the chemical form of the radionuclide. The inhaled dose is called a "committed" dose, because the exposure is for as long as the radionuclide is in the body, though the activity of the nuclide decreases exponentially as it decays. The NRC considers the total effective dose equivalent: the sum of the inhalation and external doses.

A pool fire co-located with the cask and burning for a long enough time could damage the seals severely. However, as has already been mentioned and is discussed in detail in Appendix V, Section V.3.1.2, the conditional probability of the series of events required to produce such a fire scenario is about 10^{-19}. Even a fire offset from the cask but close enough to damage lead shielding has a conditional probability of between 10^{-14} and 10^{-10}.

The total dose collective risk from the universe of release accidents is shown in Table 5-12. Of the three casks in this study, only the Rail-Lead cask could result in a release in each kind of accident considered.

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Comment [JRC60]: Over what period of time?

Comment [JRC61]: Table provides a "total" column?

Comment [JRC62]: Is table 5-11 based on a one day exposure?

Comment [JRC63]: This committed dose is shown under the table 5-11 Inhalation column?

Comment [JRC64]: This is shown in the table 5-11 "total" column?

Comment [JRC65]: True, but what is the point here?

Table 5-12. Total collective dose risk (person-Sv) for release accidents per shipment for each route

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	3.6E-09	2.2E-09	1.9E-09	9.6E-10
KEWAUNEE	1.5E-09	7.4E-10	7.2E-10	5.1E-10
INDIAN POINT	6.1E-08	2.3E-09	2.4E-09	7.7E-10
IDAHO NATIONAL LAB	3.7E-10	6.0E-10	1.6E-10	1.1E-09

These dose risks are negligible by any standard.

The total dose risks from loss-of-lead shielding accidents are shown in Table 5-13 (which is the same as Table 5-7, repeated here for ease of comparison), and the sum of the two is shown in Table 5-14.

Table 5-13. Total collective dose risk (person-Sv) for each route from a loss of shielding accident

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	4.4E-10	2.7E-10	2.4E-10	1.4E-10
KEWAUNEE	1.9E-10	9.1E-11	8.6E-11	7.7E-11
INDIAN POINT	7.4E-09	2.8E-10	2.8E-10	1.0E-10
IDAHO NATIONAL LAB	5.6E-11	9.5E-11	2.1E-11	1.3E-10

Table 5-14. Total collective dose risk (person-Sv) from release and loss of shielding accidents

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	4.0E-09	2.5E-09	2.1E-09	1.1E-09
KEWAUNEE	1.7E-09	8.3E-10	8.1E-10	5.9E-10
INDIAN POINT	6.8E-08	2.6E-09	2.7E-09	8.7E-10
IDAHO NATIONAL LAB	4.3E-10	7.0E-10	1.8E-10	1.2E-9

Table 5-15 shows the total collective dose risk for an accident involving the Rail-Lead shielded cask in which there is neither loss of lead shielding nor a release. Since the collective dose risk for this type of accident depends in the TI, the collective dose risk from an accident involving the truck cask would be the same. For the Rail-Steel cask carrying canistered fuel, the collective dose risk would be slightly less because the TI is smaller. For this analysis, the cask was assumed to be immobilized for ten hours.

Table 5-15. Total collective dose risk (person-Sv) from no-release, no-loss of shielding accidents

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	2.07E-07	1.29E-07	1.12E-07	6.42E-08
KEWAUNEE	2.22E-07	9.00E-08	3.80E-08	4.62E-08
INDIAN POINT	4.31E-08	2.88E-06	1.24E-07	1.40E-07
IDAHO NATIONAL LAB	4.71E-08	2.52E-08	4.56E-08	1.02E-08

Table 5-16 shows the collective accident risk for the 16 routes from loss of neutron shielding.

Table 5-16. Total collective dose risk (person-Sv) from loss of neutron shielding

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	5.2E-09	3.5E-09	3.6E-09	1.5E-09
KEWAUNEE	3.3E-09	1.9E-09	2.2E-09	1.1E-09
INDIAN POINT	4.5E-09	2.9E-09	3.2E-09	1.1E-09
IDAHO NATIONAL LAB	7.6E-10	1.9E-09	2.4E-10	2.9E-09

5.6 Conclusions

The conclusions that can be drawn from the risk assessment presented in this chapter, keeping in mind that these apply to the three types of casks studied, are:

- The sixteen routes selected for study are an adequate representation of U.S. routes for spent nuclear fuel transportation, and there was relatively little variation in the risks per km over these routes.
- The overall collective dose risks are vanishingly small.
- The collective dose risks for the two types of extra-regulatory accidents, accidents involving a release of radioactive material and loss-of-lead-shielding accidents, are negligible compared to the risk from a no-release, no-loss-of-shielding accident. There is no expectation of any release from spent fuel shipped in inner welded canisters from any impact or fire accident analyzed.
- The collective dose risk from loss of lead shielding is comparable to the collective dose risk from a release, though both are very small. The doses and collective dose risks from loss of lead shielding are larger than were calculated in NUREG/CR-6672 as a result of better precision in the finite element modeling and a more accurate model of the dose from a gap in the lead shield.
- The conditional risk of either a release or loss of shielding from a fire is negligible.
- The consequences (doses) of some releases and some loss of shielding scenarios are larger than cited in the regulation of 10 CFR 71.51, and are significant, but are neither acute nor lethal.
- These results are not unexpected and are in agreement with previous studies.

Comment [JRC66]: Is this a conclusion or a finding based on analysis? How were the routes were shown to be representative?

CHAPTER 6

OBSERVATIONS AND CONCLUSIONS

The present document is an assessment of the risks of transporting spent nuclear fuel, updating the assessment performed for NUREG-0170, *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes*, published in 1977. Both NUREG-0170 and this document provide a technical basis for the regulations of 10 CFR Part 71. Other studies, like the Modal Study (Fischer, et al., 1987) and NUREG/CR-6672 (Sprung, et al., 2000), alsosupport the conclusions of NUREG-0170.

Regulations and regulatory compliance analyses are different from risk assessments. A regulation must be conservative because its purpose is to ensure safety, and 10 CFR Part 71, which regulates transportation, requires a conservative estimate (i.e., overestimate) of the damage to a cask in an accident and the radiation emitted from the cask during routine transportation. The original technical basis for 10 CFR Part 71, NUREG-0170, was also conservative, but for a different reason: only limited data were available to perform the required assessment, so NUREG-0170 deliberately used conservative parameter estimates. The NRC's conclusion was that NUREG-0170 showed transportation of radioactive materials to be safe enough, even with conservative assumptions, to support the regulation.

When an assessment is used to inform regulation, it should be as realistic as possible to provide information needed to confirm or revise the regulations it informs. Realistic assessment depends on the data availability and accurate and precise modeling techniques that have become increasingly available in the years since 1977. Consequently, the Modal Study and NUREG/CR-6672 made good progress in assessing transportation risks more realistically. As a result, both the calculated consequences and risks of radioactive materials transportation decreased. The decrease in risk means that the regulations provide a greater level of safety than previously recognized.

The present study is a more accurate analysis than the previous analyses. Certified spent fuel cask types are analyzed, rather than generic designs. Recent (2005 or later) accident frequency data and population data are used in the analyses, and the modeling techniques have been upgraded as well. This study, the Spent Fuel Transportation Risk Assessment, is another step in building a complete picture of spent nuclear fuel transportation radiological safety, and is an addition to the technical basis for 10 CFR Part 71. Also, it represents the current state of the art for such analyses. The results of this study are compared with preceding risk assessments in the figures that follow.

6.1 Routine Transportation

Figure 6-1 and Figure 6-2 show results of routine truck and rail transportation of a single shipment of spent nuclear fuel. Figure 6-1 plots average collective radiation dose (person-Sv) from truck transportation, and Figure 6-2 plots average collective radiation dose from rail transportation. These average doses include the doses to the population along the route, doses to occupants of vehicles sharing the route, doses at stops, and doses to vehicle crew.

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Collective doses from routine transportation depend directly on the population along the route and the number of other vehicles that share the route, and inversely on the vehicle speed. Doses to occupants of vehicles that share the route depend inversely on the square of the vehicle speed.

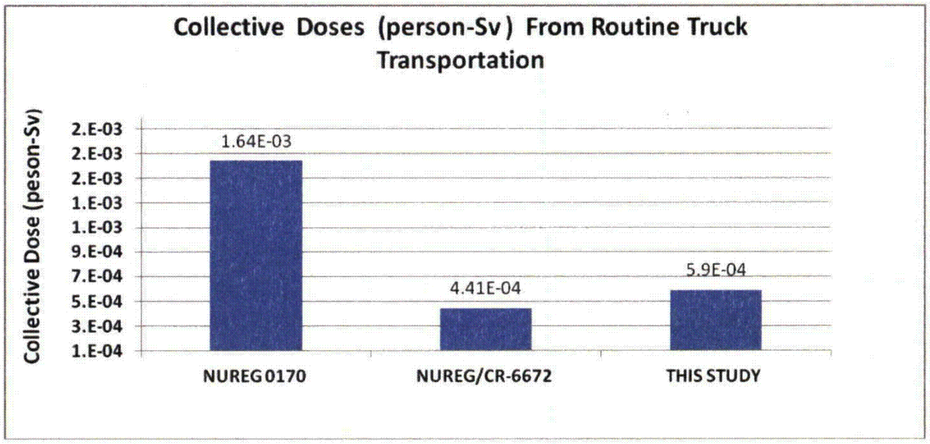

Figure 6-1. Collective doses (person-Sv) from routine truck transportation.

The NUREG-0170 results for truck transportation were based on a single long route, constant values of rural, suburban, and urban population densities, on different and conservative vehicle speeds on rural, urban, and suburban roads, on a fixed rate of vehicle stops, and on 1975 estimates of vehicle density (vehicles per hour), all of which led to conservative results. NUREG/CR-6672 used more realistic distributed route lengths, population densities, vehicle occupancy and density, vehicle dose rate and stop time and used the means of the distributions as parameters. As Figure 6-1, the conservatism was decreased by over a factor of three.

The collective average dose in the present study is larger than the NUREG/CR-6672 result because present populations are generally larger, particularly along rural routes, and the vehicle densities are much larger (see Chapter 2). These increases were offset by the greater vehicle speeds used in the present study.

Figure 6-2 shows the differences between NUREG 0170, NUREG/CR-6672, and the present study for calculation of average doses to the public for routine rail transportation.

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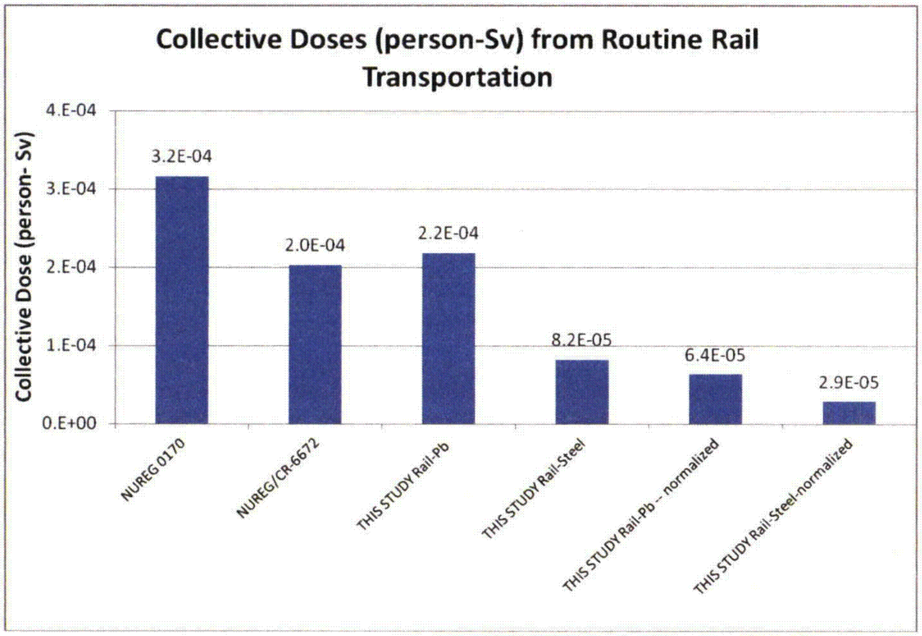

Figure 6-2. Collective doses (person-Sv) from routine rail transportation.

Comment [JRC67]: What does normalized mean?

Comment [JRC68]: Change axis label from Pb

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The difference in dose between the Rail-Lead cask and the Rail-steel cask occurs because the latter cask has a smaller external dose rate (Chapter 2). The differences in crew doses between the studies reflect the considerable difference between the methods used in the different studies.

The differences in the collective doses from routine transportation between the cited studies are not the result of differences in external radiation from the spent fuel casks. The 1975 version of 10 CFR Part 71[18] specified the same limit on external radiation (the transport index) as Part 71 specifies today.

The differences in results are due primarily to vehicle speed, population and vehicle densities, and differences in calculating train crew and railyard worker doses. These differences are summarized below.

- Differences in vehicle speed. The faster the cask moves past a receptor, the less that receptor is exposed. NUREG-0170 and NUREG/CR 6672 used 80 kph for all truck routes and 64 kph on rural rail routes, 40 kph on suburban rail routes, and 24 kph on urban rail routes. The truck speeds used in this study are 108 kph on rural routes, 102 kph on suburban routes, and 97 kph on urban routes, and the rail speed is 40 kph on rural and suburban routes and 24 kph on

[18] A copy is provided in NUREG-0170.

urban routes. The present speeds are based on data instead of the estimated values used in the previous studies.

- Differences in populations along the routes. NUREG-0170 used six persons per km^2 for rural populations, 719 per km^2 for suburban routes, and 3861 per km^2 for urban routes. NUREG/CR-6672 used 1990 census data provided by the codes HIGHWAY and INTERLINE and used the mean values of Gaussian distributions of population densities on 200 routes in the United States. This study uses 2000 census data provided by TRAGIS (Johnson and Michelhaugh, 2002), with some updates based on 2008 census data, for the rural, suburban, and urban truck and rail route segments in each state traversed in each of the sixteen routes studied. The variation from the NUREG-0170 values is considerable.

- Differences in vehicles per hour on highways. NUREG-0170 and NUREG/CR-6672 both used the 1975 values of 470 vehicles per hour on rural routes, 780 on suburban routes, and 2800 on urban routes. This study used 2002 state vehicle density data for each state traversed. The national average vehicle density is 1119 vehicles per hour on rural routes, 2464 on suburban routes, and 5384 on urban routes. This large difference in vehicle density contributes to the difference in collective doses for routine truck transportation between NUREG/CR-6672 and this study.

- Differences in calculating doses to rail crew. NUREG-0170 calculated doses to rail and railyard crew by estimating the distance between the container carrying radioactive material and the crew member. NUREG/CR-6672 used the Wooden (1980) calculation of doses to railyard workers, and did not calculate a dose to the crew on the train. This study calculated all doses using the formulations in RADTRAN 6, calculated an in-transit crew dose, used an updated value for the time of a classification stop (27 hours instead of 30 hours), and used in-transit stop times from TRAGIS rather than the stop dose formula, pegged to total trip length, used in NUREG/CR-6672. The in-transit crew dose calculated in this study was small enough that it contributed a negligible amount to these doses.

Dose to the maximally exposed individual is a better indication of the radiological effect of routine transportation than collective dose. The same event results in different collective doses depending on the population affected, which varies both spatially and temporally. The dose to the maximally exposed individual is shown in Figure 6-3 for NUREG-0170 and for the three cask types of this study. NUREG/CR-6672 did not calculate this dose for routine transportation.

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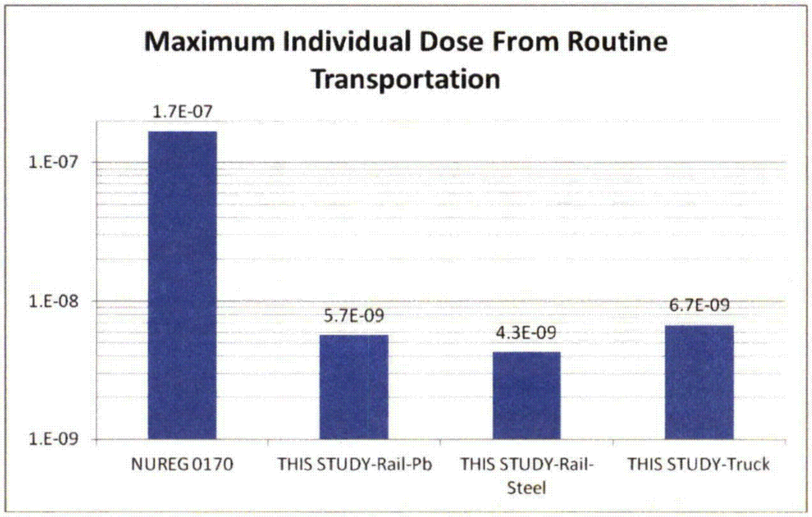

Figure 6-3. Maximum individual dose (Sv) from routine transportation.

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6.2 Transportation Accidents

Radiological accident risk is expressed in units of "dose risk" that include the probability of an accident and the conditional probability of certain types of accidents. The units used are dose units (Sv) because probability is a unitless number. NUREG-0170, NUREG/CR-6672, and this study all used the version of RADTRAN available at the time of the study to calculate dose risk, but the input parameters differed widely. In addition, improvements in RADTRAN and in other modeling codes described in earlier chapters resulted in a more accurate analysis of cask behavior in an accident.

The results shown in Figure 6-4 and Figure 6-5 for this study are averages over the 16 routes studied As was discussed in Chapters 3, 4, and 5, a lead-shielded rail cask, the Rail-Lead cask in this study, is the only cask type of the three studied that can either release radioactive material or can lose lead gamma shielding in a rail or highway traffic accident.

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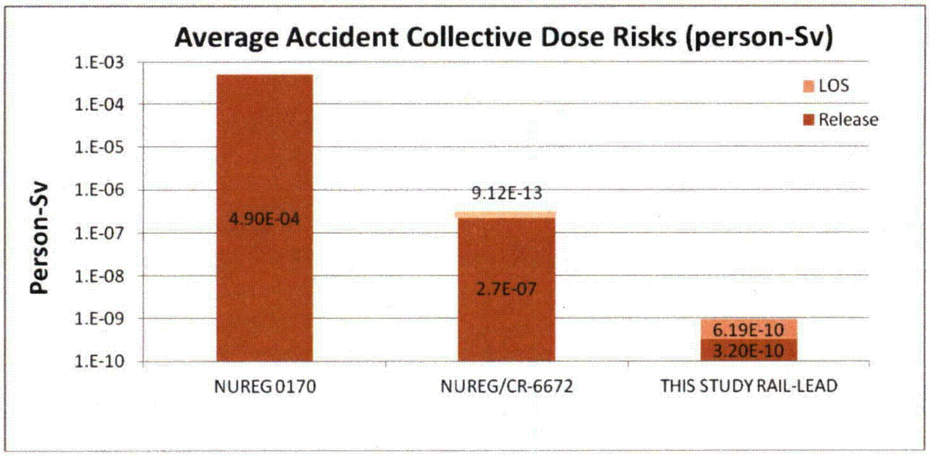

Figure 6-4. Accident collective dose risks from release and LOS accidents. The LOS bar representing the NUREG/CR-6672 collective dose is not to scale.

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Unlike the results for routine transportation, the results shown in Figure 6-4 depend on different amounts of radioactive material released and different amounts of lead shielding lost. NUREG-0170 used a scheme of eight different accident scenarios, four of which postulated release of the entire releasable contents of the cask, two of which postulated no release, one postulated a ten percent release, and one postulated a one percent release. The range of conditional probabilities was from 1×10^{-5} for the most severe (100 percent release) accident to 80 percent for the two no-release accident scenarios. The NUREG-0170 "universe" of accidents and their consequences was based primarily on engineering judgment and was clearly conservative.

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NUREG/CR-6672 analyzed the structural and thermal behavior of four generic cask designs—two truck and two rail casks—in great detail, and analyzed the behavior of the five groups that best describe the physical and chemical nature of the radioactive materials potentially released from the spent fuel through the casks. These five groups are particulate matter, semi-volatile substances, ruthenium, gas, and CRUD. The spent fuels considered were high burnup and low burnup PWR and BWR fuel. This analysis resulted in 19 truck accident scenarios and 21 rail accident scenarios, each with an attendant possibility, including a no-release scenario, with better than 99.99 percent probability.

The present study followed the analytical outline of the NUREG/CR 6672 analysis, but analyzed the structural and thermal behavior of a certified lead-shielded cask design loaded with fuel that the cask is certified to transport. Instead of the 19 truck scenarios and 21 rail scenarios that included potential releases of radioactive material, the current study resulted in only seven rail scenarios that included releases, as described in Chapters 3 and 5. The only parts of the cask structure that could be damaged enough to allow a release are the seals. Release could take place through the seals only if the seals fail and if the cask is carrying uncanistered fuel. No potential truck accident scenario resulted in seal failure, nor did any fire scenario. In the present study, only the Rail-Lead cask response to (extremely severe)accident conditions resulted in a release.

A comparison of the collective dose risks from potential releases in this study to both NUREG-0170 and NUREG/CR-6672 is appropriate, since the latter two studies considered only potential releases. The collective dose risks decrease with each succeeding study as expected, since the overall conditional probability of release and the quantity of material potentially released decreases with each successive study.

The collective dose risk from a release depends on dispersion of the released material, which then either remains suspended in the air, producing cloudshine, or is deposited on the ground, producing groundshine, or is inhaled. All three studies used the same basic Gaussian dispersion model in RADTRAN, although the RADTRAN 6 model is more flexible than the previous versions and can model elevated releases. NUREG-0170 calculated only doses from inhaled and resuspended material. NUREG/CR-6672 included groundshine and cloudshine as well as inhaled material, but overestimated the dose from inhaled resuspended material. The combination of improved assessment of cask damage and improved dispersion modeling has resulted in the decrease in collective dose risk from releases shown in Figure 6-4.

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Frequently, public interest in the transportation of spent fuel focuses on the consequences of possible accidents (without regard to their likelihood). The average estimated consequences (collective doses) from potential accidents involving release for the present study is 2 person-Sv. This consequence is orders of magnitude less than the 110 person-Sv in NUREG-0170 and the 9000 person-Sv estimated from Figure 8.27 in NUREG/CR-6672.

Comment [JRC70]: Why wouldn't this be MEI dose?

NUREG-0170 did not consider loss of spent fuel cask lead shielding, which can result in a significant increase the dose from gamma radiation being emitted by the cask contents. NUREG/CR-6672 analyzed 10 accident scenarios in which the lead gamma shield could be compromised and calculated a fractional shield loss for each. An accident dose risk was calculated for each potential fractional shield loss. The present study followed the same general calculation scheme, but with a more sophisticated model of gamma radiation from the damaged shield and with 18 potential accident scenarios instead of 10. Much of the difference between the NUREG/CR-6672 dose risks from shield loss and this study is the inclusion of accident scenarios that have a higher conditional probability than any such scenarios in NUREG/CR-6672. The consequence of loss of lead shielding estimated in NUREG/CR-6672 Table 8.13 is 41,200 person-Sv, about 100 times the 690 person-Sv estimated in this study. Lead shield loss clearly affects only casks that have a lead gamma shield; casks using DU or thicker steel shielding would not be affected.

More than 99.999 percent of potential accident scenarios do not affect the cask at all and would not result in either release of radioactive material nor increased dose from loss of lead shielding. However, these accidents would result in an increased dose from the cask external radiation to the population near the accident because the cask remains at the location of the accident until it can be moved. A nominal ten hours was assumed for this delay in this study. The resulting collective dose risk from this accident is shown in Figure 6-5 for all three cask types studied. Even including this additional consequence type, the accident collective dose risk from this study is less than that reported in either NUREG-0170 or NUREG/CR-6672.

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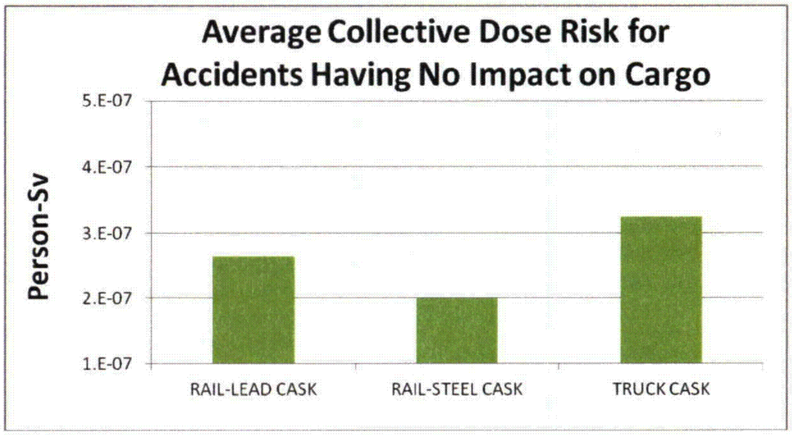

Figure 6-5. Average collective dose from accidents that have no impact on the cargo.

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In conclusion, the three studies reviewed here show that the NRC regulation of transportation casks ensures safety and health. The use of data in place of engineering judgment shows that accidents severe enough to cause loss of shielding or release of radioactive material are improbable and the consequences of such unlikely accidents are serious but not dire. Moreover, these consequences depend on the size of the population exposed rather than on the radiation or radioactive material released. The consequences (doses) to the maximally exposed individual, 1.6 Sv to a member of the public from a release and 1.1 Sv from loss of lead shielding to a possible first responder, could result in latent health consequences rather than immediate health effects.

The most significant consequence of an accident, in addition to any non-radiological consequence of the accident itself, is the external dose from a cask immobilized at the accident location. Average collective doses from this type of accident for the 16 routes studies are shown in Figure 6-5. The most significant parameters contributing to this dose are the accident frequency and the length of time that the cask sits at the accident location. Even in this case, the significant parameter in the radiological effect of the accident is not the amount or rate of radiation released, but the exposure time.

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