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. This is more severe than the majority of the thermal environments a cask may be exposed to in an accident that results in a fire. 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. Large open pool fires can burn at temperatures higher than the 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.

Comment [XXX1]: Please provide a reference for this statement.

For this risk study, computer codes capable of modeling fires and the thermal response of casks exposed to fires in a realistic fashion are used to analyze the response of the Rail-Steel and the Rail-Lead casks to three different hypothetical 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 exposed to a severe hypothetical fire scenario is also presented.

Deleted: A discussion

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 spent nuclear fuel transportation industry. 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 hypothetical fire accident scenarios are analyzed for each rail cask and one for the truck cask. A fuel pool that conforms to the regulatory requirement in 10 CFR 71.73 is used as the basis for each scenario. This regulation specifies a fuel pool that extends between one and three meters horizontally beyond the external surface of a cask. In this study, all fuel pools were assumed to extend three meters from the sides of each cask analyzed to ensure they would be fully engulfed by the fire.

Comment [XXX2]: Is this a conservative assumption considering that with such a large pool fire, there will be considerable cool spots (i.e., oxygen deprived) in the center? If not conservative OK, but at least discuss.

H-4

4.2.2 Fire duration

The duration of the hypothetical fires for the rail cask analysis 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. To estimate the duration of the fires, this amount of fuel is 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 beyond the surfaces of the casks are used in the computer 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 14m x 9m. A pool of this size would need to be 0.9m deep to pool 30,000 gallons of liquid fuel, a condition that is extremely unlikely to be met in any accident scenario. If the fuel in such a pool were to ignite, this pool fire would burn for about 3 hours. This fire duration is estimated using a nominal hydrocarbon fuel recession (evaporation) rate of 5mm 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 more unlikely case in which 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 3-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.

Comment [XXX3]: As discussed during the meeting at SNL, making the assumption that the pool fire extends 3 meters on each side of the cask leads to a pool fire that is much shorter in duration than one that extends 3-m form the cask (I believe we calculated it to be 7.5 hours for the 1-m extension and 3 hours for the 3-m extension) (not to mention that the bigger fire is also cooler at its center due to oxygen deprivation). I am fine with using a 3-hour duration, but this should not be the justification for it. Rather, as we discussed at SNL, historical data showing that a 3-hour fire is a good estimate of the near worst-case fire that could be encountered should be used to justify this duration. We discussed that Chris Bajwa could provide the historical data to make the justification.

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 2.3m x 6m, a regulatory pool that extends horizontally 3 meters beyond the outer surface of the cask would be 8.3m x 12m. To pool 9,000 gallons of gasoline in a pool of this area, the pool would need to be 0.3m 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 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 hypothetical fire accident scenarios different 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.

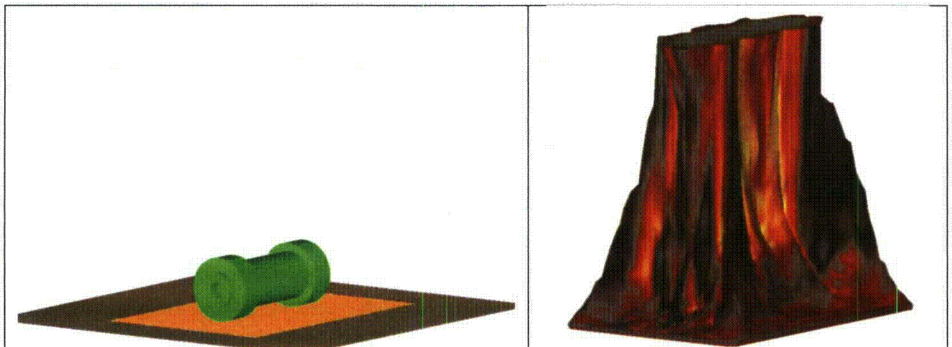
   This scenario represents the hypothetical case in which the liquid fuel spilled as a consequence of the accident flows to the location where the cask comes to rest following the accident and forms a large pool under (and concentric with) the cask.

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.

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.



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

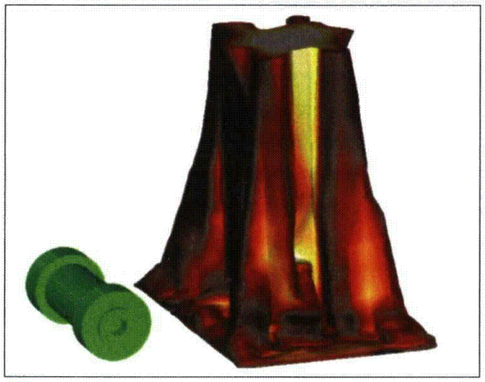


Figure 4-2. Cask lying on ground 3 meters from pool fire

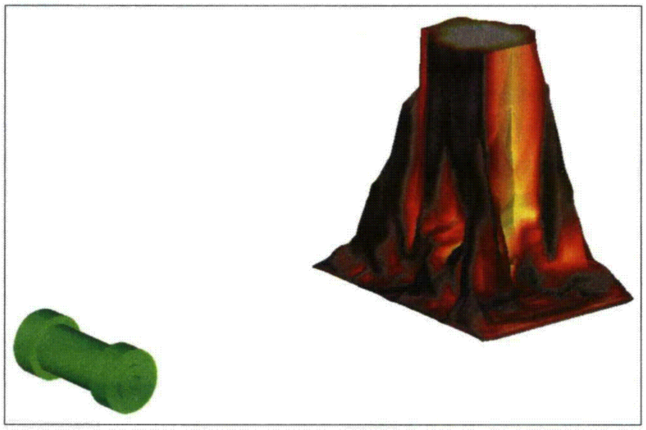


Figure 4-3. Cask lying on ground 18 meters from pool fire

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.

In addition to these hypothetical accident scenarios, two 30-minute regulatory HAC fire analyses are performed based on the conditions described in 10 CFR 71.73. In the first analysis a commercially-available finite element (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) and radiation heat transfer computer model is used. In this model, the cask is positioned one meter above the fuel pool and the fire is realistically modeled as shown in Figure 4-4.

Comment [XXX4]: Why are these analyses performed (i.e. what is their purpose)? Please provide some additional explanation as to why these additional analysis were done.

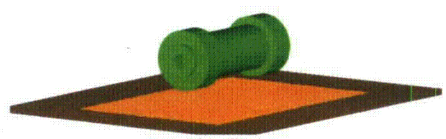
	
Cask elevated 1m above flammable liquid fuel pool region (shown in orange)	Regulatory fire engulfing the cask

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.

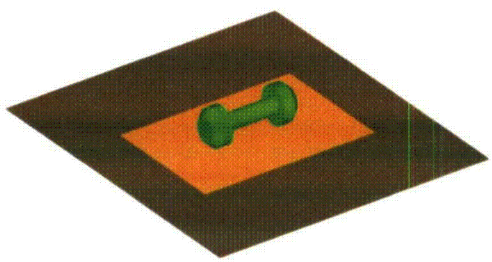
	
Cask in the middle of flammable liquid fuel pool region (shown in orange)	Fire engulfing the cask

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 body. 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. However, the temperature scale for the Rail-Steel cask differs slightly from the scale for the Rail-Lead cask.

Results of the analyses are presented in the following order:

1. Regulatory 800°C (1475°F) uniform heating (30 minutes)
2. Regulatory CFD fire (30-minute fire)
3. Cask lying on the ground in the middle of a 3-hour pool fire
4. Cask lying on the ground 3 meters from a 3-hour pool fire
5. Cask lying on the ground 18 meters from a 3-hour pool fire

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

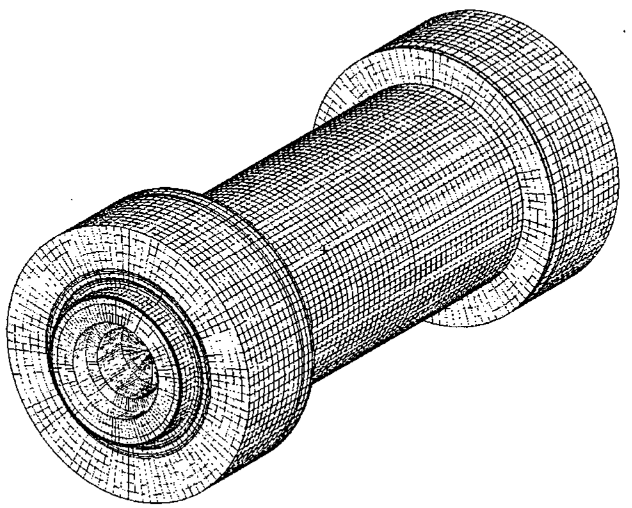
The heat transfer within the Rail-Steel and the Rail-Lead casks is modeled with the computer code MSC PATRAN-Thermal (P-Thermal) (MSC, 2008). This code is commercially available and is used to solve a wide variety of heat transfer problems. P-Thermal has been coupled with CAFE, allowing for a refined 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).

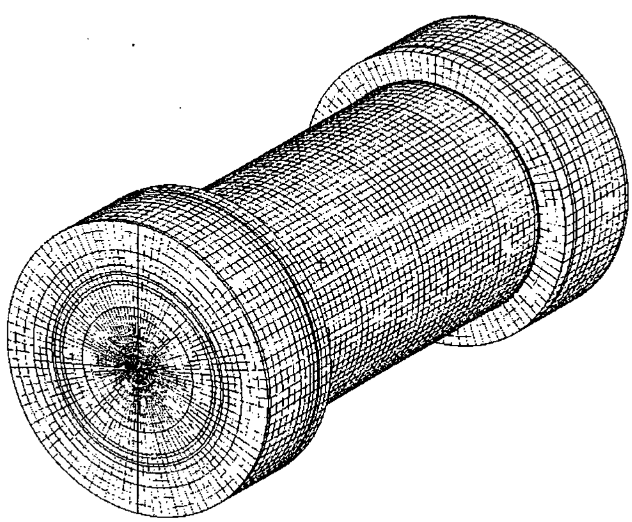
Comment [MF5]: – the polymeric neutron shield is assumed to melt completely and be replaced by air for all the three casks. The loss of this shield is not mentioned at all later in the Partial Summaries of page 87, page 96, page 101, and in the Chapter Conclusions, page 102. For completeness, the loss of this shield should be mentioned in the Summary sections and in the Chapter Conclusions.

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.



Rail-Steel cask



Rail-Lead cask

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

4.3.3 Simulation of the spent fuel region

The fuel region comprising the fuel basket and the fuel assemblies is not modeled explicitly. 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 solid cylinder inside the cask. The thermal response of the homogenized fuel region is similar to the overall response of the actual fuel region and provides sufficient information for this study. The details of how the effective properties of the homogenized fuel region are determined and applied to the model are presented in Appendix IV.

Comment [MF6]: a justification of the adequacy of modeling the fuel as a homogeneous region should be included. This fuel modeling also applies to the truck cask, page 97. How can the maximum fuel temperature be obtained using a homogeneous model?

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. 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. This figure 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 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. Note that these plots 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.

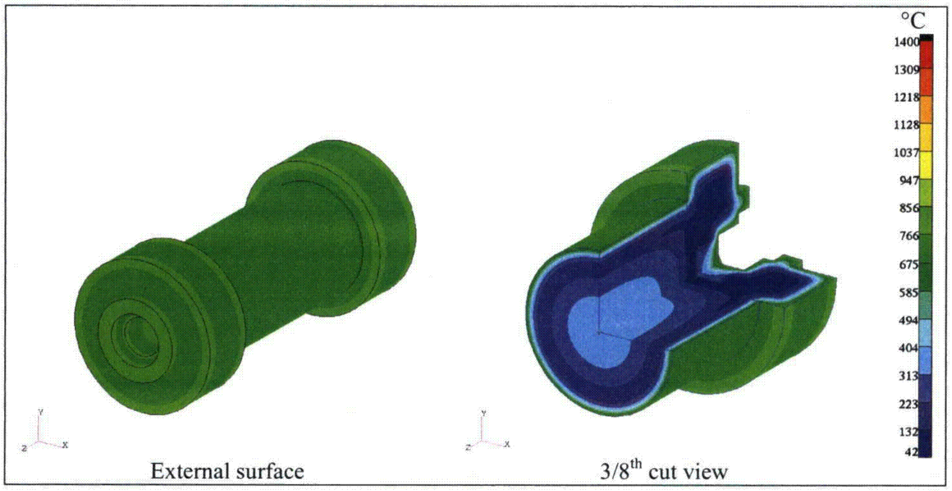


Figure 4-7. Temperature distribution of the Rail-Steel cask at the end of the 30-minute 800°C regulatory uniform heating

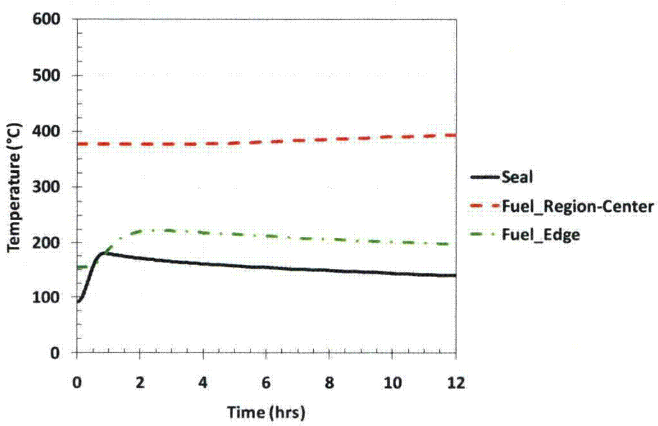


Figure 4-8. Temperature of key cask regions, Rail-Steel cask – Regulatory uniform heating

Comment [XXX7]: The use of the term "fuel" in the figure key is somewhat confusing. This refers to the spent nuclear fuel, but it could be interpreted to refer to the fire fuel. Please rephrase as either "spent fuel" or "content fuel". This comment applies to several figures.

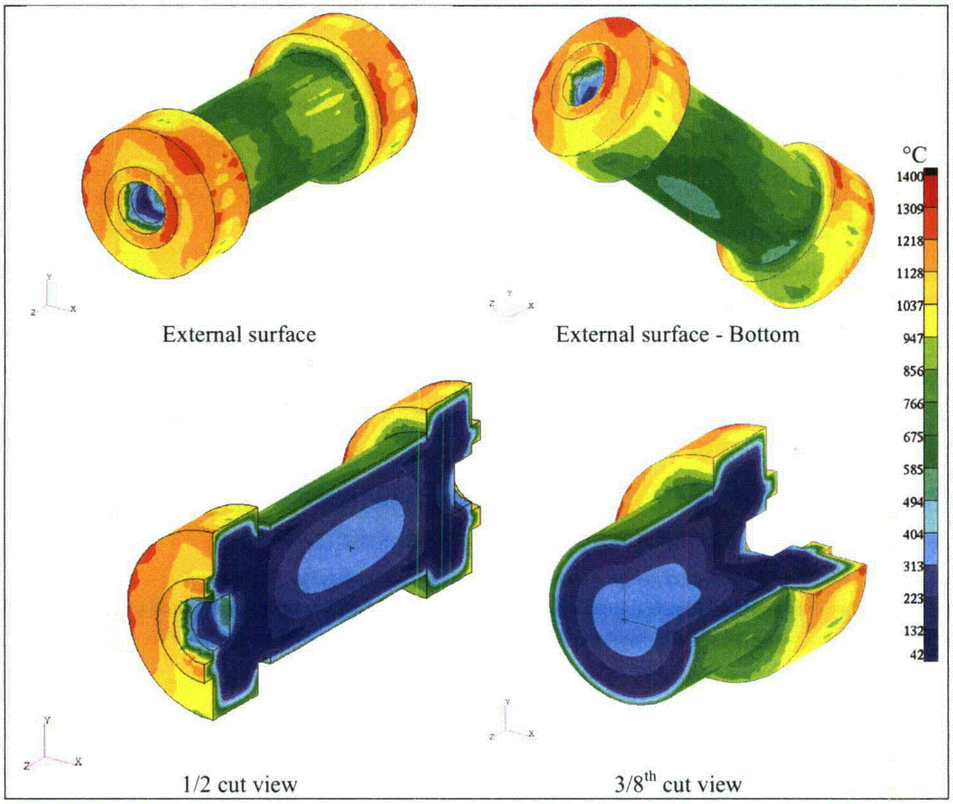


Figure 4-9. Temperature distribution of the Rail-Steel cask at the end of the 30-minute regulatory CAFE fire

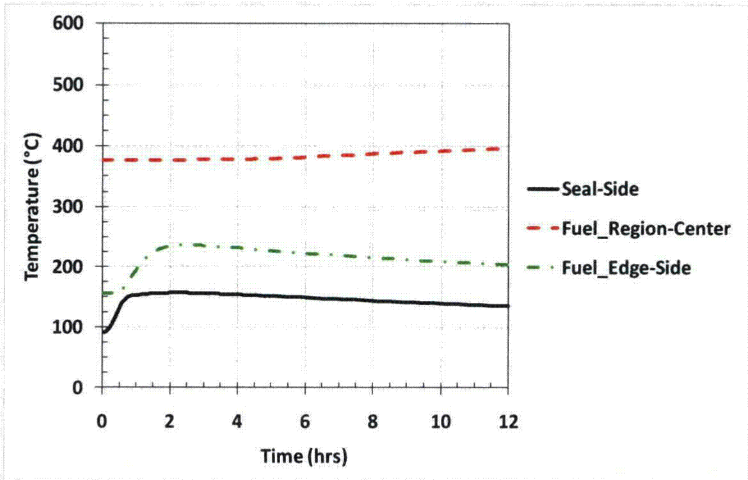


Figure 4-10. Temperature of key cask regions, Rail-Steel cask – Regulatory CAFE fire

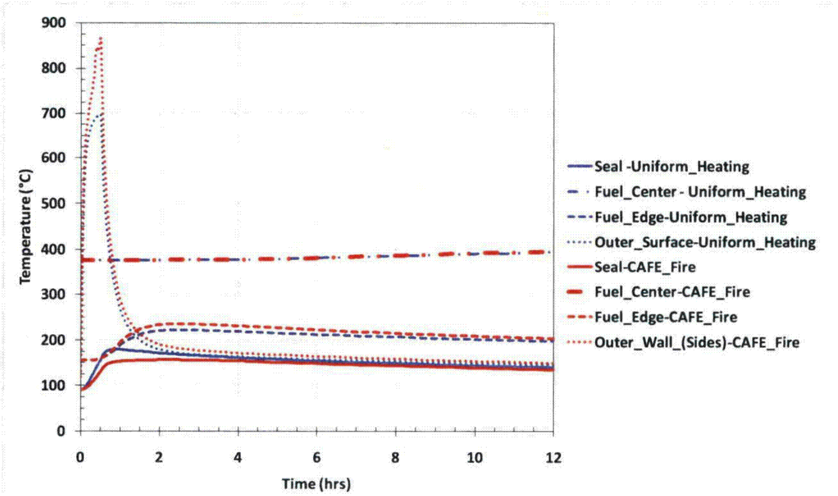
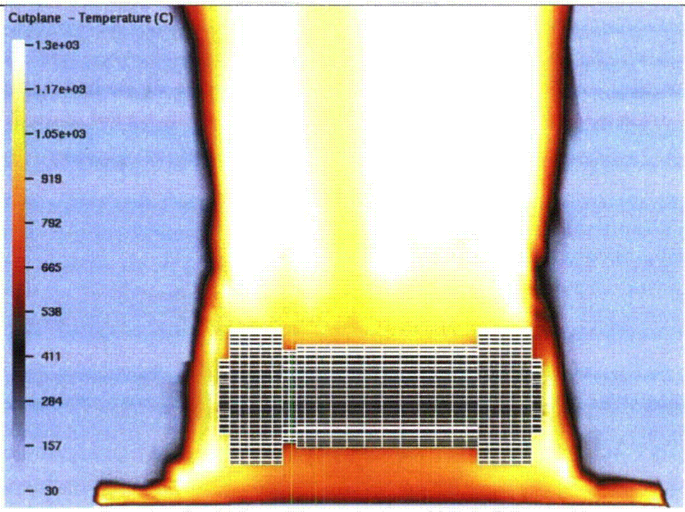
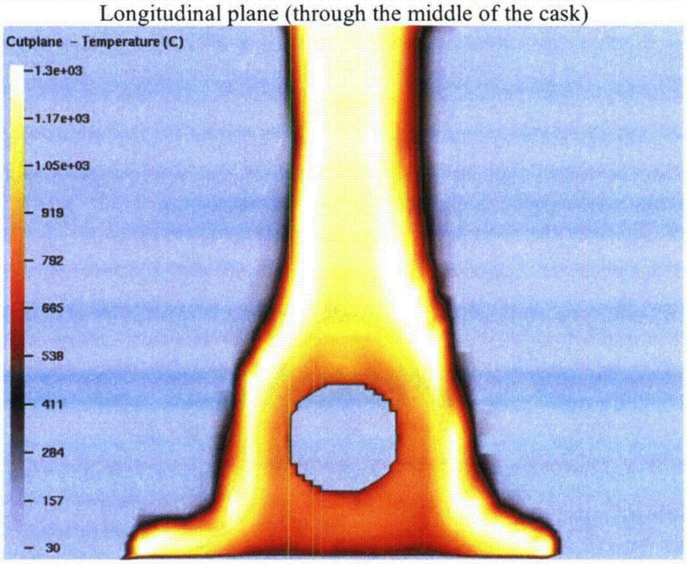


Figure 4-11. Comparison of regulatory fire analysis - Rail-Steel cask: Uniform heating vs. CAFE fire

Comment [MF8]: Comparison with Fig. IV-11, page 397 of Appendix IV, there is a discrepancy for the outer wall (sides) temperature CAFÉ fire. Value under 900°C in Fig. 4-11 and over 900°C in Fig. IV-11.



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

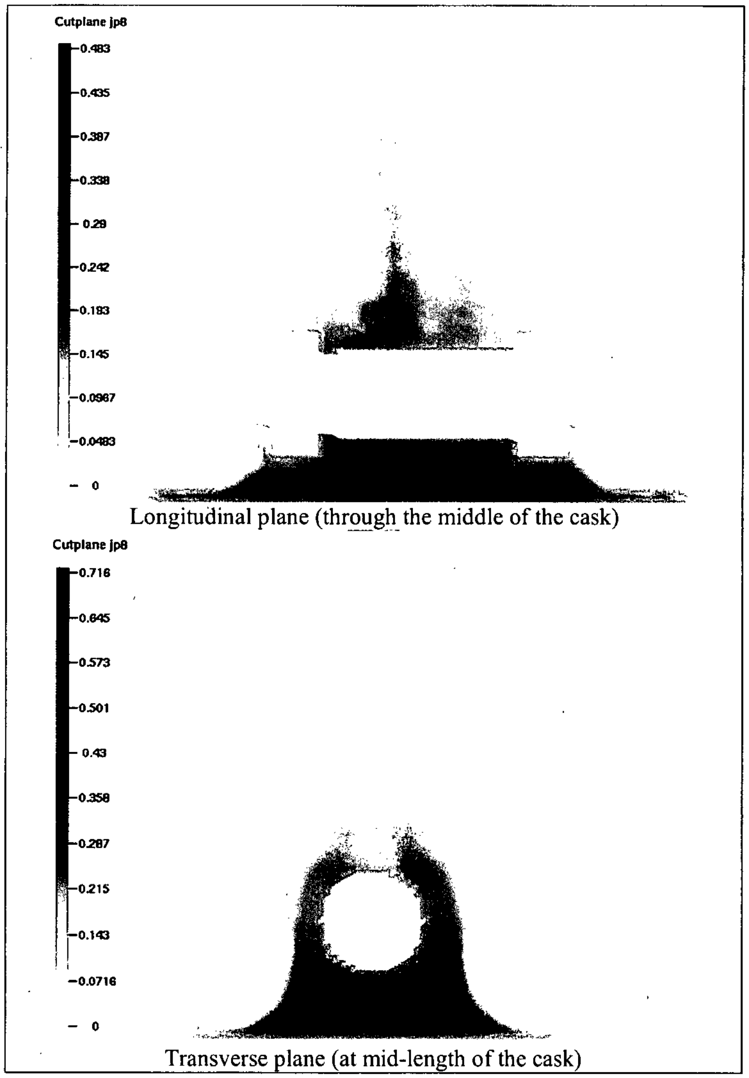


Figure 4-13. Fuel concentration plots from the regulatory CAFE fire analysis

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 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.

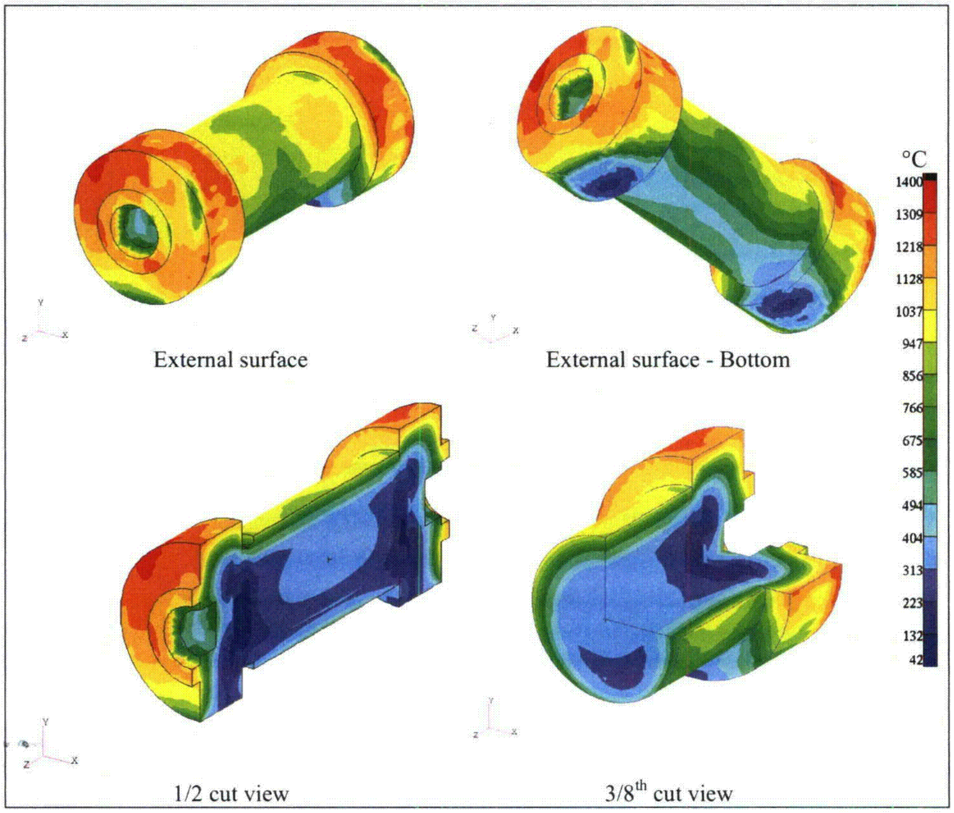


Figure 4-14. Temperature distribution of the Rail-Steel cask at the end of the 3-hour concentric CAFE fire - cask on ground

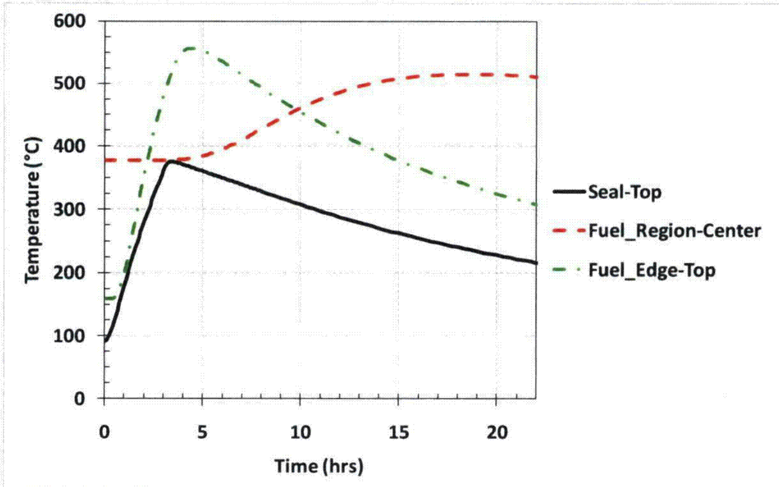
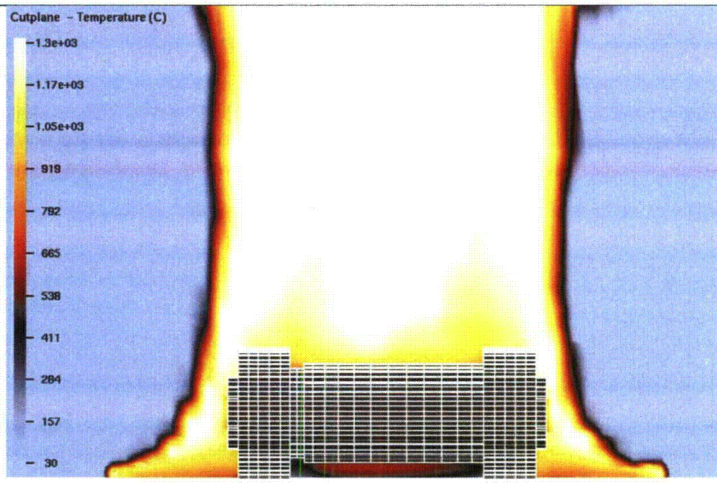


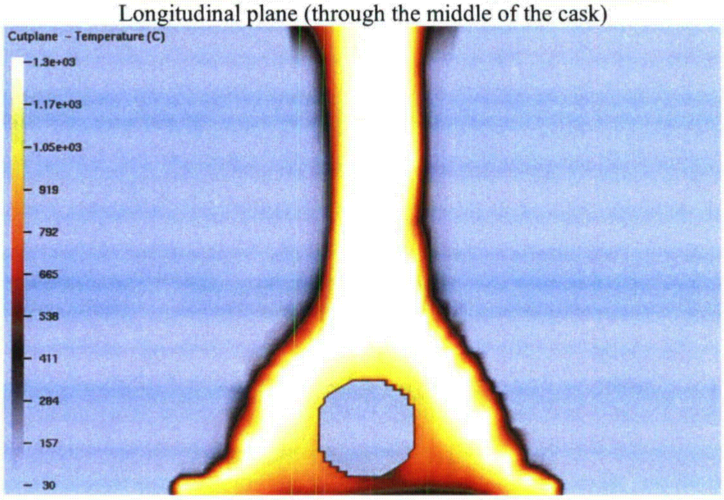
Figure 4-15. Temperature of key cask regions, Rail-Steel cask – Cask on ground, concentric fire

Comment [XXX9]: It is surprising that the *Seal-Top* and *Fuel_Edge-Top* temperatures peak so quickly after the fire, especially when compared to the *Fuel_Region-Center*. However, this finding is relatively consistent throughout the various analyses.

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

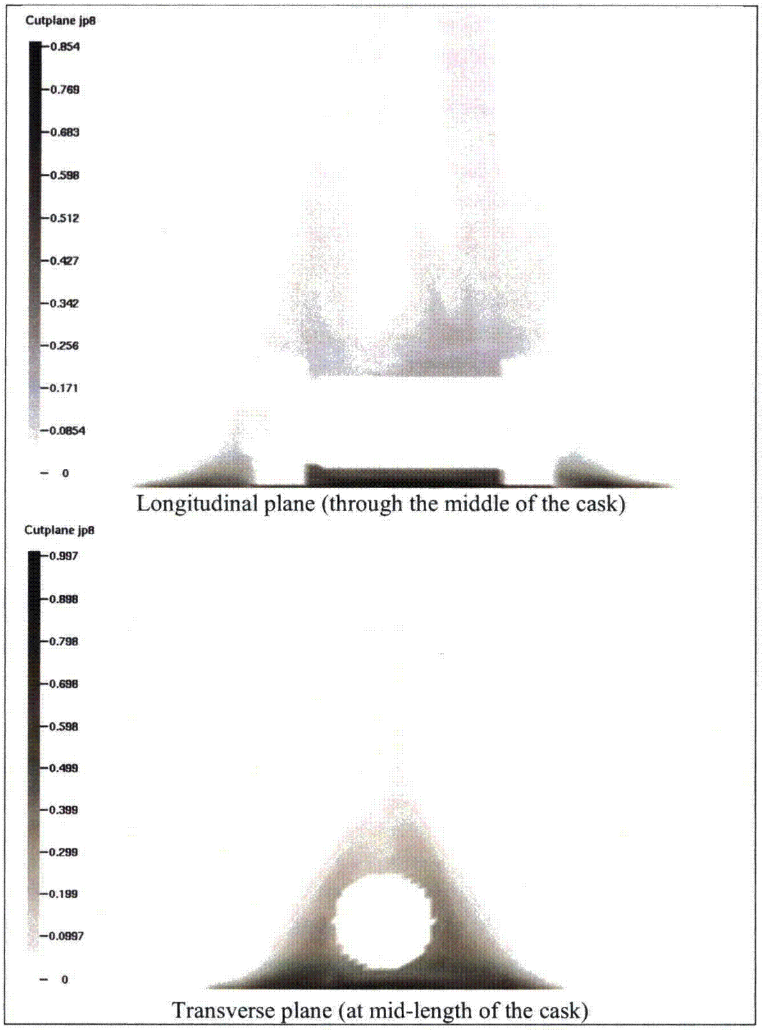


Figure 4-17. Fuel concentration plots from the CAFE fire analysis of the cask on ground

The results of the offset fire analyses are summarized in Figure 4-18 through Figure 4-21. In the case of the three-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 region did not reach their temperature limits. Therefore, offset fire scenarios will not cause this package to release radioactive material.

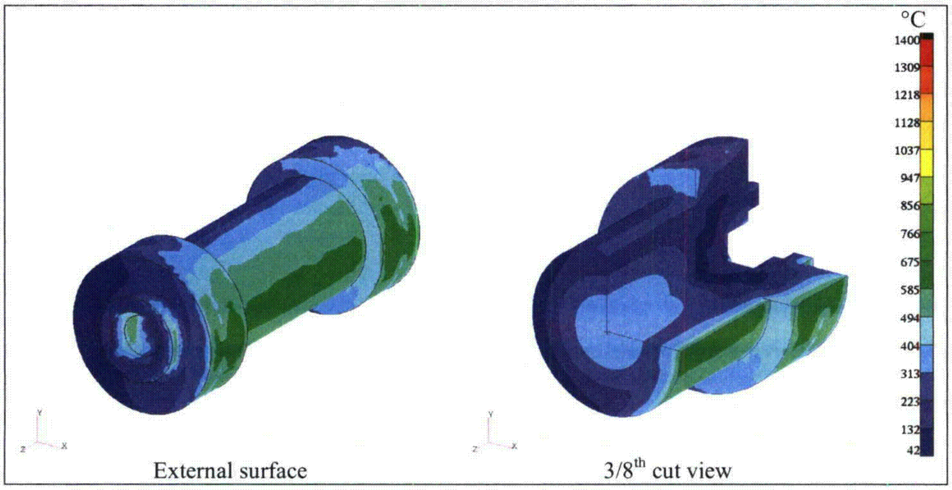


Figure 4-18. Temperature distribution of the Rail-Steel cask at the end of the 3-hour 3m offset CAFE fire - cask on ground

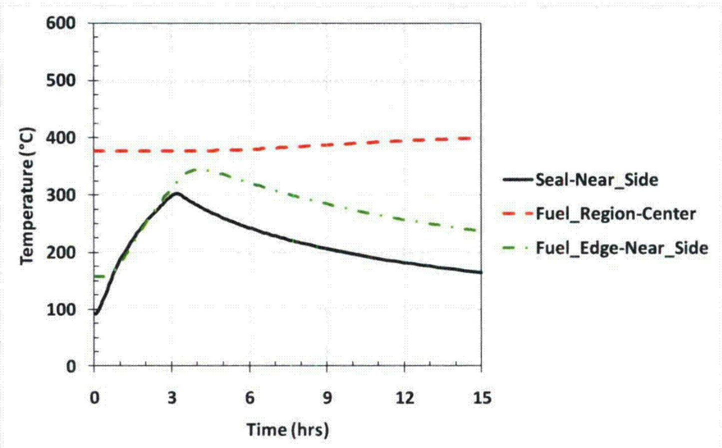


Figure 4-19. Temperature of key cask regions, Rail-Steel cask – Cask on ground, 3m offset fire

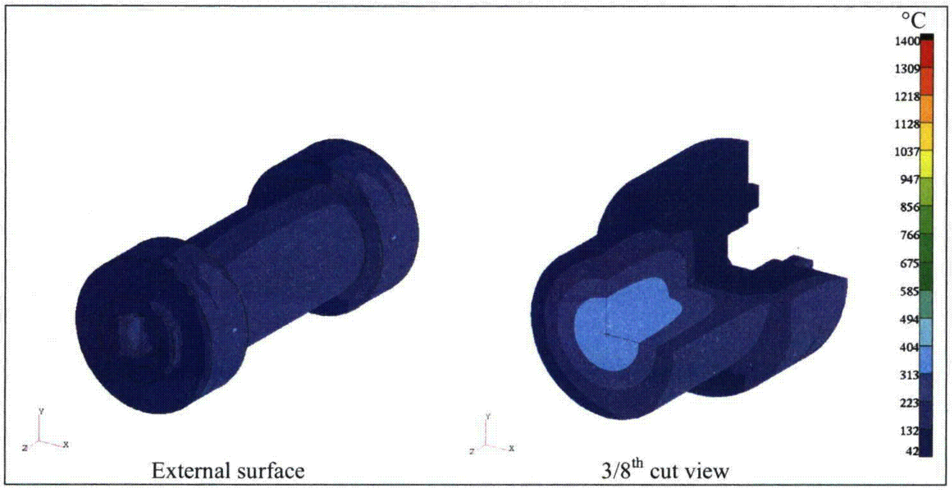


Figure 4-20. Temperature distribution of the Rail-Steel cask at the end of the 3-hour 18m offset CAFE fire - cask on ground

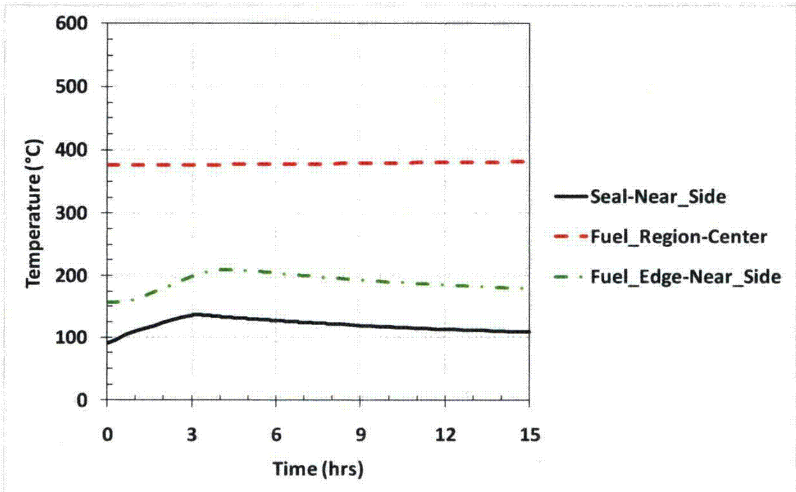


Figure 4-21. Temperature of key cask regions, Rail-Steel cask – Cask on ground, 18m offset fire

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, the fuel region stayed 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.

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.

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 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 fuel 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.

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.

Appendix IV contains additional plots with more information about temperature distributions at more locations in the cask.

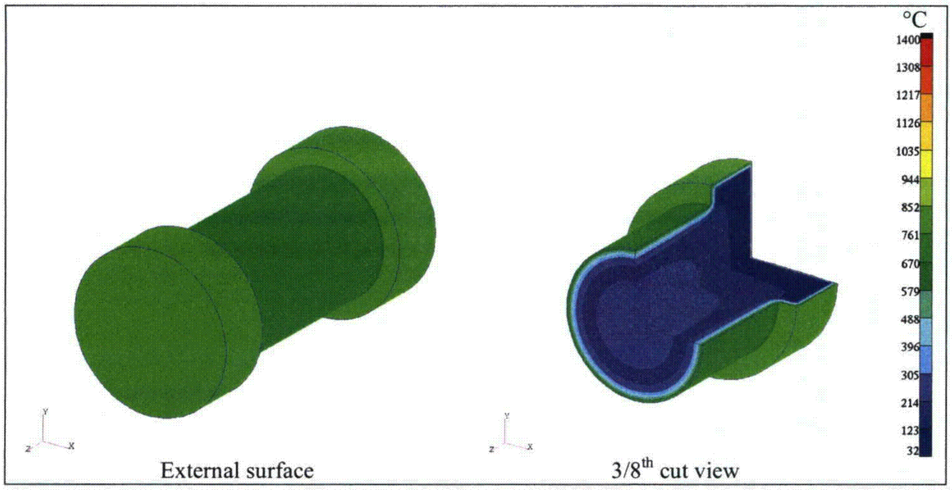


Figure 4-22. Temperature distribution of the Rail-Lead cask at the end of the 30-minute 800°C regulatory uniform heating

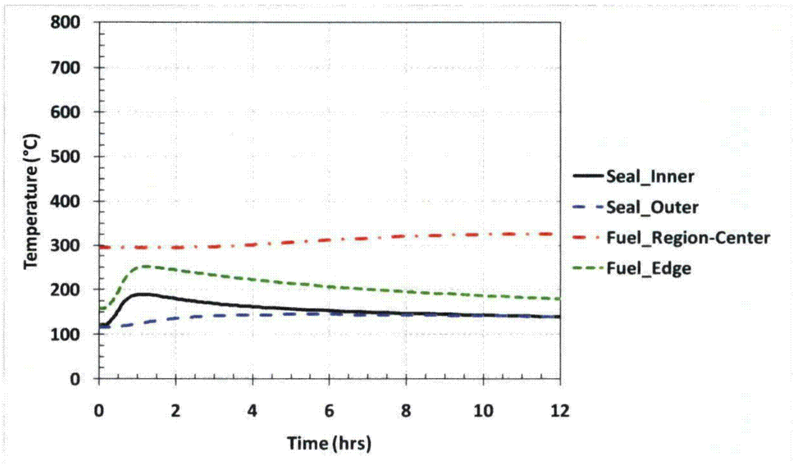


Figure 4-23. Temperature of key cask regions, Rail-Lead cask – Regulatory uniform heating

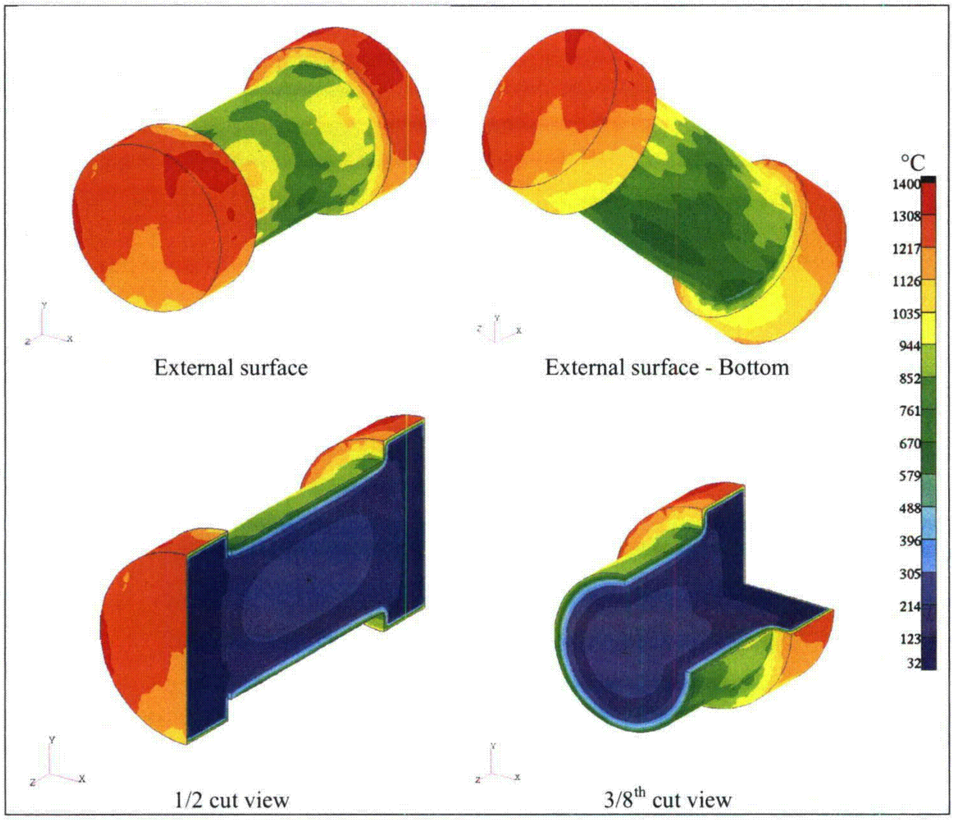


Figure 4-24. Temperature distribution of the Rail-Lead cask at the end of the 30-minute regulatory CAFE fire

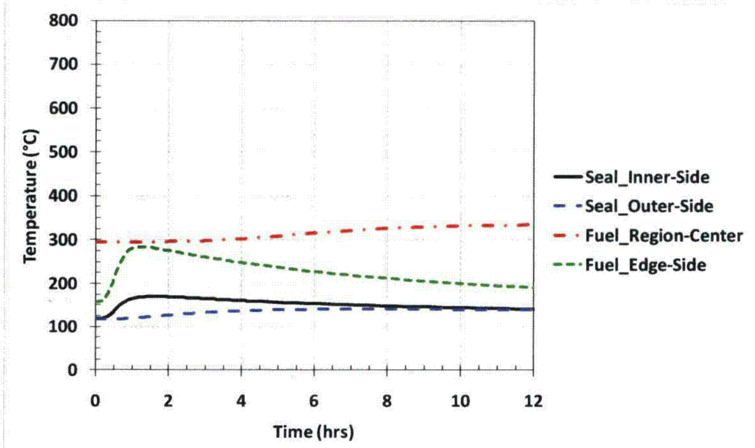


Figure 4-25. Temperature of key cask regions, Rail-Lead cask – Regulatory CAFE fire

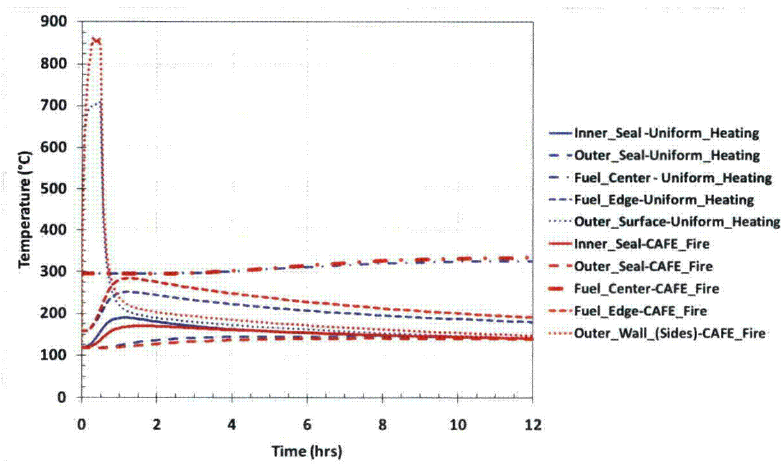


Figure 4-26. Comparison of regulatory fire analysis – Rail-Lead cask: Uniform heating vs. CAFE fire

Comment [MF10]: Fig 4-26, and Fig. IV-21 page 418 (Appendix IV) – temperature of outer wall CAFÉ fire is below 900°C (50C) in Fig. 4-26 but it is well over 900°C in Fig. IV-21. This is the same comment of Page 78 – Fig. 4-11.

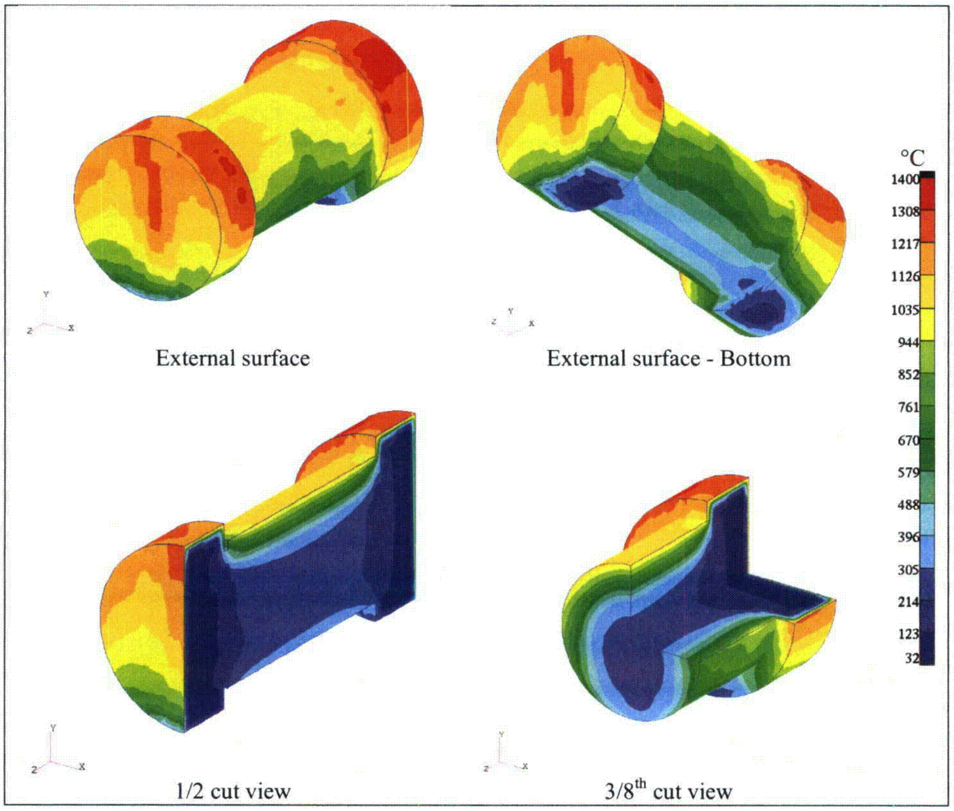


Figure 4-27. Temperature distribution of the Rail-Lead cask at the end of the 3-hour concentric CAFE fire - cask on ground

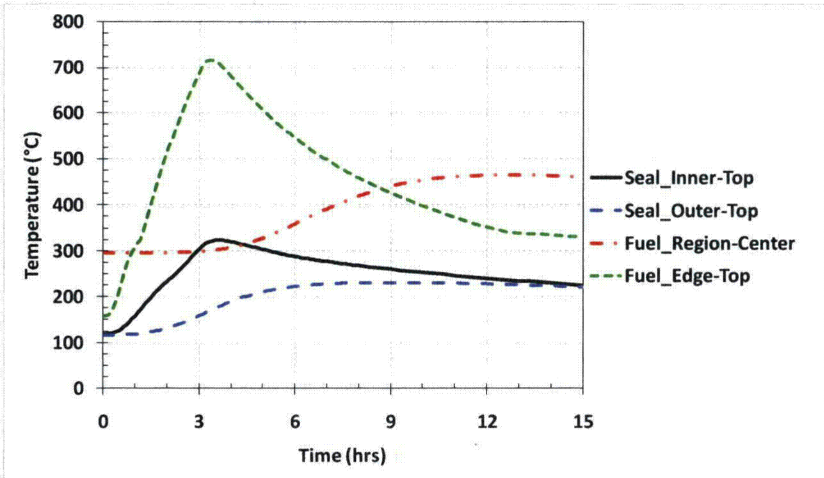


Figure 4-28. Temperature of key cask regions, Rail-Lead cask – Cask on ground, concentric fire

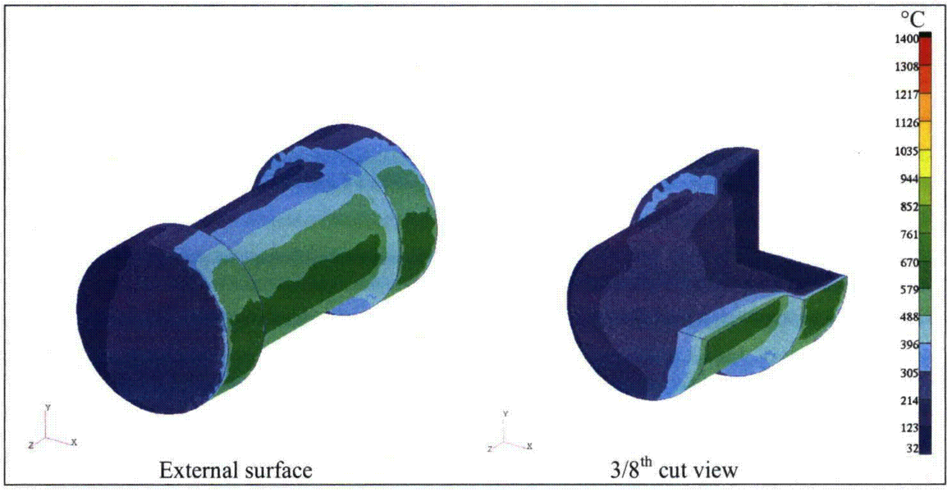


Figure 4-29. Temperature distribution of the Rail-Lead cask at the end of the 3-hour 3m offset CAFE fire - cask on ground

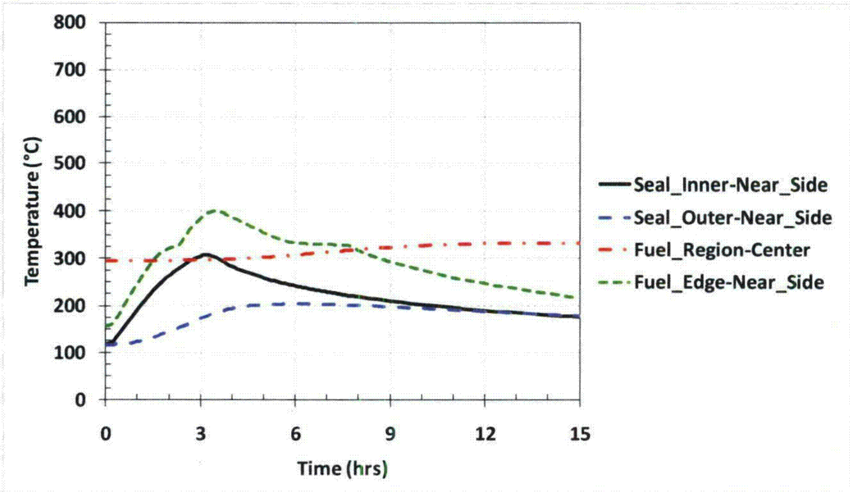


Figure 4-30. Temperature of key cask regions, Rail-Lead cask – Cask on ground, 3m offset fire

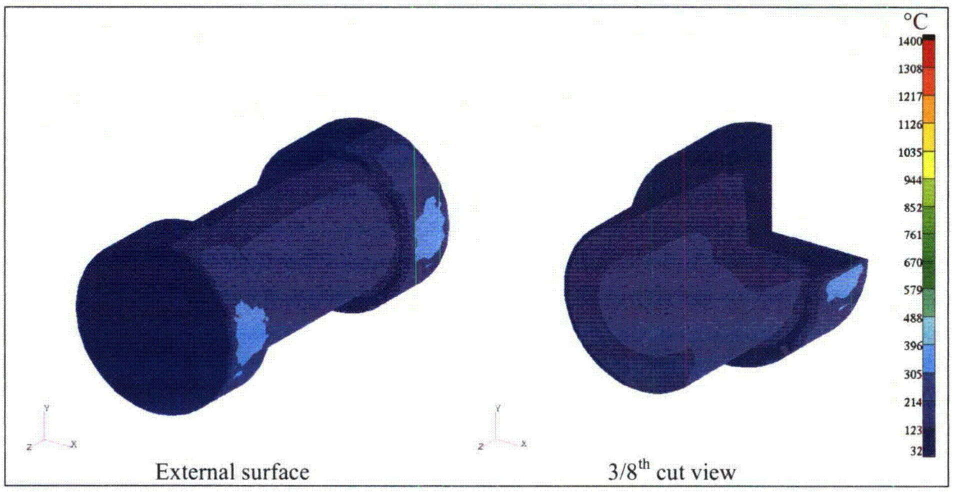


Figure 4-31. Temperature distribution of the Rail-Lead cask at the end of the 3-hour 18m offset CAFE fire - cask on ground

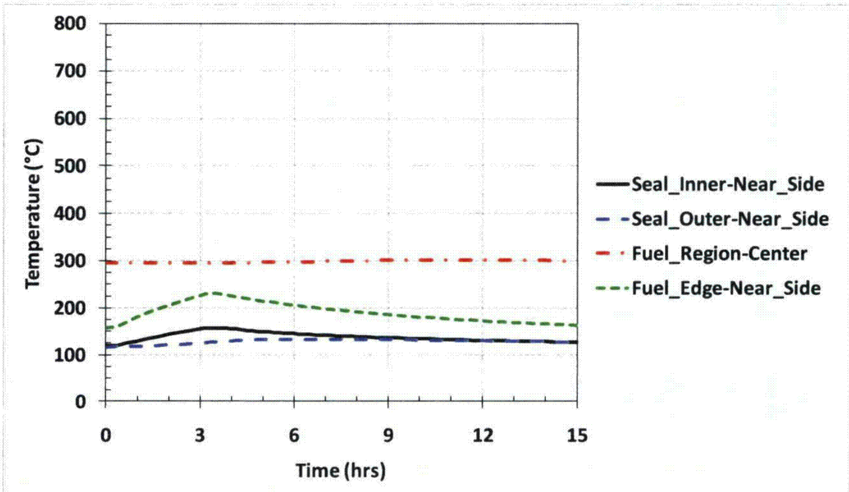


Figure 4-32. Temperature of key cask regions, Rail-Lead cask – Cask on ground, 18m offset fire

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. 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 buckled 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 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 0.5m (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 0.127m (5 inches), which translates to a 2% loss of shielding. These loss-of-shielding fractions are used as part of the work presented in Chapter 5 to estimate the consequences.

Comment [MF11]: Melting of the lead shield, appears to be very small, only 8.1% and 2%. These amounts cannot be checked - further details of these calculations should be provided so that they can be checked independently.

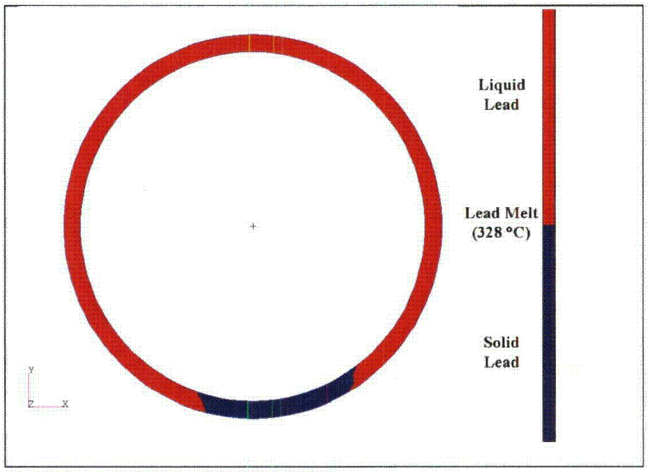


Figure 4-33. Rail-Lead cask lead gamma shield region - maximum lead melt at the middle of the cask – Scenario: Cask on ground, 3-hour concentric pool fire

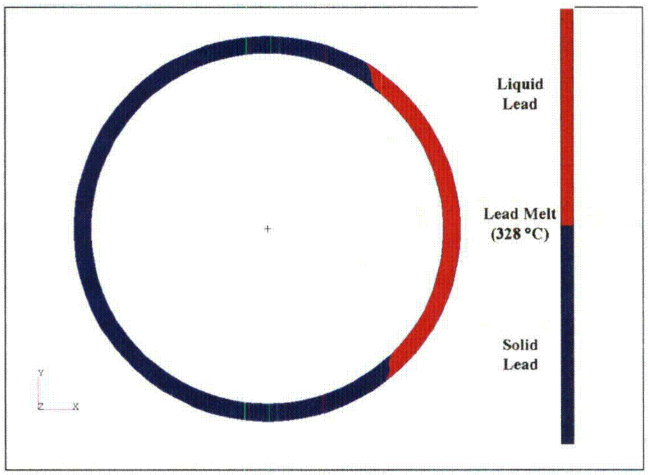


Figure 4-34. Rail-Lead cask lead gamma shield region - maximum lead melt at the middle of the cask – Scenario: Cask lying on ground, 3-hour 3-meter offset pool fire

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. 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 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 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 consideration 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.

Comment [XXX12]: Not sure what this sentence is trying to say. Is it that melting of DU is not considered (i.e. taken into account) in any of the analyses or is it that melting of the DU is not a concern based on the results of the analyses, or is it something else? Please reword for clarity.

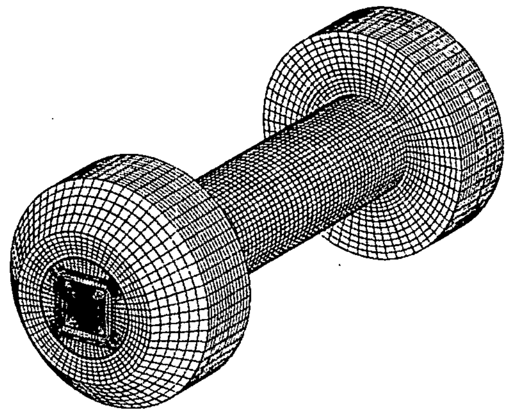


Figure 4-35. Finite element model of the Truck-DU cask

4.4.2. Simulation of the spent fuel region

As with the rail casks, the fuel region comprising the fuel basket and the fuel 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 fuel 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. 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 4-38 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.

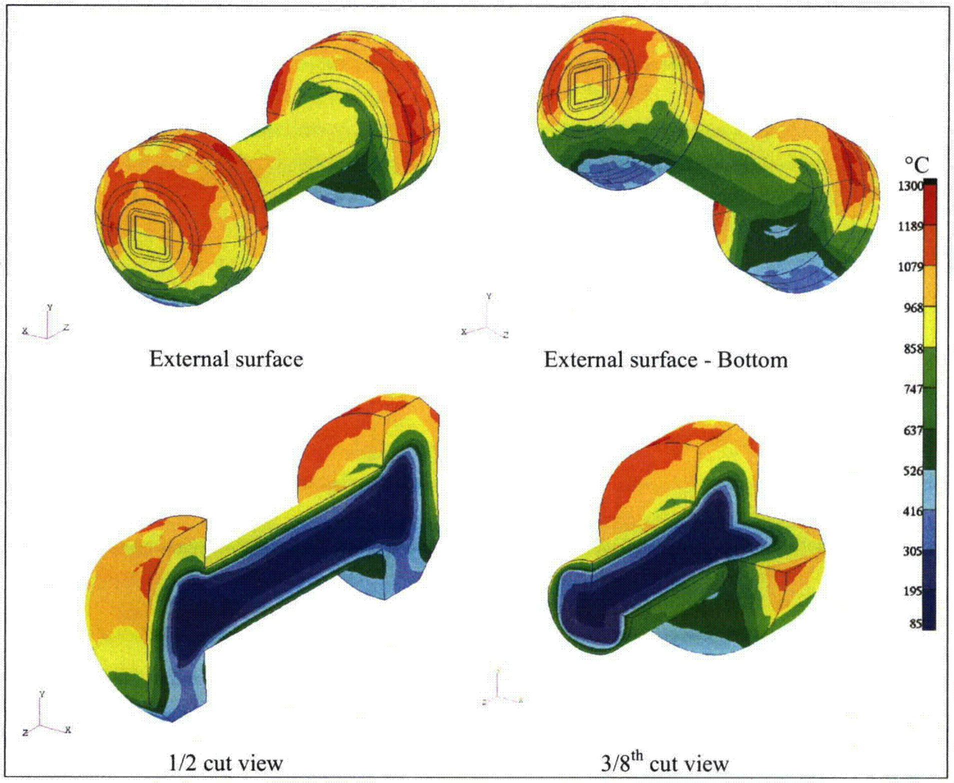


Figure 4-36. Temperature distribution of the Truck-DU cask at the end of the 1-hour concentric CAFE fire - cask on ground

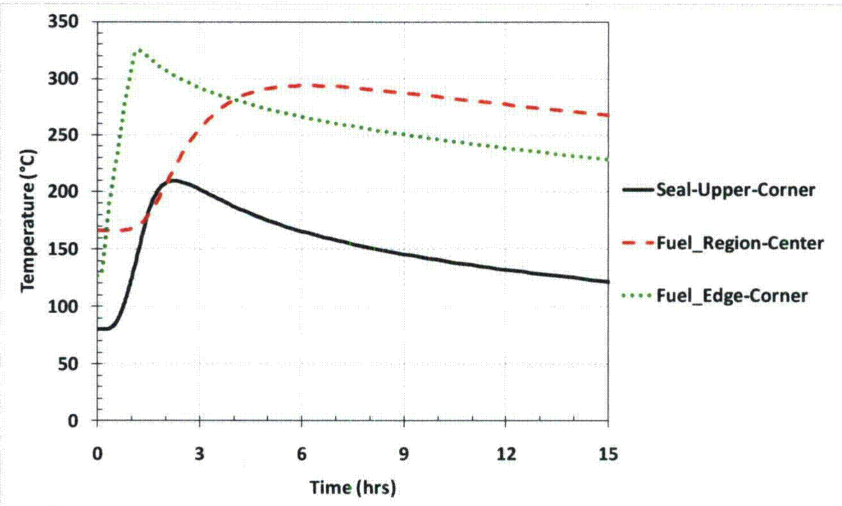
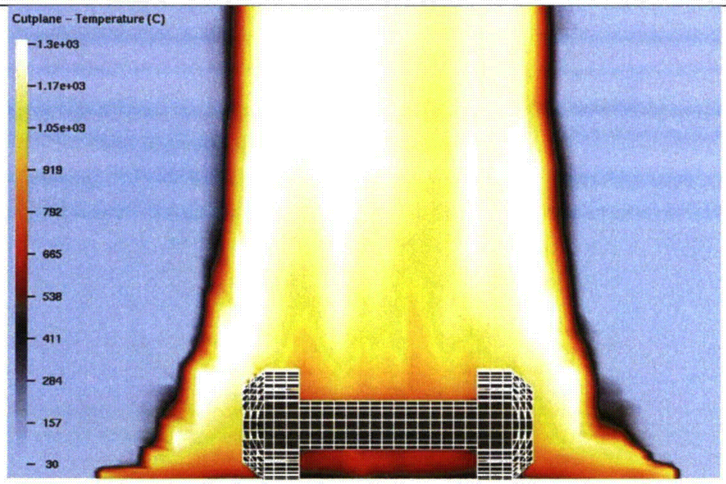
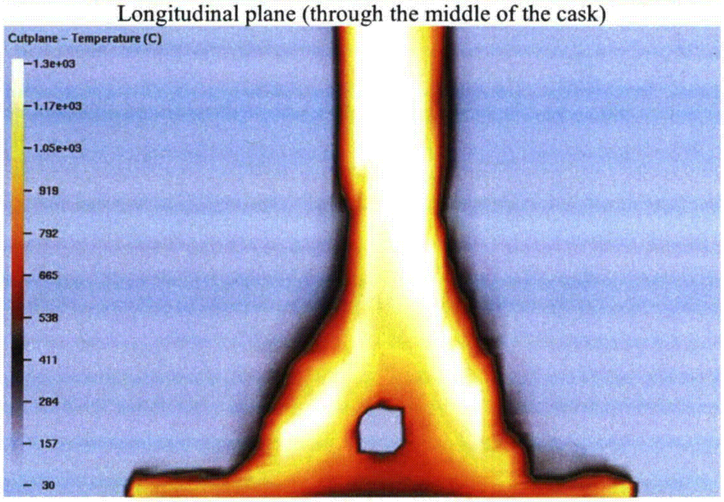


Figure 4-37. Temperature of key cask regions, Truck-DU cask – Cask on ground, concentric fire



Longitudinal plane (through the middle of the cask)



Transverse plane (at mid-length of the cask)

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

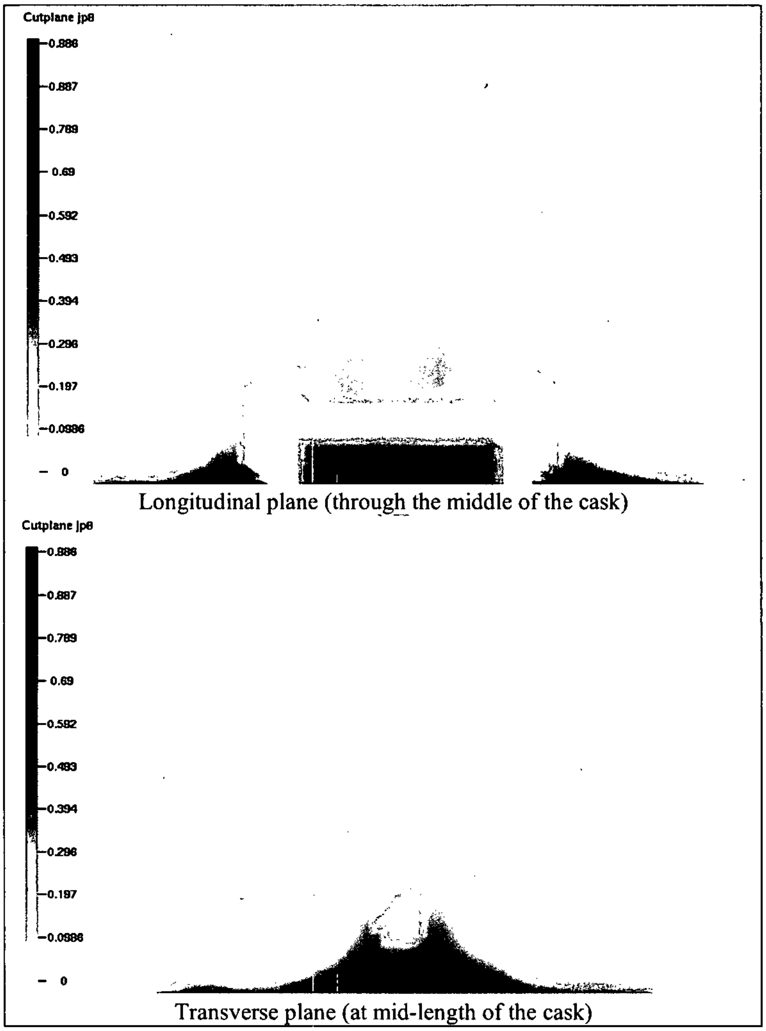


Figure 4-39. Fuel concentration plots - CAFE fire analysis of the Truck-DU cask lying on ground

Summary of Truck-DU cask analysis results

The results presented here show that the Truck-DU cask is capable of protecting the fuel rods from burst rupture and is also capable of maintaining containment when exposed to the severe fire environment analyzed in this study. That is, the fuel region stayed 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 hypothetical fire accident scenarios for rail casks. These are 1) a rail cask subjected to the regulatory fire described in 10 CFR 71.73, 2) a rail cask on the ground concentric with a fuel pool sufficiently large to engulf the cask, 3) a rail cask on the ground with a pool fire offset by the width of a rail car (3 meters), 4) and a rail cask on the ground with a pool fire offset by the length of a rail car (18 meters). These analyses are performed for the Rail-Steel and the Rail-Lead casks. 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 fuel 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. Additionally, the results of a realistic analysis of a hypothetical fire accident scenario were also presented. The results show the Truck-DU cask is able to maintain containment if it were to be exposed to a realistically maximum truck accident fire duration of about an hour. 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 all realistic fire accidents.

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