Proceedings of the 15th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

RECENT ASSESSMENTS IN THE U.S. OF SPENT FUEL PACKAGES EXPOSED TO SEVERE THERMAL ENVIRONMENTS DIFFERENT FROM REGULATORY STANDARDS

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ABSTRACT

The regulatory-driven design of radioactive material transportation packages leads package vendors to perform analyses that demonstrate the ability of packages to meet the regulatory requirements. For risk assessment and communication, the analysis of package response to thermal environments that are more severe than those described in the regulations is required. In general, experimental and analytical assessments of casks exposed to thermal insults other than the regulatory environment are performed in the U.S. by the Department of Energy national laboratories.

This paper provides a brief summary of some recent thermal analyses of spent fuel transportation packages exposed to thermal environments different from regulatory standards. The analyses were performed by Sandia National Laboratories under several different projects for multiple customers. These analyses examined the response of spent fuel packages exposed to severe thermal environments different from the regulatory hypothetical accident condition. One assessment determined the response of four generic casks to very long duration engulfing fires. The results from these analyses included fire durations necessary to reach critical temperatures of the fuel and seals. In another assessment, two certified spent fuel casks were analyzed for exposure to one-hour pool fires. The height of the cask above the pool was varied to study the effect of the vapor dome on the heating of the casks. Another assessment investigated the effect of offset long-duration fires on rail cask performance, which showed that casks can withstand offset fires of much longer duration than the regulatory fire. Other assessments examined the response of packages to thermal environments resulting from propane fires and realistic liquid hydrocarbon fires that included various positions of the transportation rail car in the simulation.

INTRODUCTION

Packages that are used for the transportation of radioactive materials are required to withstand the hypothetical accident conditions specified in 10CFR71.73 without release of their contents. For large packages, the hypothetical accident conditions consist of a 9m [30ft] free drop onto an essentially unyielding surface, a free drop of 1m [40in] onto a 15cm [6in] diameter puncture spike, exposure to a 30-minute fully-engulfing hydrocarbon fuel fire, and immersion in 15m [50ft] of water. The severity of the thermal environment is accentuated by the requirement that the fire be fully engulfing. This thermal environment is intended to envelop the severity of the vast majority of possible real accidents. While the thermal insult to a package from this environment is well defined, real world accidents (actual or postulated) are difficult to quantify. The joint probability of the necessary events that must happen in order to fully engulf a transportation cask by a long-duration fire after an accident is very low. Based upon accident statistics presented in the Modal Study (Fisher *et al.*, 1987) and by Clauss *et al.* (1994), only about 0.06% of all fires resulting from truck accidents and 0.5% of all fires resulting from rail accidents could meet these criteria. To achieve a fire as severe as the regulatory conditions, enough fuel must be supplied to a location with topography that allows for the formation of a pool just below the transportation cask and ignite. The other possibility is for fuel to flow under the cask at a rate that allows the formation a fuel film large enough to fully engulf the cask and be ignited. However, a permeable ground (dirt or gravel) will absorb the liquid fuel, which will limit the size and intensity of the fire. While it is difficult to obtain all the conditions of the hypothetical accident described in the regulations, real life accidents resulting in severe fires do occur. Halstead (1999) identified several historic accidents that had the potential to compromise a spent fuel transportation cask. But papers by Ammerman *et al.* (2003) and Lopez *et al.* (2005b) analyzed the mechanical and heat transfer response of spent nuclear fuel (SNF) casks to some of these historic accidents and concluded that the mechanical and thermal environments studied would not have failed a cask had it been involved in such or similar accidents. This paper provides a brief summary of thermal (heat transfer and fire) analyses performed by Sandia National Laboratories examining the response of spent fuel packages exposed to severe thermal environments different from the regulatory hypothetical accident condition. Temperature units are not reported consistently throughout this paper as they are reported as they appear in the referenced documents.

THERMAL ANALYSES IN NUREG/CR- 6672

In *Reexamination of Spent Fuel Shipment Risk Estimates*, NUREG/CR-6672 (Sprung *et al.*, 2000), cask response to thermal loads, specifically the times required to heat the cask seal to seal decomposition temperatures and spent fuel rods to burst rupture temperatures, were estimated by performing one-dimensional axisymmetric thermal analyses. The thermal analyses were performed on four generic casks and considered the neutron shield compartment and the decay heat load produced by the spent fuel in the cask. The analyses examined two fire environments, a 1000°C [1832°F] extra-regulatory fire environment and an 800°C [1475°F] regulatory fire environment. Both fires were assumed to be fully engulfing and optically dense. The heat transfer analyses were performed with the commercially available code MSC PATRAN/Thermal (MSC Software Corporation). Three-year cooled high burn-up spent fuel was used for the thermal calculations in contrast with the ten-year average burn-up fuel that will typically be transported in the casks of the design types considered. The conservatism introduced by this assumption is large. The results from these thermal analyses were used to estimate the dependence of cask leak areas on the heating times required for an engulfing hydrocarbon fuel fire to heat the cask to temperatures where elastomeric seals are seriously degraded (350°C [662°F]) or rods can fail by burst rupture (750°C [1382°F]).

Results Summary - Thermal Response to a Long Duration 800°C [1475°F] Fire

The regulatory requirements specify that thermal cask analysis be done with an 800°C [1475°F] fire. The response of the generic casks analyzed in NUREG/CR-6672 to an 800°C [1475°F] fire is presented in Table 1. This table lists the time required for the interior surface of each generic cask to rise to 350°C [662°F] and 750°C [1382°F] in the 800°C [1475°F] fire. Although the regulations stipulate a 30-minute fire, these analyses were extended to assess failure times of the seals and the fuel in order to estimate risks.

Table 1. Time (hours) required for the generic cask internal surface to get to two characteristic temperatures in a long duration engulfing, optically dense, 800°C [1475°F] fire.

Temperature (°C) [°F]	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
350 [662]	1.77	1.06	1.69	2.37
750 [1382]	4.88	5.07	6.32	>11

Results Summary - Thermal Response to a Long Duration 1000°C [1832°F] Fire

In addition to the regulatory 800°C [1475°F] fire environment analysis, the extra regulatory 1000°C [1832°F] fire environment was also considered. The temperature history of the interior surface of each of the four generic casks that were analyzed under these conditions is presented in Figure 1. Changes in the slopes of these temperature curves occur because of internal phase transitions in carbon steel (at 770°C) and depleted uranium (at 667°C and 775°C) and the melting of lead (at 327.5°C). Table 2 lists the time required for the interior surface of each generic cask to rise to 350°C [662°F], 750°C [1382°F], and 1000°C [1832°F] in a fully engulfing, optically dense, 1000°C [1832°F] fire. Note that, because of thermal lags, some cask temperatures would continue to rise if the fire went out at each of these times.

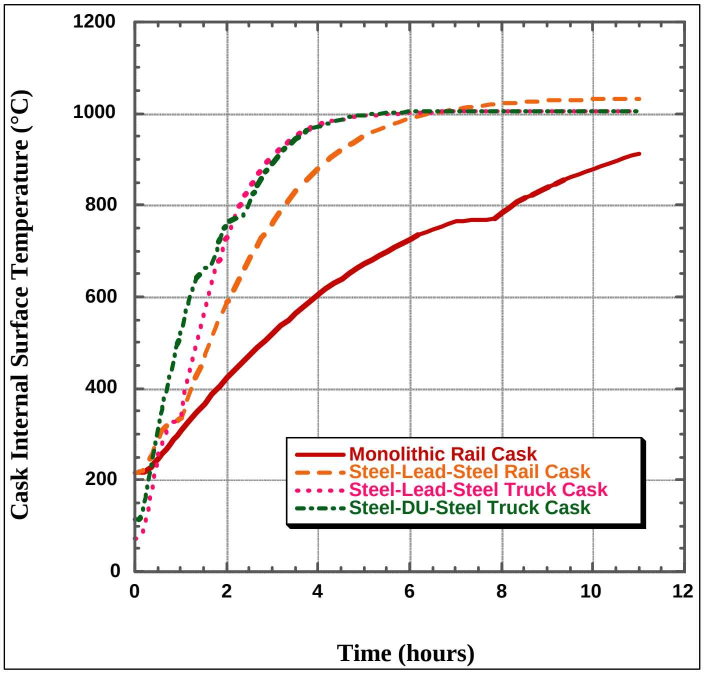


Figure 1. Internal surface temperature histories of the generic casks in a 1000°C [1832°F] long duration fire [°F=9/5*C+32].

The times required to reach the indicated temperatures at the inside surface of the inner shell, as shown in Figure 1, were used in Section 7.0 of NUREG/CR-6672 to estimate the probability of seal degradation and rod burst during cask exposure to long duration hydrocarbon fueled fires. The temperature of the inner surface of the cask body was used as an indicator of seal and rod response to heating in a fire for several reasons. First, inspection of the results of these calculations indicates that, when heated by a fire, temperatures in the lead or depleted uranium gamma shield are similar to, though usually 10 to 20°C [18 to 36°F] hotter than, the temperature of the cask's inner surface. Second, although seal location is dependent on cask design, seal well temperatures are also expected to closely track cask inner surface temperatures. Thus, because a somewhat low seal degradation temperature of 350°C [662°F] was chosen, the estimated time to reach seal degradation temperature is expected to be conservative. Moreover, inspection of the probability distributions for fire duration presented in NUREG/CR-6672, Tables 7.26 and 7.27, indicate that risk estimates will not be very sensitive to this choice. Through similar arguments, fuel rod bundle temperatures are also expected to closely track the temperature of the inside surface of the cask, although for "hot" fuel, the inner-fuel-assembly temperatures could be significantly higher. However, the assumption is made that this temperature should be a reasonable surrogate for average spent fuel rod temperatures.

Table 2. Time (hours) required for the generic cask internal surface to get to three characteristic temperatures in a long duration engulfing, optically dense, 1000°C [1832°F] fire.

Temperature (°C) [°F]	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
350 [662]	1.04	0.59	1.06	1.37
750 [1382]	2.09	1.96	2.91	6.57
1000 [1832]	5.55	5.32	6.43	>11

FIRE SIMULATIONS IN NUREG-1768

In *Package Performance Study Test Protocols*, NUREG-1768 (U.S. NRC, 2003), the U.S. Nuclear Regulatory Commission (NRC) examined the response of transportation casks to extreme transportation accident conditions. A summary of the thermal analyses that were performed for the test protocols that were published for public review are presented next.

A series of three-dimensional fire analyses were conducted with a reference rail cask (HI-STAR 100) and a reference truck cask (GA-4). The FEA code MSC PATRAN/Thermal was used to capture the heat transfer response of the casks and it was coupled with the Container Analysis Fire Environment (CAFE) CFD fire code (Suo-Anttila *et al.*, 1999, Lopez *et al.*, 2003, and Suo-Anttila *et al.*, 2005), which simulates fires in a realistic manner. Three cases were investigated for the rail cask to better understand the effect of the vapor dome on heat transfer from the fire to the cask and to estimate the height above the fuel pool surface at which the package should be placed so that it is outside of the vapor dome and receives a nearly uniform heat flux from the fire envelope. The vapor dome is the region in the middle of the fire, just above the fuel pool, which contains vaporized fuel that cannot burn due to the lack of oxygen.

The heights of the rail cask above the fuel pool surface were 1.3m (Case 1), 0.3m (Case 2), and 3.3m (Case 3). The position of the cask in Case 1 is approximately the location stipulated in the regulations (e.g., 10CFR71.73), Case 2 represents the cask laying on the ground after an accident, and Case 3 was included to demonstrate the height necessary to position the cask just above the vapor dome. Figure 2 shows two-dimensional snapshots of the CAFE fires for these three elevations. In these views, the cask is represented by the void area in the middle of the fire. The effect of package placement in the fire is clearly demonstrated in this figure. For example, in Cases 1 and 2 about half of the cask is within the vapor dome region whereas in Case 3 the cask seems to be mostly outside the vapor dome. Even though the plots in Figure 2 are temperature plots and not fuel concentration plots, the vapor dome can be roughly identified by the darker (cooler) region that is below and next to the cask, which has a temperature of about 750K [890°F].

For the truck cask, only a 1.0m above-the-pool simulation was performed. A three dimensional view of this simulation is shown in Figure 3. In each case, the casks were fully engulfed by a simulated fire. In each simulation, the fire engulfed the package for one hour and quiescent (no wind) conditions were assumed for the duration of the simulation. Analysis of the simulation results show that, in order to expose the package to a relatively uniform heat flux around its circumference, the package needs to be placed high enough so that it lies above the fuel vapor dome of the fire. In a real accident, it would be nearly impossible for a rail cask to end up suspended three meters [9.8ft] above a fuel pool. Therefore, when a cask is analyzed assuming a thermal environment that heats it uniformly, the cask is analyzed in a thermal environment that may be more severe than if it were exposed to a real fire in a realistic post-accident setup.

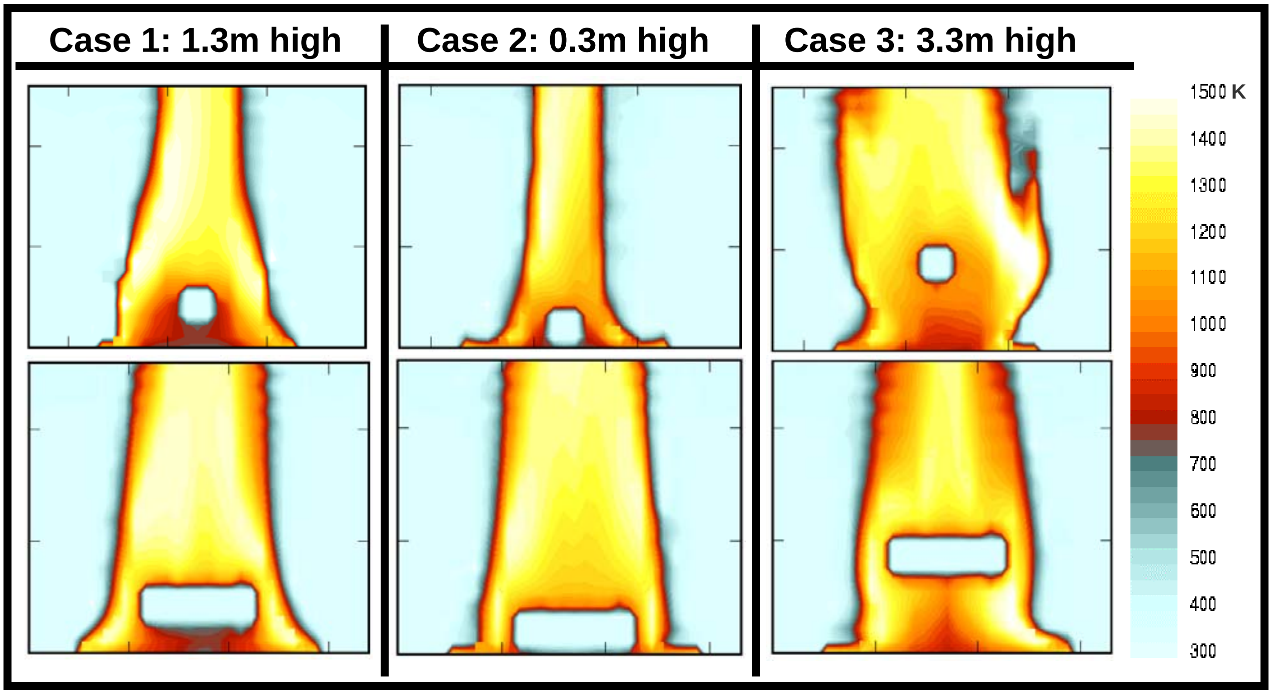


Figure 2. Two-dimensional views of CAFE-3D fires for Cases 1, 2, and 3 [°C=K-273; °F=9/5*K-460].

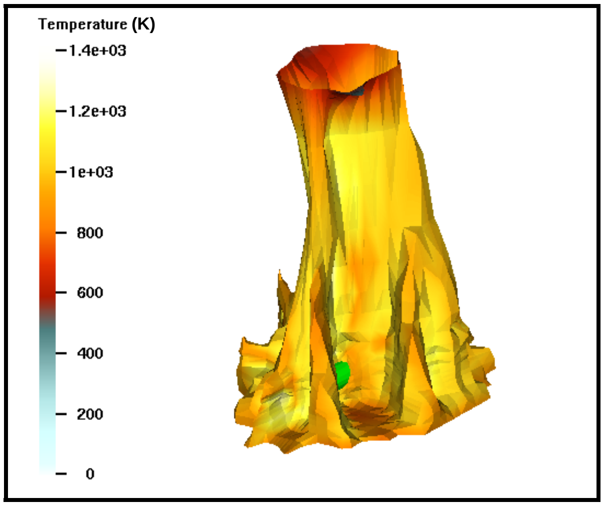


Figure 3. Three-dimensional view of CAFE fire engulfing the GA-4 truck cask [°C=K-273; °F=9/5*K-460].

OFFSET FIRES

In a study by Khalil *et al.* (2005), a rail cask was placed on the ground at different locations relative to the center of the fire. The CAFE-3D and PATRAN/Thermal computer codes were used to assess the effects on the cask of long duration fires that do not fully engulf the cask. The purpose of these analyses was to estimate the time that it takes to heat important regions of a transportation cask (seal and fuel) to temperatures of concern when the cask is exposed to several configurations of sub-regulatory size fires. An intact rail cask was used for this study, including both the impact limiters and the neutron shield. Results are presented in a format useful to risk analysts.

Three different pool fire shapes were simulated: a 1m [3.28ft] wide by 10m [32.8ft] long (1x10), 4m [13ft] wide by 10m [32.8ft] long (4x10), and 6m [19.7ft] wide by 10m [32.8ft] long (6x10). The cask model was first placed with its center above the center of the pool fire (concentric), and then the cask was moved away from the center of the fire along the radial direction of the cask model. The distance of the cask center from the center of the pool was increased in increments of two meters [6.6ft] (Xoffset = 2m [6.6ft], 4m [13.1ft], and 6m [19.7ft], where Xoffset is the distance between the center of the pool and the center of the cask) until the temperature of the modeled fuel inside the cask did not reach the temperature of concern for fuel rods. The 6x10 fire engulfed the cask in the concentric position which makes this case similar to a fully engulfing regulatory pool fire. The cask was placed on the ground for all fire scenarios. The fires were assumed to last ten hours. The fire locations were chosen to approximate a wide spectrum of possible fires.

The temperature history of the hottest fuel rod zone for each fire scenario is presented in Figure 4. The temperature of concern for the fuel region was conservatively assumed to be 700°C (973K) [1292°F]. This plot shows that the fire scenarios where fuel rods reached the temperature of concern first were with the center of the 4x10 and 6x10 fire being two meters [6.6ft] away from the center of the cask (2m [6.6ft] offset). Note that, because the offset between the cask and the fire is reported as a center-to-center distance, the actual separation between the side of the cask and the edge of the fire is less than the specified offset distance. A possible explanation of this behavior could be related to the vapor dome of the fire. The vapor dome, the region where insufficient oxygen limits combustion, surrounds more of the cask in the concentric fire than in the 2m [6.6ft] offset fire. Note that for a regulatory pool fire configuration, the cask is located 1 m above the fire surface, and the vapor dome effect would be smaller than in the concentric case discussed here. Figure 4 also suggests that, for some of the fire scenarios studied, the fuel rods will not reach the temperature of concern regardless of fire duration.

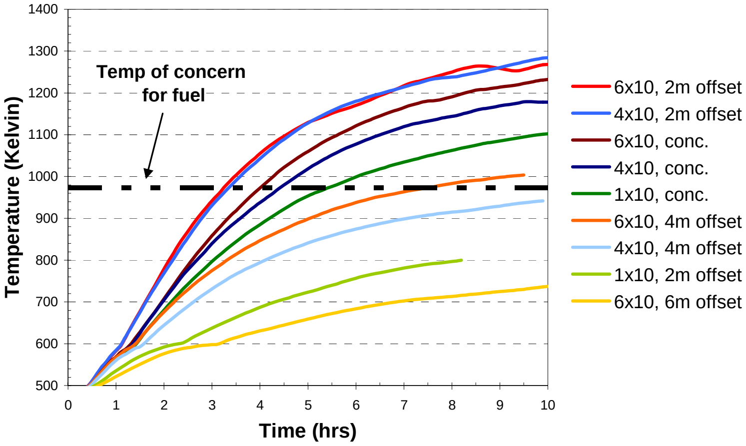


Figure 4. Temperature history for the fuel region [°C=K-273; °F=9/5*K-460; ft=m*3.28].

The temperature history of the hottest zone in the seal region for each fire scenario is presented in Figure 5. In this study, the temperature of concern for the seal (typically an elastomeric O-ring) was assumed to be 350°C (623K) [662°F]. The seal was not modeled. Instead, the temperature response of the region where a seal would be located was examined. The cask model included the impact limiters, which typically insulate the seal region. In the worst cases calculated, the seal region temperatures exceed the temperature of concern in one to two hours. However, seal failure may not be a concern until fuel rods burst at time scales like those shown in Figure 4.

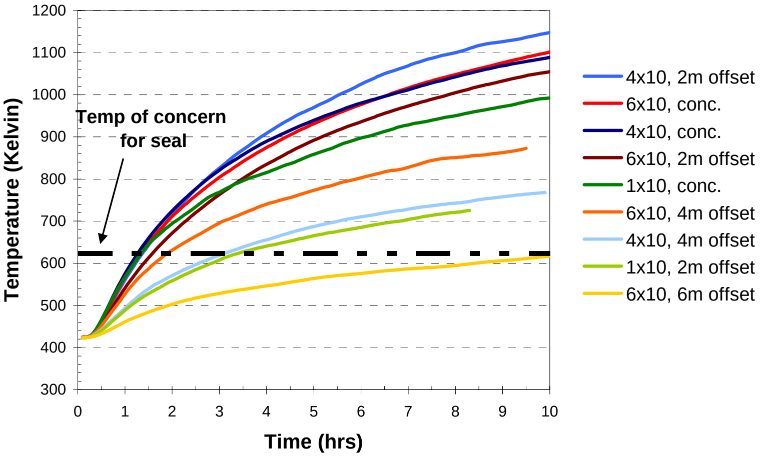


Figure 5. Temperature history for the seal region [°C=K-273; °F=9/5*K-460; ft=m*3.28].

It is clear that in all cases fuel rods did not reach the temperature of concern until after 3 hours of exposure to the fire. However, statistics for fire duration distributions for truck/train pool fires with diameters of 7.6m [25ft] or less, like those that were developed by Clauss and Blower (1999), show that typically the duration of a fire following an accident will not be more than two hours. In addition, the results for some of the fire scenarios presented in this paper show that the fuel rods will not reach the temperature of concern regardless of fire duration when the cask is placed just a few meters away from the fire.

REALISTIC FIRE ACCIDENT SCENARIOS

In a study by Lopez *et al.* (2006), various three-dimensional fire calculations were performed with the CAFE fire code to determine the heat transfer response of a generic SNF rail cask to a realistic accident scenario and four possible variations of this scenario. The most severe of all the cases studied was one where a pool fire was set next to the cask and wind blew the hot flames onto the cask. However, results showed that the robust nature of the SNF rail cask provided enough thermal resistance to withstand such a fire and thus protect the environment from any release.

Description of the scenarios analyzed

For the analyses, it was assumed that an accident occurred in which a train carrying a spent nuclear fuel cask derailed and the car carrying the cask overturned in such a way that the cask ended up lying on the ground still attached to the railcar by the tiedowns. Five different variations of this basic accident scenario description were considered for analysis. A description of each case is provided next. For each case, the assumption was made that there is enough liquid fuel present to form a 5m [16.4ft] by 10m [32.8ft] pool and burn for an hour. Only the position of the fuel pool relative to the cask and the wind conditions were varied from case to case.

Case 1: Pool Fire Next to the Cask Car Bed, 5 m/s [11mph] Wind - In this case, the pool fire was assumed to be next to the rail car in such a way that the car bed shielded the cask from the hot flames. A 5 m/s [11 mph] wind leaning the fire onto the cask car was also assumed.

Case 2: Pool Fire Next to the Cask, 5 m/s [11mph] Wind - In this case, the pool fire was assumed to be next to the cask and a 5 m/s wind leaned the fire onto the cask. Here, the car bed helped trap the heat from the fire in the vicinity of the cask and enhanced the heating.

Case 3: Pool Fire Under the Cask, 5m/s [11mph] Wind - In this case, the pool fire was assumed to be under the cask. A 5 m/s wind that helped trap hot gases from the fire between the cask and the car bed was also assumed. In this case, the car bed also helped to maintain the flames near the cask.

Case 4: Pool Fire Next to the Cask, No Wind - Similar to Case 2, the pool fire was assumed to be next to the cask. However, calm (no wind) conditions were assumed. In this case, the car bed had little effect on the heating of the cask.

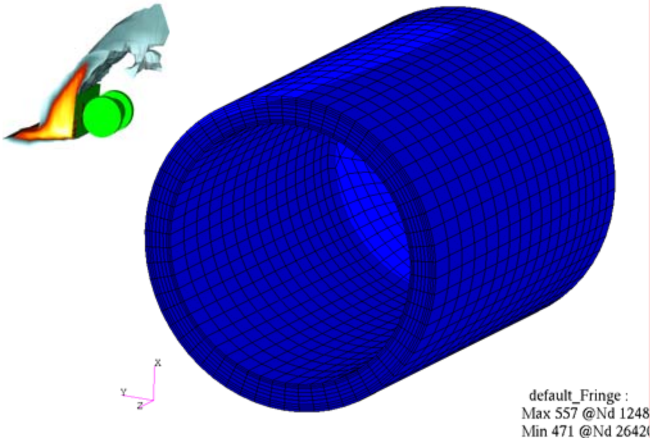
Case 5: Pool Fire Under the Cask, No Wind - Similar to Case 3, the pool fire was assumed to be under the cask. However, calm (no wind) conditions were assumed. The car bed helped to maintain the flames near the cask.

Results Summary

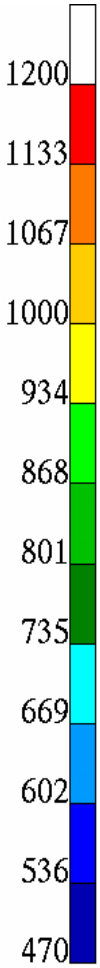
Before transient fire calculations were performed, the steady state temperature distribution of the generic package was calculated by simulating the normal conditions of transport specified in the regulations (10CFR71.71). The steady state solution was used as the initial condition for all five transient cases that were studied. Temperature distributions of only the cask wall after the cask was exposed to the five different one hour fires are presented in Figure 6. These fringe plots show the temperature contours of half of the cask wall. The cask internals were not included in the fringe plots to illustrate the gradient through the wall better. In the transient analyses, the change in temperature was tracked at the following locations: the seal region of the cask, the inner wall at the center of the cask, the outer wall at the center of the cask, and the hottest region on both faces of the rail car bed. For each cask region, eight locations were monitored and the hottest temperature of each region was plotted to observe the relative severity between the cases that were studied. The data generated in these simulations suggest the following:

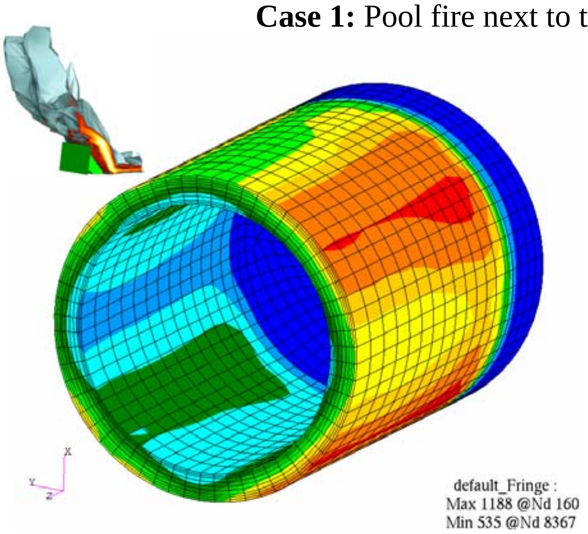
- The rail car bed provided significant protection in Case 1 and the cask did not heat up appreciably.
- Comparing Case 1 with Case 2, the rail car bed heated to similar temperatures but the cask heated much less in Case 1.
- Comparing Case 2 with Case 4,
    - the cask inner and outer wall temperatures raised much more in Case 2.
    - the cask car also heated much more in Case 2.
    - the temperature of the center of the fuel region just started to rise at the end of the one hour run.
- Comparing Case 3 with Case 5,
    - Case 5 was a more severe case.
    - lead melt occurred after 41 minutes in Case 3 and after 33 minutes in Case 5.
- In Case 5, the temperature of the outer surface of the cask tracked the temperature of the cask railcar better than in any of the other cases.
- Even though Cases 2 and 4 are analogous to Cases 3 and 5 (same pool location, but one with wind and one without), the difference in the temperature response between Cases 2 and 4 is much greater than the difference between Cases 3 and 5.

Since the cask used for the analyses presented in this paper was a generic cask with only approximate and generic dimension, the times to reach certain threshold temperatures in any given region should not be used to make specific conclusions about any currently certified steel-lead-steel SNF rail cask. However, the comparison of relative severity of one case versus another is a much better and appropriate use of the data presented here. Therefore, one can conclude that the Case 2 was definitively the worst case of all. When comparing the one-hour results of this case with those presented by Lopez, *et al.* (2005b), both studies showed a very similar seal response. On the other hand, the inner temperature response in Case 2 of this paper was more accelerated and resulted in higher <u>localized</u> internal cask temperature than that in the paper mentioned above. However, when the temperature of all monitored locations at the inner wall are averaged, the 8m by 10m fully-engulfing fire in Lopez, *et al.* (2005b) predicted a slightly higher temperature than Case 2 of this paper (741K [874°F] versus 726K 847°F]). Note that while the inner wall temperatures of the cask increased by about 300 Kelvin [80°F], the spent fuel roads stayed below the rod burst temperature specified by Sprung *et al.* (2000).

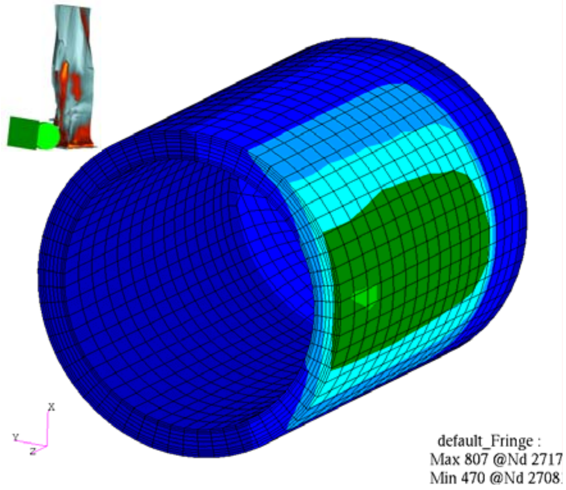


Case 1: Pool fire next to the cask car bed, 5m/s wind

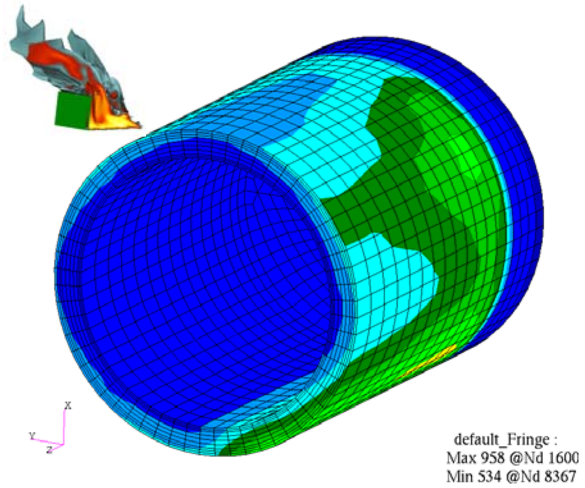




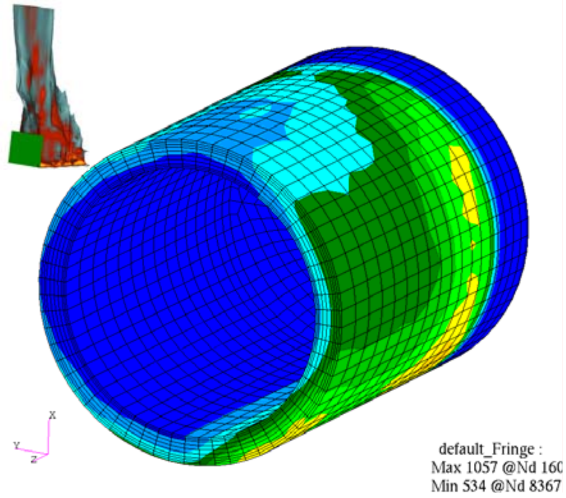
Case 2: Pool fire next to the cask, 5m/s wind



Case 4: Pool fire next to the cask, no wind



Case 3: Pool fire under the cask, 5m/s wind



Case 5: Pool fire under the cask, no wind

Figure 6. Cask temperature distribution for Cases 1-5 at one hour. Temperature scale is for the cask only and not for the smaller fire thumbnails depicting each case configuration. Temperatures are in Kelvin [°C=K-273; °F=9/5*K-460].

Because the spent fuel rods are not expected to burst and the seal temperature for any of the cases studied was below seal failure temperatures, no radioactive release is expected from any of the studied scenarios. Overall, these results demonstrate that the requirements placed on spent fuel transportation casks by the NRC result in designs that can withstand very severe “real world” accidents.

DEFLAGRATION FROM THE RUPTURE OF A PROPANE/BUTANE TANKER

For the simulation of this accident type, Lopez, *et al.* (2005b) assumed that a long tear with a cross-sectional area of 2.4 m^2 formed in a rail tank car. A mass flux rate of 50 kg/m^2-s [10.2 lbs/ft^2-s] of liquid propane (which burns similar to butane) at a temperature of 150 K (-190° F) was used. For the purpose of the paper, this constant rate was assumed to last for 10 seconds and the propane was assumed to immediately vaporize and ignite once it came out of the tank. The simulation depicted in Figure 7 shows the fireball forming rapidly and burning during the 10-second discharge. The fire ball dispersed within 10 seconds after the propane discharge was complete. For this scenario, it was assumed that the cask is located relatively close to the propane tank and that it is deep within the vapor dome during the discharge phase. Being within the vapor dome limits the heating effect due to lower temperatures caused by lack of oxygen.

During this simulation, the temperature at the seal location and cask inner wall did not rise in an appreciable manner. This cask behavior is expected because, even if the fire were to burn at the hottest possible (stoichiometric) temperature, the time of exposure of the cask to that type of thermal environment would simply be too short relative to its thermal mass to significantly heat the seal or the cask internals. The short time of exposure is estimated after a large propane tanker rupture because propane will vaporize rapidly even at room temperature regardless of the amount of propane in the tank as long as the hole is large enough to prevent substantial pressure from building up in the tanker. An additional simulation assuming the fuel did not ignite until after it was dispersed was also performed. Results from this simulation were almost identical to those from the case presented above (no significant heating of inner components).

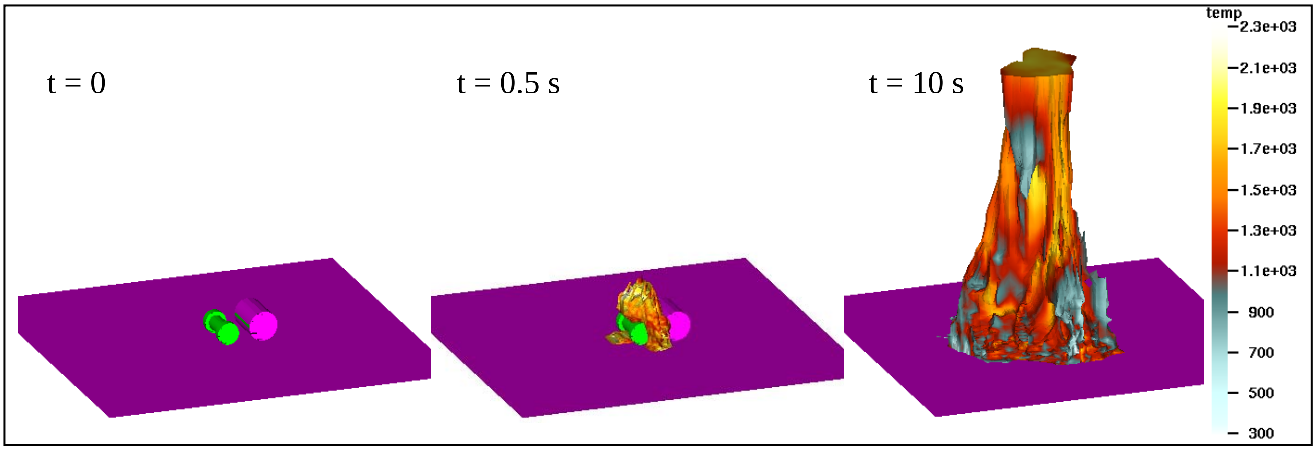


Figure 7. First 10 seconds of the tanker fire simulation. The cask is the green object and the tank is the pink object. Temperature scale is in Kelvin [°C=K-273; °F=9/5*K-460].

Analyses from the report clearly showed that gas fires resulting from a propane or butane tanker deflagration are not a threat to spent fuel casks because of their short duration.

PIPELINE FIRES

A study by Lopez *et al.* (2001) examined fire environments that could occur in rail accidents involving typical casks and to determine whether rod burst and/or seal failure represent a problem under such occurrences. The method used to address these issues was a detailed three-dimensional finite-element computer simulation of torch and engulfing fire environments. The results were intended to provide details and information in a form that would be a useful reference for future risk-based studies of these accidents.

The transportation cask that was studied has the overall dimensions of a typical legal-weight truck cask. Four different kinds of accidents were modeled for this study. These were: 1) a fire jet impinging at the center of the cask, 2) a fire jet impinging at the seal end of the cask (without impact limiter) from the side, 3) a vertical flare radiating to the side of the cask from about ten meters [32.8ft] away, and 4) a fully engulfing fire (for comparison). All fire scenarios were modeled assuming different fire temperatures to cover a wide range of fires that could be found in these accidents.

The results from Case 1 indicate that rod burst could be a problem after 2 hours and 20 minutes if the fire jet has a temperature of about 1200°C [2192°F], after an hour and 30 minutes if the fire jet has a temperature of about 1400°C [2552°F], and after an hour for a fire jet temperature of about 1600°C [2912°F]. However, in this case the seals do not fail so the spent fuel released to the cask cavity from the burst rupture is contained in the cask. The results from Case 2 indicate that seal failure could occur. However, because there is no rod failure, no significant release is expected. Without rod failure, the only radioactive material that can be released is CRUD. CRUD can only be released to the environment if the internal cavity of the cask is pressurized due to heating before seal failure. The results from Case 4 indicate that rod burst could occur after 7 hours if the fully engulfing fire has a temperature of about 800°C [1475°F], after 3 hours and 20 minutes if the fire has a temperature of about 1000°C [1832°F], and after 2 hours for a fire temperature of about 1200°C [2192°F]. In this case rod burst rupture is a potential problem because the seal has already failed and some of the spent fuel released from burst rupture will be swept out of the cask in the depressurization of the rods. Neither seal failure nor rod burst occurred in Case 3 during the simulated ten-hour fire.

CONCLUSIONS

Regulations and standards exist to ensure safety in spent nuclear fuel transport. However, test conditions specified in regulations and standards are not always perceived to be bounding for all transportation accidents. Often times, after a very severe accident occurs, concerned citizens question if a certified SNF transportation package would survive such environments. The analyses and efforts that were summarized in this paper are only a few of the very many efforts in the U.S. that intend to answer some of these questions and educate, through the use of scientific methods, people interested in getting a realistic assessment of real life accidents. With increased computer power and new computer code developments, engineers can examine different accident scenarios with realistic modeling to assess the performance of SNF packages if exposed to severe real life accidents. Often times, analyses reveal that accident scenarios that seem to be more severe than the regulatory requirements really are not; as was demonstrated in some of the analyses presented in this paper. This is corroborated by numerous analyses (not discussed in this paper) of other severe (real or postulated) accidents such as those involving fire in tunnels (Adkins *et al.*, 2006 & 2007, and Lopez, *et al.*, 2005) that also show the ability of SNF transportation casks to withstand fire environments that are severe but different from the regulatory environment. These works demonstrate that the requirements placed on spent fuel transportation casks result in designs that can withstand very severe “real world” accidents.

ACKNOWLEDGMENTS

The works presented in this paper were sponsored in recent years by the U.S. NRC and the U.S. DOE.

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[*] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.