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SPENT FUEL TRANSPORTATION RISK ASSESSMENT: CASK FIRE ANALYSES

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ABSTRACT

The NRC has recently completed an updated Spent Fuel Transportation Risk Assessment, NUREG-2125[1]. This assessment considered the response of three certified casks to a range of fire accidents in order to determine whether or not they would lose their ability to contain the spent fuel or maintain effective shielding. The casks consisted of a lead shielded rail cask that can be transported either with or without an inner welded canister, an all-steel rail cask that is transported with an inner welded canister, and a DU shielded truck cask that is transported with directly loaded fuel. For the two rail casks, large pool fires that were concentric (fully engulfing), offset from the casks by 3 meters, and offset from the cask by 18 meters were analyzed using the Computational Fluid Dynamics CAFE-3D fire modeling code coupled with the Finite Element Analysis PATRAN-Thermal heat transfer code. All of the fires were assumed to last for three hours. In addition to these extra-regulatory fires, the regulatory 30-minute fire was analyzed using both the regulatory uniform 800 degrees C boundary condition and the more realistic CAFE-3D fire modeling code. For the truck cask, only the engulfing fire case was analyzed, using a one-hour fire duration. In all of the fire analyses the seal region of the cask stayed below the failure temperature: therefor there would be no release of radioactive material. Also, the temperature of the fuel rods stayed below their burst-rupture temperature, providing another barrier to release. For the lead shielded cask, very severe fires cause some of the lead to melt. There is no leak path for this molten lead to exit the shield region, but its expansion during the melting and subsequent contraction due to solidification during cool-down results in a reduction in gamma shielding effectiveness.

INTRODUCTION

Certified Type B casks are designed to withstand a fully-engulfing fire for 30 minutes while maintaining critical functions, including protecting the public from doses of radiation exceeding regulatory limits. Certification analyses of the hypothetical accident condition (HAC) fire

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specified in 10 CFR 71.73, "Hypothetical Accident Conditions," generally impose a thermal environment on the cask similar to or more severe than most thermal environments a cask may be exposed to in actual transportation accidents involving a fire[2]. Large open-pool fires can burn at temperatures higher than the average temperature of 800 degrees Celsius (C) (1,475 degrees Fahrenheit (F)) specified in HAC fire regulations. Actual fire plumes have location- and time-varying temperature distributions that vary from about 600 degrees C (1,112 degrees F) to more than 1,200 degrees C (2,192 degrees F)[3,4]. Therefore, an evenly-applied 800 degrees C (1,475 degrees F) fire environment used in a certification analyses applies a similar heating as an actual fire.

NUREG-2125 used computer codes capable of modeling both fire behavior and the thermal responses of objects engulfed in those fires in a realistic way to analyze the response of the Rail-Steel and the Rail-Lead casks to three different fire configurations. This paper describes these configurations and discusses the casks' temperature responses. 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: the rated seal temperature (350 degrees C (662 degrees F) for elastomeric seals used in the Rail-Lead cask and the Truck-DU cask and 649 degrees C (1,200 degrees F) for the metallic seal used in the Rail-Steel cask) and the fuel rod burst rupture temperature (750 degrees C (1,382 degrees F) for all casks[5]). These temperature limit values are the same as those used in NUREG/CR-6672[6] 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[7]. Section 7.2.5.2 in NUREG/CR-6672 explains that 350 degrees C (662 degrees F) is a conservative temperature limit the SNF transportation industry typically uses for elastomeric seals. Section 7.2.5.2 of NUREG/CR-6672 also provides the rationale for the use of 750 degrees C (1,382 degrees F) 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 under any of the accident scenarios analyzed. If only the seals are compromised, a CRUD-only release would result. If the fuel rods and seals are both compromised, a release of CRUD and spent fuel constituents would ensue. In either case, the consequences of the release would have to be evaluated. In addition, other thermally induced phenomena that could cause a degradation of the package are considered. These include the melting of lead in the Rail-Lead cask, solid/solid phase changes in the uranium in the DU-Truck casks, and rapid oxidation of the stainless steel in all of the casks.

DESCRIPTION OF ACCIDENT SCENARIOS

Pool Size

Three fire accident scenarios were 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 1 and 3 meters (3.3 and 10 feet) horizontally beyond the external surface of a cask. To ensure that the fire fully engulfed the large casks analyzed in this study, all fuel pools extended 3 meters (10 feet) from the sides of the cask.

Fire Duration

The fire duration 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 113,562 liters (30,000 gallons) of flammable or combustible liquids (i.e., hydrocarbon-based liquids). To estimate the duration of the fires, all of 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 analyzed. That is, fuel pools extending horizontally 3 meters (10 feet) beyond the surfaces of the casks are used in the fire models. Provided that relatively small differences exist 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 feet×29.5 feet). A pool of this size would have to be 0.9 meters (3 feet) deep to pool 113,562 liters (30,000 gallons) of liquid fuel, a condition extremely unlikely to occur in any accident scenario. If all of the fuel in this pool were to ignite and burn (i.e., none of the fuel runs off or soaks into the ground), the pool fire would burn for approximately 3 hours. This fire duration is estimated using a nominal hydrocarbon fuel recession (evaporation) rate of 5 mm (0.2 inches) per minute, which is typical of large pool fires[4,8,9]. This large pool area could also burn for up to 3 hours—although it would be even less likely—if the liquid fuel flows at exactly the right rate to feed and maintain the pool area for the duration of the fire. Since these pooling conditions are very difficult to obtain, the fire duration presented here is considered conservative. NUREG/CR-7034[10] corroborates that it is very difficult for a rail cask to be subjected to long duration, large fires. Nonetheless, a 3-hour fire that does not move 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 in this study.

In the case of the Truck-DU cask, fire duration is based on the fuel capacity of a typical petroleum tank truck. One of these tank trucks can transport approximately 34,070 liters (9,000 gallons) of gasoline on the road. Provided that the overall dimensions of the Truck-DU cask are 2.3 meters×6 meters (7.5 feet×19.7 feet), a regulatory pool that extends horizontally 3 meters (10 feet) beyond the outer surface of the cask would be 8.3 meters×12 meters (27.2 feet×39.4 feet). To pool 34,070 liters (9,000 gallons) of gasoline in this area, the pool would have to be 0.3 meter (1 foot) deep, a configuration difficult to obtain in an accident scenario and therefore unlikely to occur. This type of pool fire would burn for a little more than 1 hour. As discussed for the rail cask pool fire, the other possibility of maintaining an engulfing fire which can burn for that duration is if, for example, gasoline flowed at the right rate to maintain the necessary fuel pool conditions. This scenario is also very unlikely. NUREG/CR-7035[11] corroborates the assertion that it is very difficult for a truck cask to be subjected to long duration, large fires. Nevertheless, 1 hour is used as the duration of a fire not moving over time for the conservative analysis of the Truck-DU cask.

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 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.

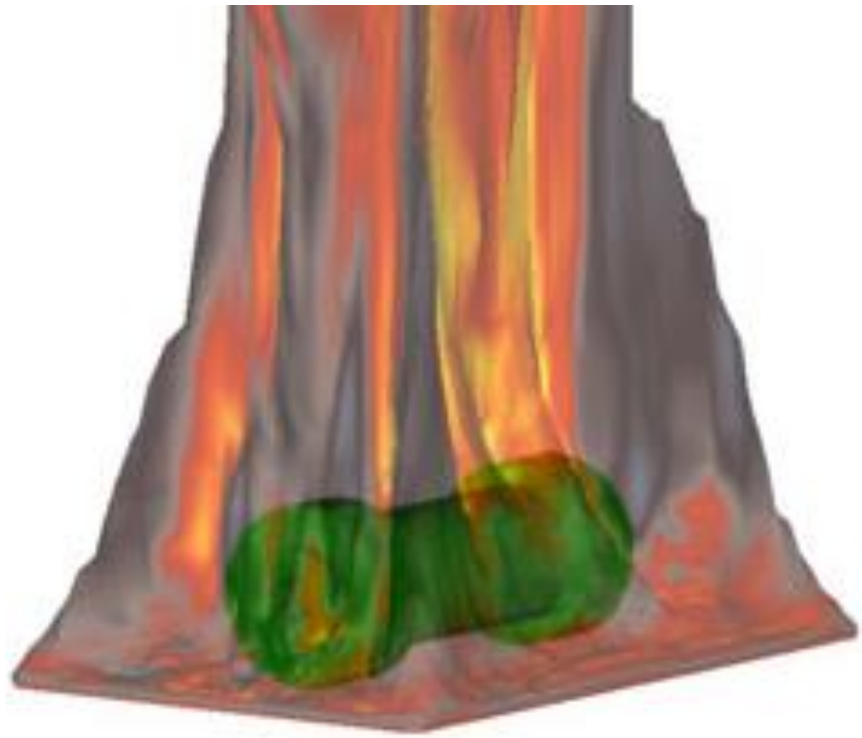

Figure 1. Cask lying on ground concentric with the fuel pool, the transparency of the flames has been increased so the cask can be seen; in the actual fire simulation, and in a real fire, the flames are opaque

(2) Cask lying on the ground 3 meters (10 feet) away from the pool of flammable liquid (with the side of the cask aligned with the long side of the fuel pool). 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) (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 long side of the fuel pool). 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, which is always required when radioactive and flammable/hazardous liquids are transported on the same train) after the accident. For this scenario, the most damaging cask position is assumed (i.e., the side of the cask is assumed to face the 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 or protect the cask from the fire (i.e., such as the conveyance or other rail cars) are not included. All analyses include decay heat from the cask content.

For the truck cask only the concentric fire scenario was analyzed.

ANALYSIS OF FIRE SCENARIOS

Computer Models

Advanced computational tools generated the data necessary for this risk study. Heat transfer from the fire to the cask body was simulated for hypothetical fire accidents. Two computer codes, including all the relevant heat transfer and fire physics, were used in a coupled manner. This allows for the simultaneous detailed modeling of realistic external fire environments and heat transfer within the cask's complex geometry.

Fire simulations are performed with the CAFE code[12]. CAFE is a CFD and radiation heat transfer computer code capable of realistically modeling fires that is coupled to a commercially-available FE 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 calibration of fire codes[13,14,15,16]. 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 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. The finite element model of the Rail-Lead cask is shown in Figure 2. The model for the Rail-Steel cask is similar.

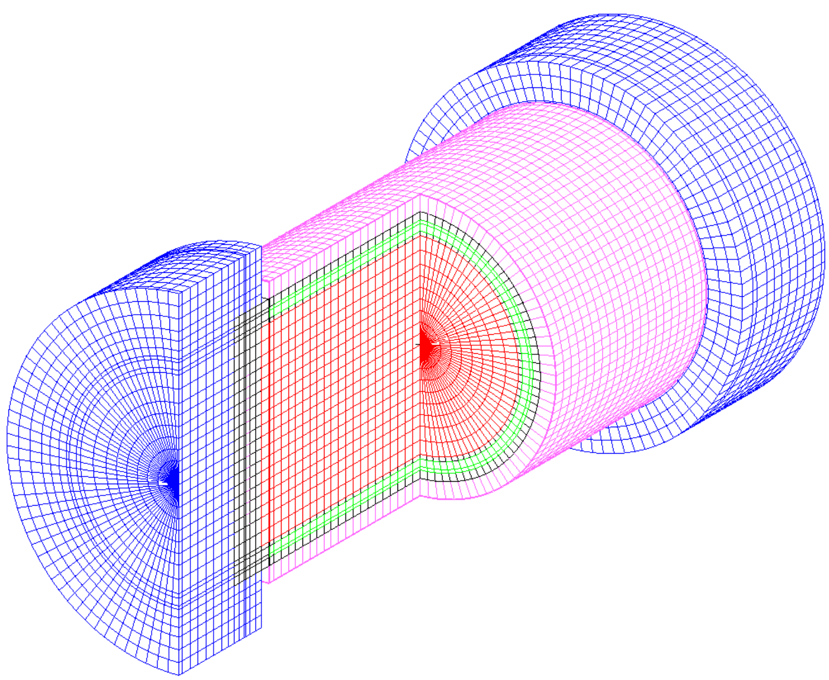

Figure 2. Finite element model of the Rail-Lead cask, the spent fuel region is shown in red, the lead gamma shielding in green, the neutron shielding layer in magenta, and the impact limiters (assumed to be undeformed) in blue.

Results for the Rail-Lead Cask

Results from the analysis of the cask lying on the ground and concentric with a pool fire that burns for 3 hours are presented in Figure 3 and 4. The vapor dome affected the temperature distribution of the cask. This is evident by the cooler temperatures observed at the bottom of the cask. In this scenario, even after 3 hours in the fire, temperatures at the bottom of the package are cooler than temperatures observed assuming uniform heating. However, the top of the cask in this configuration heats up more than the rest of the cask.

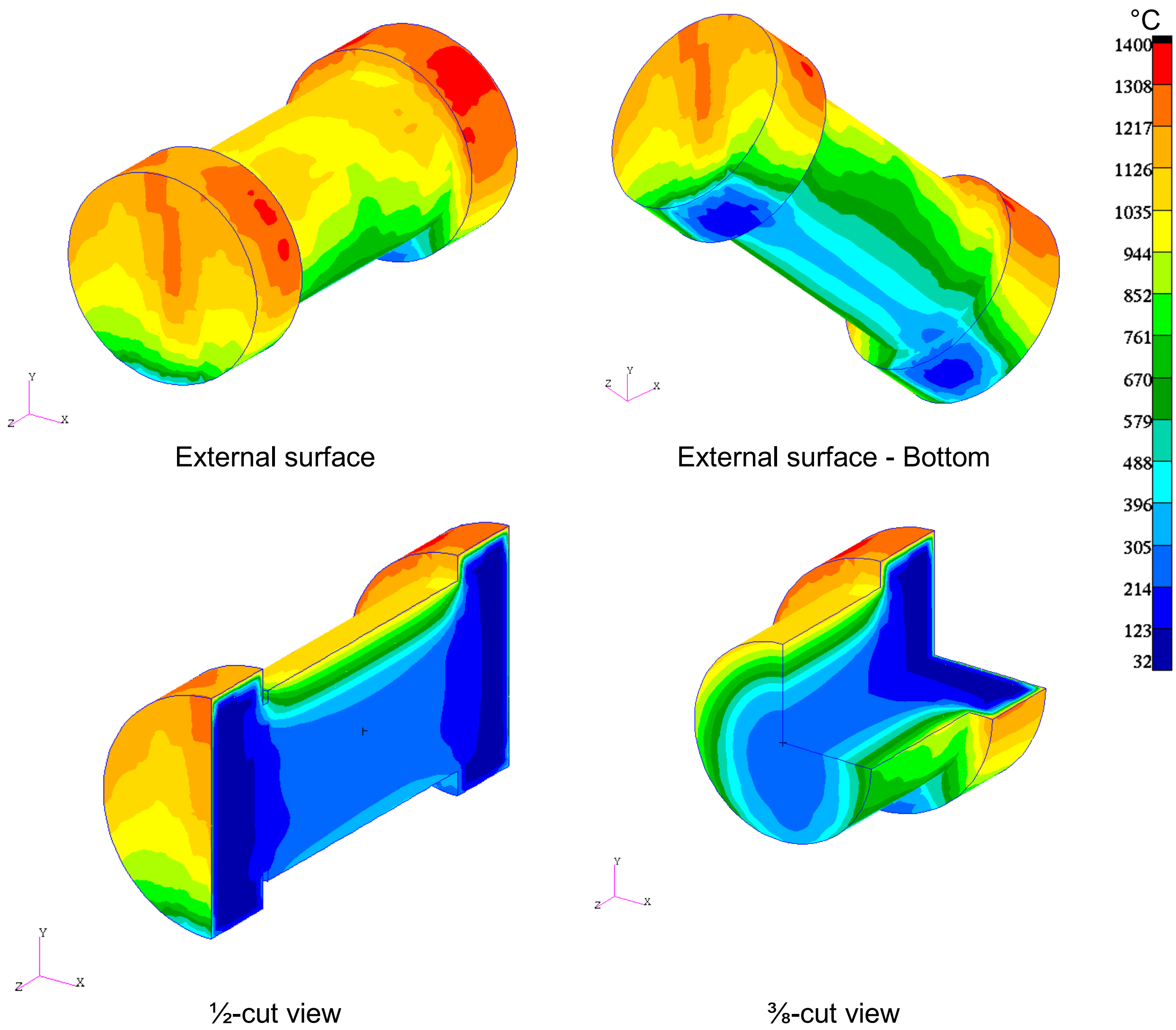

Figure 3. Temperature distribution of the Rail-Lead cask at the end of the 3-hour concentric CAFE fire with cask on ground

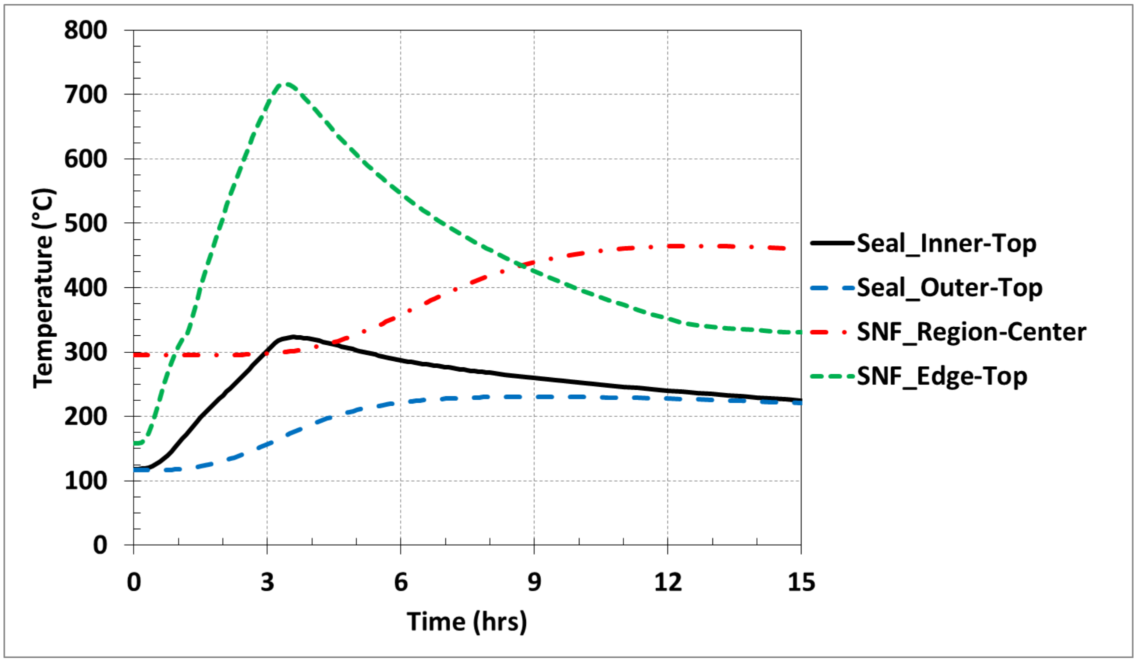

Figure 4. Temperature of key cask regions, Rail-Lead cask with cask on ground, concentric fire

There are two cases in which a portion of the lead gamma shield melts. These are the 3 hour concentric fire and the 3 hour, 3 meter (10 foot) offset fire. The lead gamma shield region that melted for each case is shown in red in Figure 5. In this figure only the lead portion of the cask wall is shown. As the figure shows, approximately 88 percent of the lead melts in the case of the 3 hour concentric fire, whereas only about 30 percent of the lead melts in the 3 hour, 3 meter (10 foot) offset fire. Because of melting and thermal expansion of some of the lead gamma shield, some loss of lead shielding is observed, which translates to an increase in gamma radiation exposure. The width of the streaming path (i.e., the gap created because of lead melt, expansion, and subsequent contraction as it solidifies) is estimated. For this estimate, it is assumed that the thermal expansion of the lead permanently deforms (buckles) the interior wall of the cask, enabling calculation of the gap in the lead gamma shield.

The results presented here show that the Rail-Lead cask is also capable of protecting the fuel rods from burst rupture and of maintaining containment when exposed to the severe fire environments analyzed, 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 lead shielding is expected when the cask is exposed to a concentric fire that burns for longer than 65 minutes and for casks that receive heat from a fire offset by 3 meters (10 feet) and that burns for longer than 2 hours and 15 minutes. Nevertheless, no release of radioactive material is expected if this cask was exposed to any of these severe thermal environments because the elastomeric seals did not reach their temperature limit. This ensures 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 analyzed.

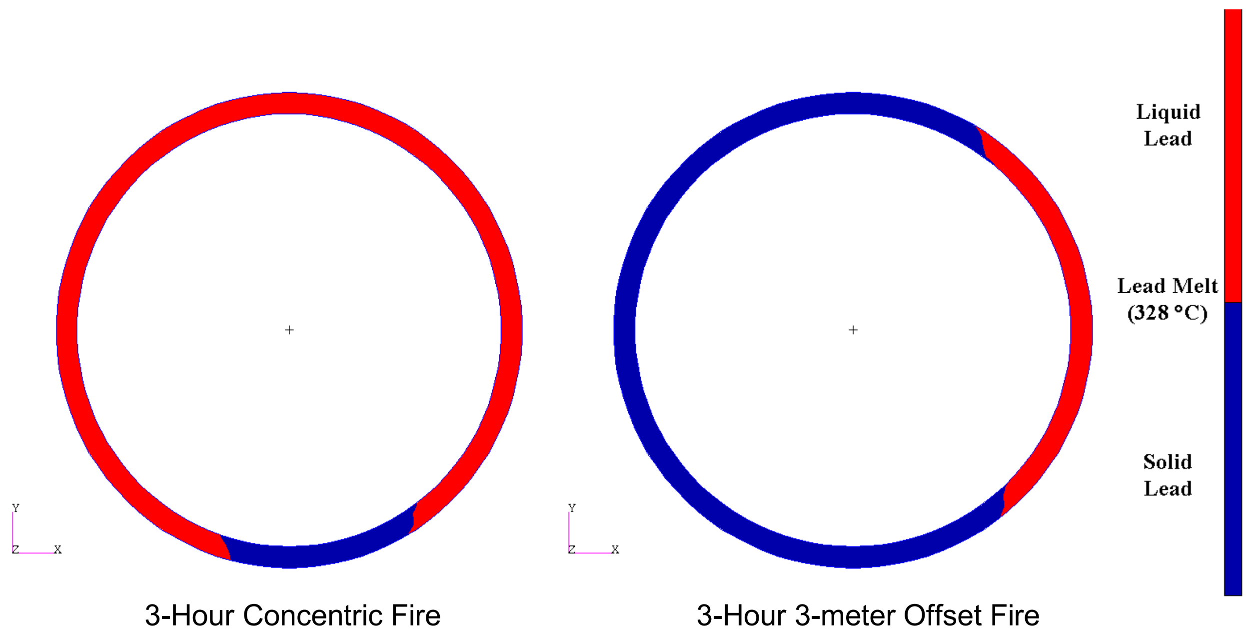

Figure 5. Lead melt regions from 3-hour fires

Results for the Rail-Steel Cask

The results show that the Rail-Steel cask is capable of protecting fuel rods from burst rupture and of maintaining containment when exposed to the severe fire environments 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 degrees C (1,382 degrees F) and the seal region stayed under 649 degrees C (1,200 degrees F) for all the scenarios 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 the shielding is a thick multilayered carbon steel wall, which is not affected in a way that could reduce its ability to provide shielding.

Results for the Truck-DU Cask

The results show that the Truck-DU cask is capable of protecting the SNF rods from burst rupture and 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 temperature is less than 750 degrees C (1,382 degrees F) and the seal region temperature is less than 350 degrees C (662 degrees F). This cask will not experience gamma shielding loss because a thick steel-DU wall provides the shielding, which is not affected in a way that could reduce its ability to provide shielding. The peak temperature in the DU gamma shielding is 406 degrees C (763 degrees F) as shown in Figure 6, well below the temperature where uranium goes through a crystal lattice phase change or the temperature where it can undergo intermetallic reactions (eutectic formation) with the stainless steel cask walls.

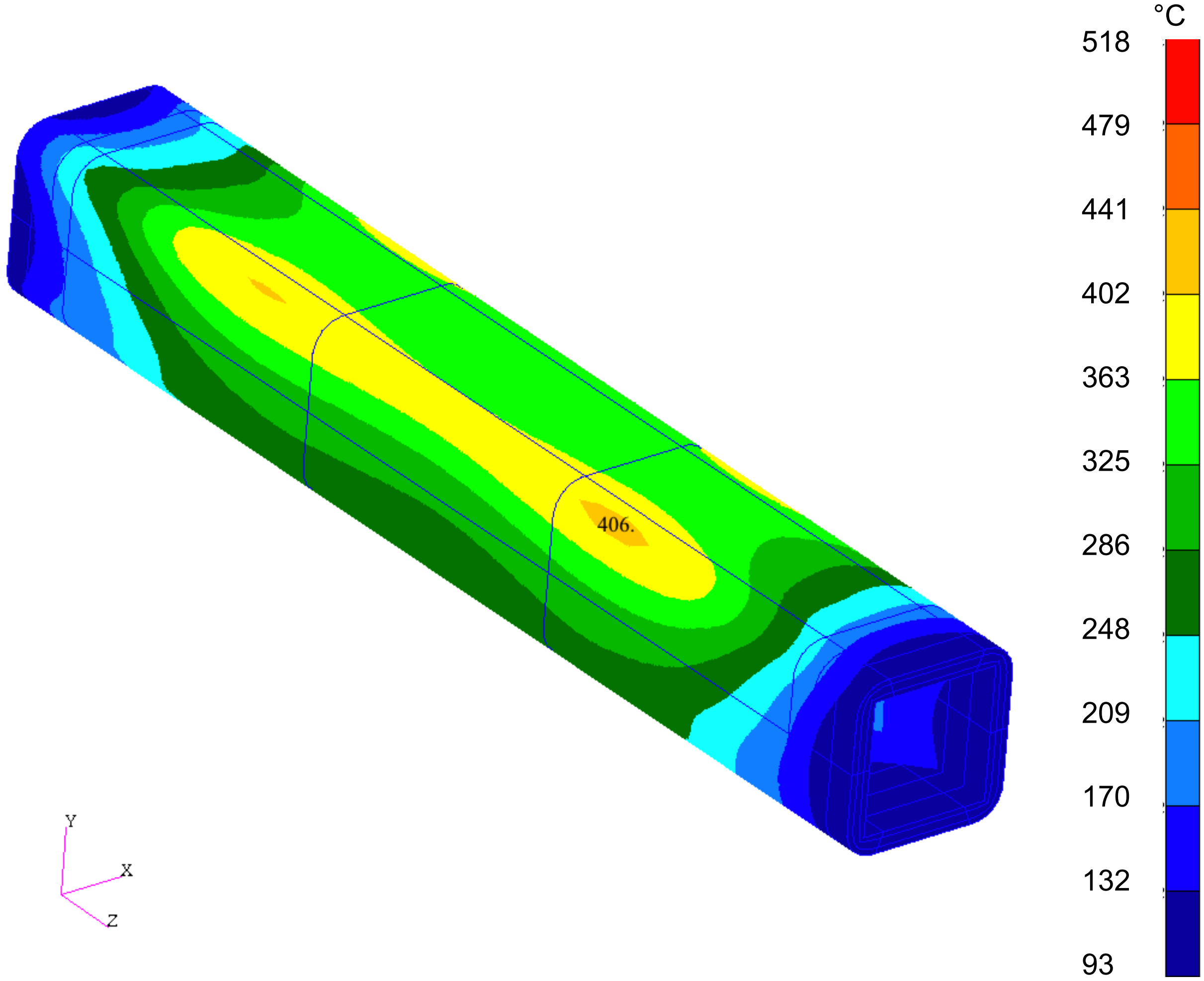

Figure 6. Peak temperature in the DU shielding during the thermal event

CONCLUSIONS

This paper presents the realistic analyses of three fire accident scenarios. These accident scenarios are identified below:

- 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).

Analyses are performed for the Rail-Steel and the Rail-Lead casks for these three fire accident scenarios. An analysis of a Truck-DU cask on the ground concentric with a hydrocarbon fuel pool sufficiently large enough 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. The neutron shield material of each cask analyzed was assumed to melt and flow out of the cask instantly at the beginning of the fire.

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. Because the seals did not fail, if the rods had been failed by an impact event that occurred before the fire, there still would have been no release from either cask. Also, if the actual rod burst temperature is lower than 750 degrees C, as is suggested by the data of Chung and Kassner[17], and some rod burst is experienced, there still would have been no release from either of the casks. However, some loss of gamma shielding is expected with the Rail-Lead cask in the event of a 3 hour engulfing fire and a 3 hour, 3 meter (10 foot) offset fire. Nevertheless, no release of radioactive material is expected to occur as a result of these hypothetical fire accidents because containment is not lost in any of the cases studied. In the case of the Truck-DU cask, containment would be maintained in the 1-hour fire accident. These results demonstrate the adequacy of current regulations to ensure the safe transport of SNF. Furthermore, the results demonstrate that SNF casks designed to meet current regulations will prevent the loss of radioactive material in realistic severe fire accidents.

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