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

EFFECTS OF TUNNEL FIRES ON THE BEHAVIOR OF SPENT NUCLEAR FUEL CASKS

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ABSTRACT

As part of the Nuclear Regulatory Commission's (NRC) overall review of the performance of transportation casks under severe accident conditions, the NRC has undertaken a number of initiatives, including an examination of the Baltimore rail tunnel fire in 2001, and the Caldecott road tunnel fire in Oakland, California, in 1982. The NRC, working with the National Transportation Safety Board (NTSB), the National Institute of Standards and Technology (NIST), and Pacific Northwest National Laboratory (PNNL), performed analyses to evaluate the potential for a release of radioactive material from the transportation casks analyzed for the Baltimore and Caldecott tunnel fire scenarios. Full details on this work have been published in NUREG/CR-6886, Rev. 1, "Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario" and NUREG/CR-6894, Rev. 1, "Spent Fuel Transportation Package Response to the Caldecott Tunnel Fire Scenario." This paper contains a summary of the results of these analyses. Most significantly, the staff found that for both tunnel fire events, a release of radioactive material from any of the casks analyzed is unlikely, and that any potential release would be very small - less than an A_2 for radionuclides of greatest concern.

BALTIMORE RAIL TUNNEL FIRE

Background

The Baltimore rail tunnel fire occurred when 11 rail cars of a 60-car CSX freight train derailed as the train was passing through the Howard Street tunnel in downtown Baltimore, Maryland. The freight train was carrying paper products and pulp board in boxcars, as well as hydrochloric acid, liquid tri-propylene, and other hazardous liquids in tank cars. A tank car containing approximately 28,600 gallons (108,263 liters) of liquid tri-propylene had a 1.5-inch (3.81-cm) diameter hole punctured in it by the car's brake mechanism during the derailment.

Ignition of the leaking liquid tri-propylene led to the ensuing fire. The exact duration of the fire is not known. Based on interviews of emergency responders conducted by the National Transportation Safety Board (NTSB), the most severe portion of the fire lasted approximately 3 hours. Other, less severe fires burned for periods of time greater than 3 hours. Approximately 12 hours after the fire started, firefighters were able to visually confirm that the tri-propylene tank car was no longer burning.

NIST Tunnel Fire Model

Experts at the National Institute of Standards and Technology (NIST), under contract to NRC, developed a model of the Howard Street tunnel fire using the Fire Dynamics Simulator (FDS) code, to predict the range and duration of temperatures present in the tunnel during the fire event.[1,2,3] The source of the fire was modeled as a pool of burning liquid tri-propylene positioned below the approximate location of the hole punctured in the tri-propylene tank car. A model of the fire as it actually occurred in the tunnel demonstrated that the fire was oxygen limited (or "starved"), with a heat release rate of approximately 50 MW. A second model, developed for use in the staff's subsequent transportation cask analyses, assumed the fire was fully ventilated and had a heat release rate of 500 MW. The duration of the fully ventilated fire was calculated to be approximately 6.7 hours, based on a reasonably sized fuel pool and consumption of approximately 28,600 gallons (108,263 liters) of liquid tri-propylene. The calculation included a post-fire cool down period of approximately 23 hours, for a total simulation time of 30 hours. Figure 1 presents a graphic of the FDS model of the Howard Street tunnel fire. In the figure, the red objects represent tank cars carrying hazardous material, the green objects are loaded box cars, and the black objects are empty railcars.

Maximum flame temperatures calculated by the FDS model assuming a fully ventilated fire were approximately 2084°F (1140°C). The model indicated that the hot gas layer above the railcars within one rail car length of the fire was 1958°F (1070°C). The maximum tunnel ceiling temperature, within a distance of one rail car from the fire, was 1832°F (1000°C).

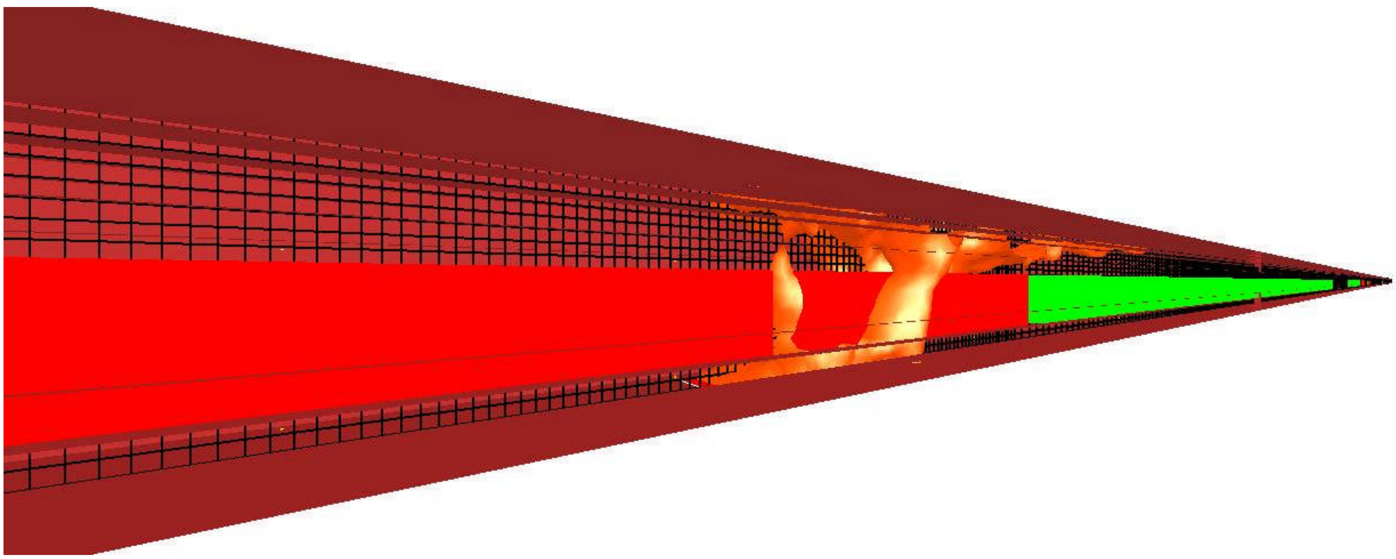


FIGURE 1. REPRESENTATION OF THE NIST FIRE MODEL OF THE BALTIMORE TUNNEL FIRE

CNWRA Materials Analysis

Staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA), along with staff from NRC and NIST, examined railcars and tank cars removed from the Howard Street tunnel approximately one year after the fire. Staff from CNWRA also collected material samples from the boxcars and tank cars inspected.

By performing metallurgical analyses on the material samples collected, including sections of the boxcars exposed to the most severe portion of the fire and an air brake valve from the tripropylene tanker car, CNWRA was able to estimate the fire exposure time and temperature for the samples tested. The material time/temperature exposures determined by the CNWRA's analyses were consistent with the conditions predicted by the NIST FDS model of the Howard Street tunnel fire. [4]

TRANSPORTATION CASKS ANALYZED

The staff investigated how a fire similar to the Howard Street tunnel fire might affect three different NRC-approved spent fuel transportation cask designs.[5] The cask designs analyzed included the HOLTEC HI-STAR 100 and the TransNuclear TN-68 rail casks, and the NAC-LWT truck cask. The cask designs were chosen because they represented shipping cask designs that have been or would likely be used in large shipping campaigns. The NAC-LWT truck cask was modeled inside an International Organization for Standardization (ISO) shipping container, representing the actual shipping configuration that is used in the Department of Energy's rail shipments of foreign research reactor fuel with this cask. Overall design features for these casks are given in Table 1.

TABLE 1. SPENT FUEL CASKS ANALYZED IN THE BALTIMORE TUNNEL FIRE STUDY

Cask Model	Transport Mode	Loaded Weight lbs (kg)	Decay Heat Load (kW)	Contents	Cask Closure Design Features
HI-STAR 100 (cask on rail car)	Rail	277,300 (125,781)	20	24 PWR[1] assemblies	Bolted Lid with O-rings, Inner Welded Canister
TN-68 (cask on rail car)	Rail	260,400 (118,116)	21.2	68 BWR[2] assemblies	Bolted Lid with O-rings
NAC-LWT (in ISO on rail car)	Truck/Rail	52,000 (23,587)	2.5	1 PWR assembly	Bolted Lid with O-rings

Figure 2 depicts the positions of the rail cars used to model the Howard Street tunnel fire scenario. The flatbed rail car containing the SNF package was assumed to be as close as possible to the fire location, based on the arrangement of rail cars required to conform to Department of Transportation regulations regarding transport of hazardous materials. A spent fuel cask must be separated from other rail cars carrying hazardous materials by a buffer car.[6] The tunnel cross-section is too narrow to allow derailed cars to slide past one another, so that at a minimum, there would be one rail car length between the tanker and the flatbed carrying the SNF package. A flatbed car was assumed to provide this buffer, resulting in the arrangement shown in Figure 2, consisting of the tank car, an empty flatbed car, and the flatbed with a spent nuclear fuel (SNF) cask. The top image of Figure 2 shows the required spacing of the rail cars. The middle image depicts the fire beginning at the site of the tank car leak, and the bottom image shows a conceptual diagram of the fully developed tunnel fire.

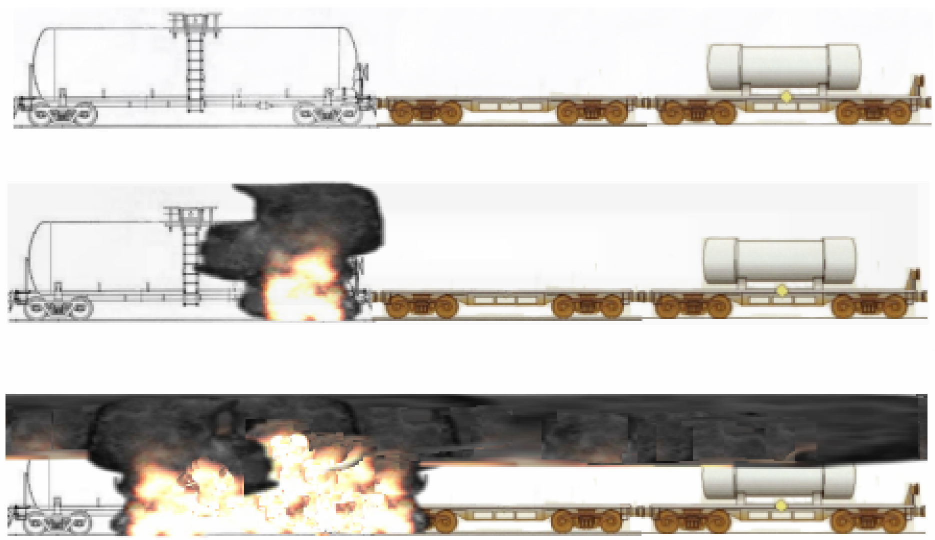


FIGURE 2. REPRESENTATION OF A SPENT FUEL CASK IN THE BALTIMORE TUNNEL FIRE SCENARIO.

[1] Pressurized Water Reactor (thermal design basis most limiting fuel and maximum decay heat loading assumed for each cask)
[2] Boiling Water Reactor (thermal design basis most limiting fuel and maximum decay heat loading assumed)

ANALYSIS APPROACH

Three dimensional models of each of the casks described above were developed for these analyses. The HI-STAR 100 and NAC-LWT casks were modeled using the ANSYS® general purpose finite element analysis (FEA) code [7] and the TN-68 cask was modeled using the COBRA-SFS finite-difference thermal-hydraulic analysis code.[8] The air and tunnel wall temperatures derived from the NIST model were used to develop the thermal boundary conditions for the ANSYS and COBRA code calculations. The normal conditions for transport described in 10 CFR 71.71 were used as initial conditions for each analysis.[9]

ANALYSIS RESULTS

The components of interest for the transport systems evaluated are the spent fuel cladding, closure seals, impact limiter core materials, and neutron shield core materials, due to the lower temperature limits of these components in comparison to other cask components. The results of the analyses for the three casks were evaluated primarily in relation to the peak predicted temperatures for these components in the fire transient and cool down.

Results for the HI-STAR 100 Cask

The maximum temperature histories for cask components obtained with the ANSYS model of the HI-STAR 100 cask are shown in Figure 3, and key results are summarized in Table 2. The analysis results show that the HI-STAR 100 cask design would maintain three important barriers throughout the fire and subsequent cool down period, which would prevent the release of radioactive materials. The welded inner canister remains intact and leak tight, preventing any release from the fuel rods themselves or from CRUD[3] adhering to the outside of the fuel rods. The temperature of the fuel cladding peaks at about 930°F (499°C) at approximately 35 hours. This is significantly below its projected burst temperature of 1382°F (750°C). This would prevent the release of fission products from within the fuel rods. The maximum temperature of 1181°F (638°C) predicted for all seal material, including the package lid closure, ports, and port covers, is below the rated continuous-use service temperature of 1200°F (649°C) for these components. Thus, the seals would not be expected to significantly degrade.

Results for the TN-68 Cask

The maximum temperature histories for cask components obtained with the COBRA-SFS model of the TN-68 cask are shown in Figure 4, and key results are summarized in Table 3. The thermal analysis for the TN-68 cask shows that during the Baltimore tunnel fire scenario, the integrity of the fuel cladding would be maintained for this cask design. At approximately 40 hours elapsed time, the temperature of the fuel cladding would peak at about 845°F (452°C), well below its projected burst temperature of 1382°F (750°C). This would prevent the release of fission products from within the fuel rods. However, the metallic helicoflex seals used on the TN-68 lid and vacuum port reach a maximum temperature of 811°F (433°C) by the end of the fire (at 6.7 hours elapsed time.) This exceeds the seals' rated service temperature of 536°F (280°C) by 275 °F (153 °C).

Even though the rated service temperature of the seals on the TN-68 cask lid is exceeded, it is still unlikely that any radioactive material would be released to the environment. Any potential release would be blocked or severely limited by the tight clearances maintained by close metal-to-metal contact between the lid and cask body. This close contact is maintained by the pre-load created by the initial torque on the lid bolts - in the case of the TN-68 cask about 850 ft-lbs (1150 N-m), which is more than eight times as tight as the typical automobile wheel lug. As depicted in Figure 5, the TN-68 lid is bolted to the cask body using forty-eight, 9-inch (22-cm) long, 2-inch (5-cm) diameter bolts. This close spacing of the bolts provides a significant engagement force on the lid that assures that the cask lid remains securely fastened during severe transportation accidents.

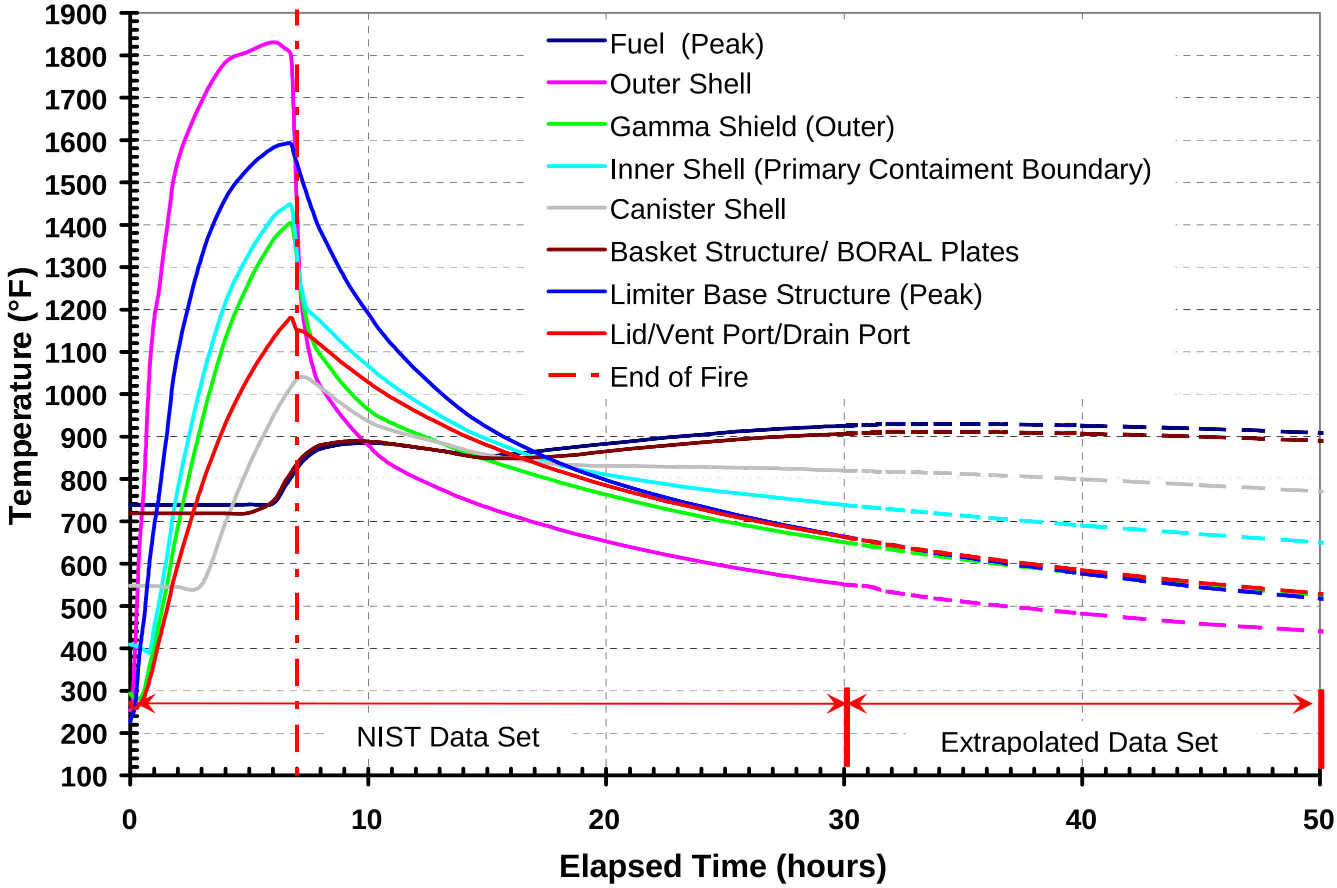


FIGURE 3. HI-STAR 100 CASK COMPONENT TEMPERATURES IN THE BALTIMORE TUNNEL FIRE SCENARIO.

TABLE 2. KEY RESULTS FOR HI-STAR-100 RAIL CASK

Peak Cladding Temperature	Cladding Burst Temperature	Temperature Margin	► **No release from spent fuel rods**
930°F (499°C)	1382°F (750°C)	452 °F (251 °C)	
Inner Canister remains intact			► **No release from cask**
Peak Temperature in Seal Region	Outer Seal Temperature Limit	Inner Seal Temperature Limit	► **No release from cask**
1181° F (638°C)	1200° F (649°C)	1200° F (649°C)	

[3] Chalk River Unknown Deposit (generic term for various residues deposited on fuel rod surfaces, originally coined by Atomic Energy of Canada, Ltd. (AECL) to describe deposits observed on fuel removed from the test reactor at Chalk River.)

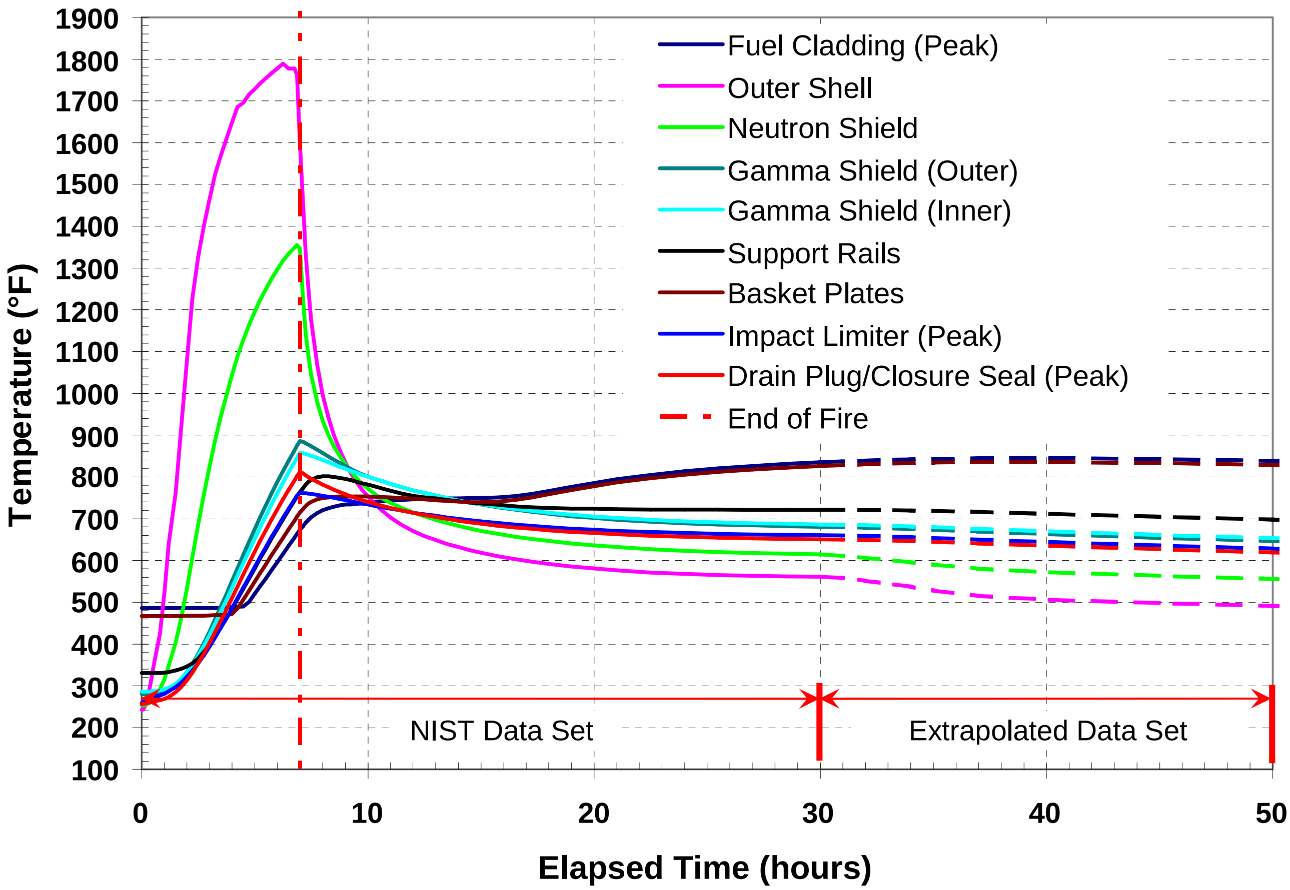


FIGURE 4. TN-68 CASK COMPONENT TEMPERATURES IN THE BALTIMORE TUNNEL FIRE SCENARIO.

TABLE 3. KEY RESULTS FOR TN-68 RAIL CASK

Peak Cladding Temperature	Cladding Burst Temperature	Temperature Margin	► **No release from spent fuel rods**
845°F (452°C)	1382°F (750°C)	537 °F (298 °C)	
Peak Temperature in Seal Region	Outer Seal Temperature Limit	Inner Seal Temperature Limit	► **Minor release of CRUD possible**
811°F (433°C)	536°F (280°C)	536°F (280°C)	

Because the fuel cladding remains intact, any potential release from the cask would consist only of CRUD particles that could flake off from individual fuel rods. The potential release pathway is illustrated in Figure 6. In order to be released outside the cask, a CRUD particle would have to travel through a narrow convoluted pathway approximately 30.5 to 35.5 cm (12 to 14 inches) in length at a minimum. It is very likely that any release pathways, if they existed, would plug or that the CRUD particles that plate out would adhere to the cask and lid inner surfaces in transit.

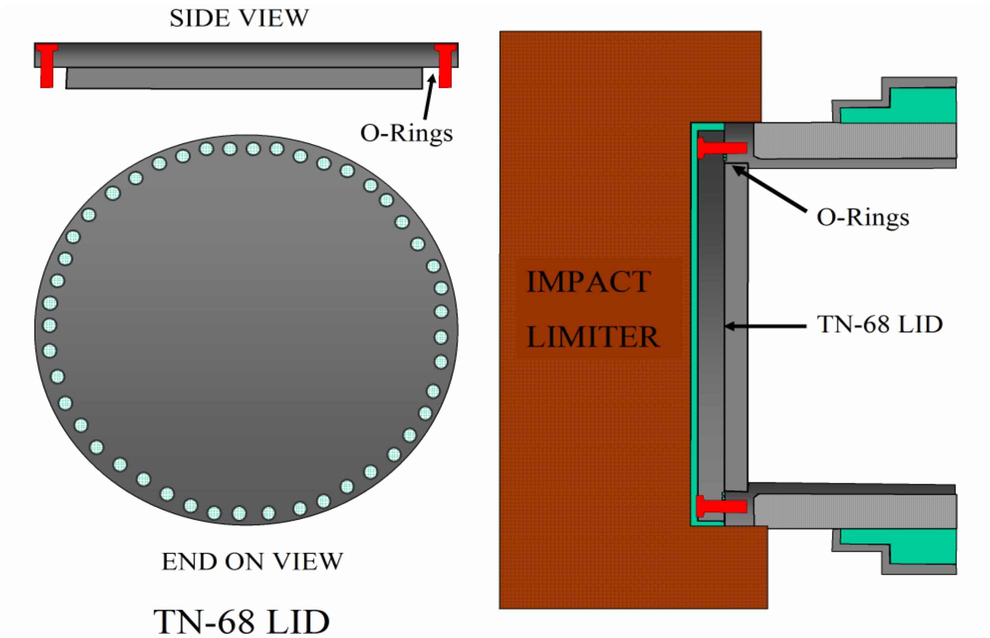


FIGURE 5. THE TN-68 CASK LID SHOWING END ON AND SIDE VIEWS, AND ATTACHMENT TO CASK BODY.

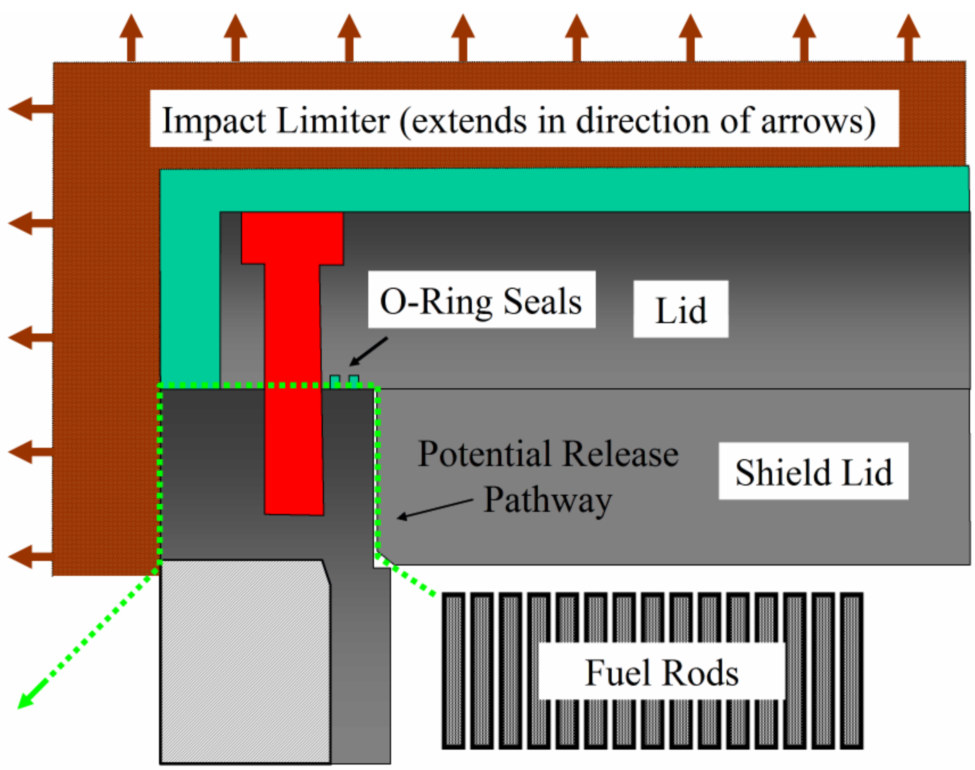


FIGURE 6. SCHEMATIC OF POTENTIAL RELEASE PATHWAY FOR TN-68 RAIL CASK.

Because the release of CRUD particles could not be entirely ruled out, a bounding calculation was made to determine the maximum expected release from the TN-68 cask if a small gap existed between the cask body and lid due to degradation of the lid seal.

The maximum expected release is defined as the total amount of releasable CRUD in the cask. The amount of releasable CRUD in the TN-68 cask was estimated using data developed by Sandia National Laboratories (SNL) for analysis of the CRUD contribution to shipping cask containment requirements [10] based on cask contents consisting of 68 BWR fuel assemblies, each assembly containing 49 fuel rods.

The major driving force for material release results from the increased gas pressure inside the cask due to increases in internal temperature. The temperature change in the cask is bounded by the difference between the maximum gas temperature predicted during the fire transient and the gas temperature at the time the cask is loaded. For this analysis, the loading temperature is defined as 100°F (38°C). The maximum gas temperature is assumed to be the maximum peak clad temperature predicted during the transient.

A deposition factor of 0.90 was used to account for the settling and deposition of CRUD particles on cask surfaces and fuel assemblies. The deposition factor was developed as part of NRC's security assessments for spent nuclear fuel transport and storage casks, and is based on an analysis of the gravitational settling of small particles. The value of 0.90 is conservative because it does not consider the effects of particle conglomeration and plugging. A value of 0.15 was used for the fraction of CRUD released due to heating of the fuel. These values are consistent with the values used in other studies [11]. The major assumptions used to estimate the potential CRUD release are given in Table 4.

TABLE 4. ASSUMPTIONS USED FOR RELEASE ESTIMATE FOR TN-68 CASK

Parameter	Assumed value
Number of Assemblies in TN-68 Cask	68 BWR
Rods per Assembly	49
Maximum “spot” CRUD Activity on Fuel Rod	300 $\mu Ci/cm^2$
Peak to axial average variation	2
CRUD decay factor (5 yr) (based on Co-60)	0.5
Average surface area per rod	1600 cm^2
Average CRUD Activity on BWR Fuel Rod (5 yr cooled)	0.12 Ci
Average CRUD Activity on BWR Assembly (5 yr cooled)	5.9 Ci
Fraction of CRUD released due to heating	0.15
Deposition Factor	0.90

A methodology similar to that developed by SNL (for NUREG/CR-6672 [10]) was used to estimate the potential release from the TN-68 cask,. This methodology was developed for evaluation of the generic risks associated with the transport of spent fuel by truck and rail from commercial power plants to potential interim storage and disposal sites. The potential release from the TN-68 cask based on five-year cooled fuel is estimated to be approximately 3.4 curies (126 kBq) of ^{60}Co. Since the A_2 value for ^{60}Co is 11 curies (407 GBq), the potential release is about 31% of an A_2. An A_2 represents the threshold below which an accident resistant package is not required and is based on a health physics model intended to provide adequate protection for first responders. The regulatory safety requirement for spent fuel casks (and other Type B packages) is that they release less than an A_2 per week after being subjected to the hypothetical accident conditions in 10 CFR Part 71 [9].

Results for the NAC LWT Cask

The maximum temperature histories for cask components obtained with the ANSYS model of the NAC LWT cask are shown in Figure 7, and key results are summarized in Table 5. The thermal analysis for the NAC LWT cask shows the integrity of the fuel cladding would be maintained for this cask design during the Baltimore tunnel fire scenario, and thus would provide an important barrier to prevent the release of radioactive materials. The peak temperature of the fuel cladding is conservatively predicted to reach 1001°F (539°C), a temperature that is below the projected burst temperature of 1382°F (750°C) for Zircaloy cladding. This peak temperature occurs at approximately 9 hours after the start of the fire (i.e., after the 7-hour fire and 2-hours into the cool down period).

However, at about 6.9 hours elapsed time, the maximum temperature predicted for the Teflon and metallic helicoflex seals used on the NAC LWT lid reaches 1356 °F (735°C). This value exceeds the continuous-use rated service temperature limits of 735°F (391°C) for the Teflon seals and 800°F (427°C) for the metallic helicoflex seals. Similarly, the peak temperature experienced by the vent and drain port seals 1410°F (766°C) at approximately 6.8 hours elapsed time, exceeds the rated long-term service temperature of the Teflon seal material.

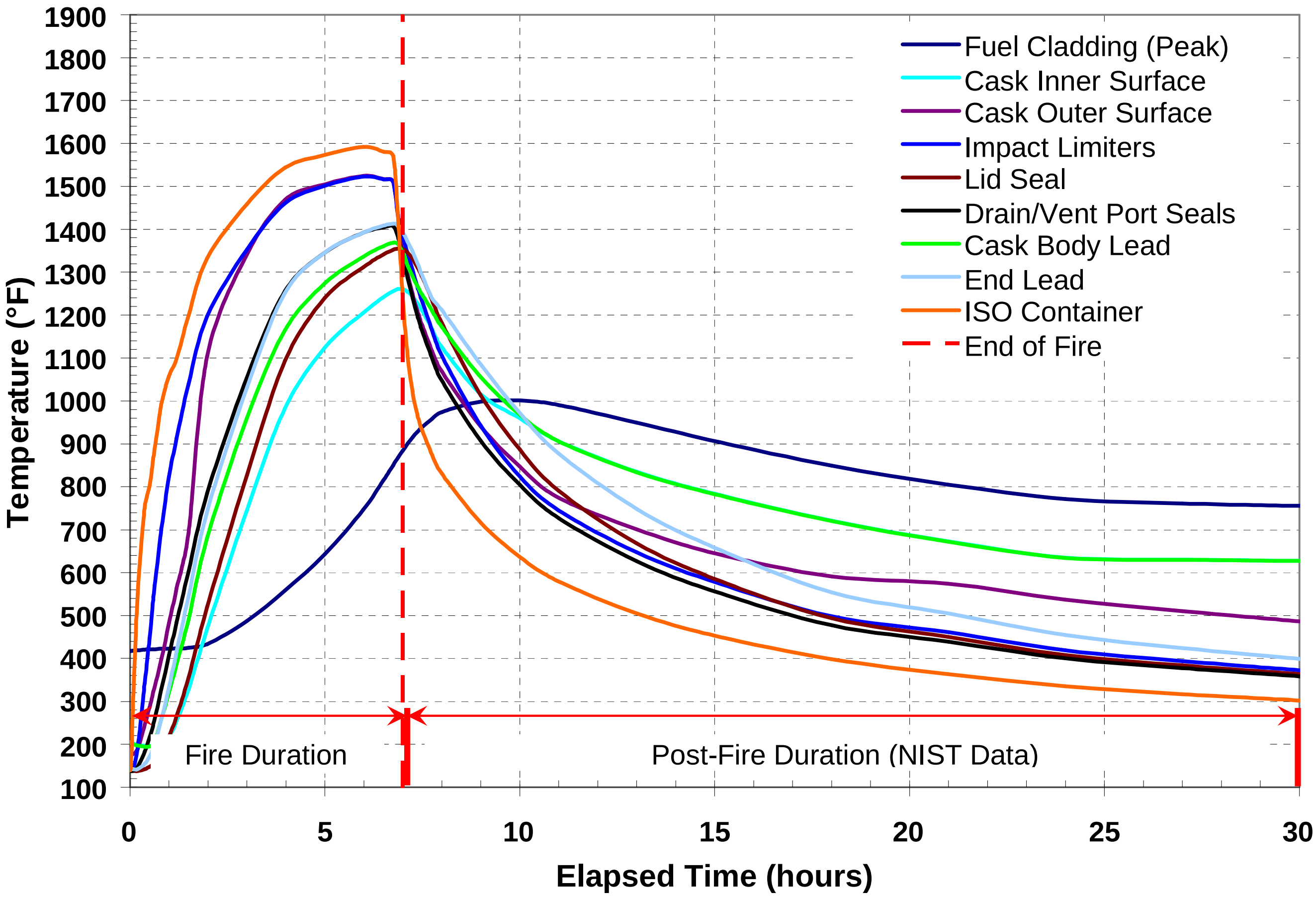


FIGURE 7. NAC LWT CASK COMPONENT TEMPERATURES IN THE BALTIMORE TUNNEL FIRE SCENARIO.

TABLE 5. KEY RESULTS FOR THE NAC-LWT TRUCK CASK

Peak Cladding Temperature	Cladding Burst Temperature	Temperature Margin	► **No release from spent fuel rods**
1001°F (539°C)	1382°F (750°C)	380°F (211°C)	
Peak Temperature in Seal Region	Outer Seal Temperature Limit	Inner Seal Temperature Limit	► **Minor release of CRUD possible**
1356°F (735°C)	735°F (391°C)	800°F (427°C)	

Even though the rated service temperature of the seals on the NAC-LWT cask lid is exceeded, it is still unlikely that any radioactive material would be released to the environment. As in the TN-68 cask, the potential for a release from the NAC-LWT would be blocked or severely limited by the tight clearances maintained by close metal-to-metal contact between the lid and cask body. This close contact is maintained by the pre-load created by the initial torque on the lid bolts. This is about 250 ft-lbs.(339 N-m.) in the case of the NAC-LWT cask. In addition, the total amount of CRUD present is very small, since the NAC-LWT can only accommodate a single PWR fuel assembly.

Because the fuel cladding remains intact, any potential release from the cask would consist of CRUD particles that could flake off from individual fuel rods. The potential release pathway is illustrated in Figure 8. In order to be released outside the cask, a CRUD particle would have to travel a narrow convoluted pathway approximately 15 inches (38 cm) in length. It is very likely that any release pathways, if they existed, would plug or CRUD particles that plate out would adhere to the cask and lid inner surfaces in transit through this pathway.

The release of CRUD particles could not be entirely ruled out, due to exceeding the seal temperature limits. Therefore, a bounding calculation was made to determine the maximum expected release from the NAC-LWT cask that could result if a small gap existed between the cask body and lid due to degradation of the lid seal.

The amount of releasable CRUD in the NAC LWT cask was based on contents consisting of one PWR fuel assembly containing 289 fuel rods. The major assumptions used to estimate CRUD release are given in Table 6. The potential release from the NAC LWT cask can be estimated in the same fashion as that used for the TN-68 release estimate above. The major driving force for material release results from the increased gas pressure inside the cask due to increases in internal temperature.

The temperature change is bounded by the difference between the maximum gas temperature predicted during the fire transient and the gas temperature inside the cask at the time the cask is loaded. For this analysis, the loading temperature is defined as 100°F (38°C). The maximum gas temperature is assumed to be the maximum peak clad temperature predicted during the transient.

The potential release from the NAC LWT cask based on five-year cooled fuel is estimated to be approximately 0.02 curies (0.74 kBq) of ^{60}Co. Since the A_2 value for ^{60}Co is 11 curies (407 kBq), the potential release is about 0.18% of an A_2.

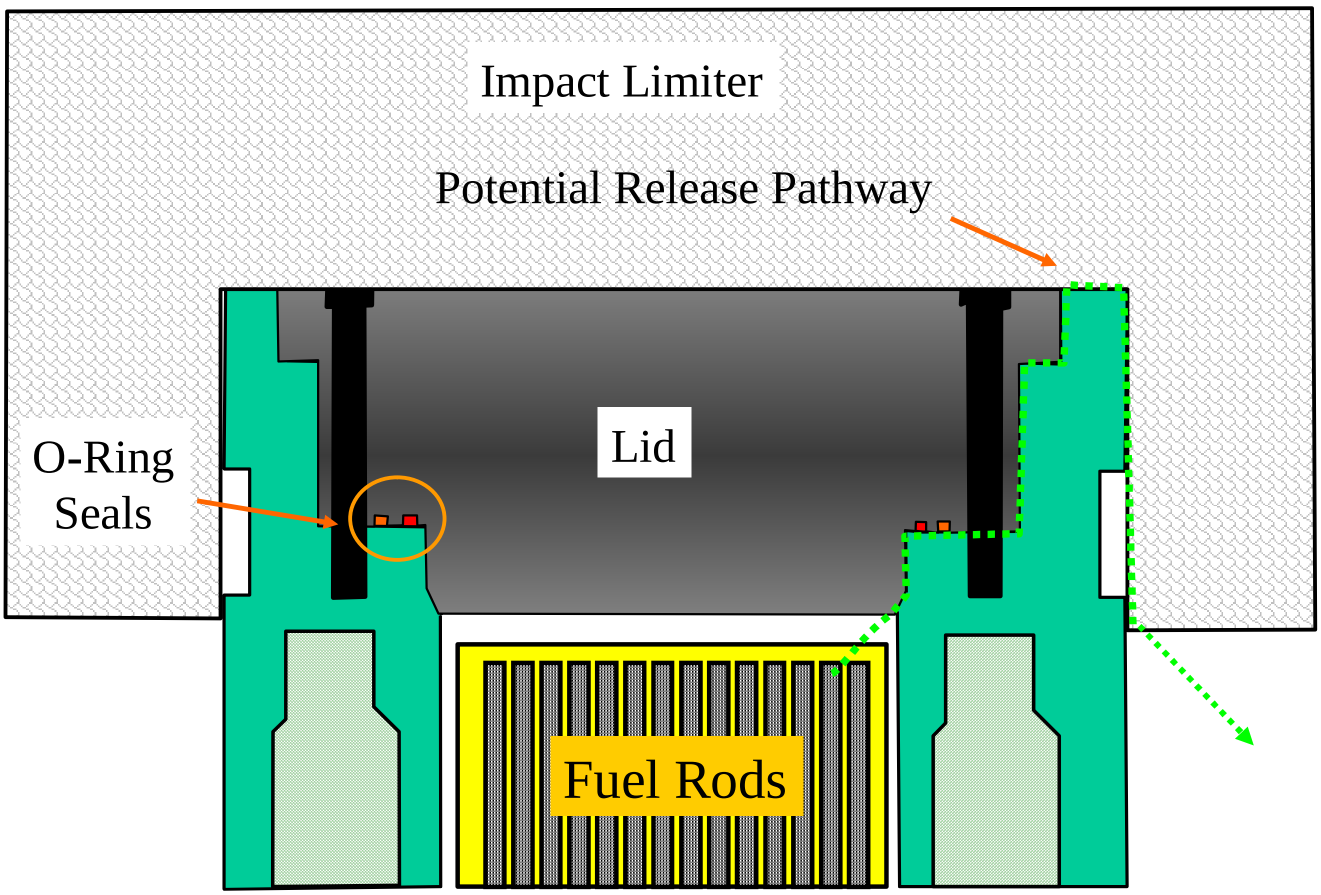


FIGURE 8. SCHEMATIC OF THE POTENTIAL RELEASE PATHWAY FOR NAC-LWT TRUCK CASK.

TABLE 6. ASSUMPTIONS USED FOR RELEASE ESTIMATE FOR NAC LWT CASK

Parameter	Assumed value
Number of Assemblies in Cask	1 PWR
Rods per Assembly	289
Maximum "spot" CRUD Activity on Fuel Rod	20 $\mu Ci/cm^2$
Peak to axial average variation	2
CRUD decay factor (5 yr) (based on Co-60)	0.5
Average surface area per rod	1200 cm^2
Average CRUD Activity on PWR Fuel Rod (5 yr cooled)	0.006 Ci
Average CRUD Activity on PWR Assembly (5 yr cooled)	1.73 Ci
Fraction of CRUD released due to heating	0.15
Deposition Factor	0.90

Potential Consequences of Loss of Shielding in Baltimore Tunnel Fire Scenario

USNRC Staff evaluated the potential for increased neutron and gamma radiation dose rates from each of the three transportation casks (TN-68, HI-STAR 100, and NAC LWT) as a result of exposure to the Baltimore tunnel fire scenario. The analysis indicates that the regulatory dose rate limits specified in 10 CFR 71.51 for accident conditions would not be exceeded by any of these casks, even though all three would be expected to lose neutron shielding in this fire scenario. Neutron shielding in SNF transportation casks is typically provided by materials that have relatively low melting temperatures (e.g., hydrocarbon resins or polymers), or are liquid at ambient conditions (e.g., water or water/glycol mixtures.) These materials are not expected to survive the design-basis accidents specified in 10 CFR 71, and the analyses of SNF transportation casks included in the safety analysis report (SAR) typically assume loss of the neutron shield in all accident scenarios.

The TN-68 and the HI-STAR 100 casks would not experience a reduction in or loss of gamma shielding material effectiveness in this fire scenario, since the shielding material in these casks consists of layers of carbon steel and stainless steel. In the NAC LWT, however, the gamma shielding material is lead. The results of the thermal analysis predict that the peak temperature of this component would be above the melting point of lead for approximately 25 hours, and the entire gamma shield would become molten within the annular cavity in the steel shell and within the cask base. Dislocation of the lead due to thermal expansion and contraction, and slumping of molten material, could possibly result in some loss of gamma shielding, as a result of increased void space within the annulus containing the lead.

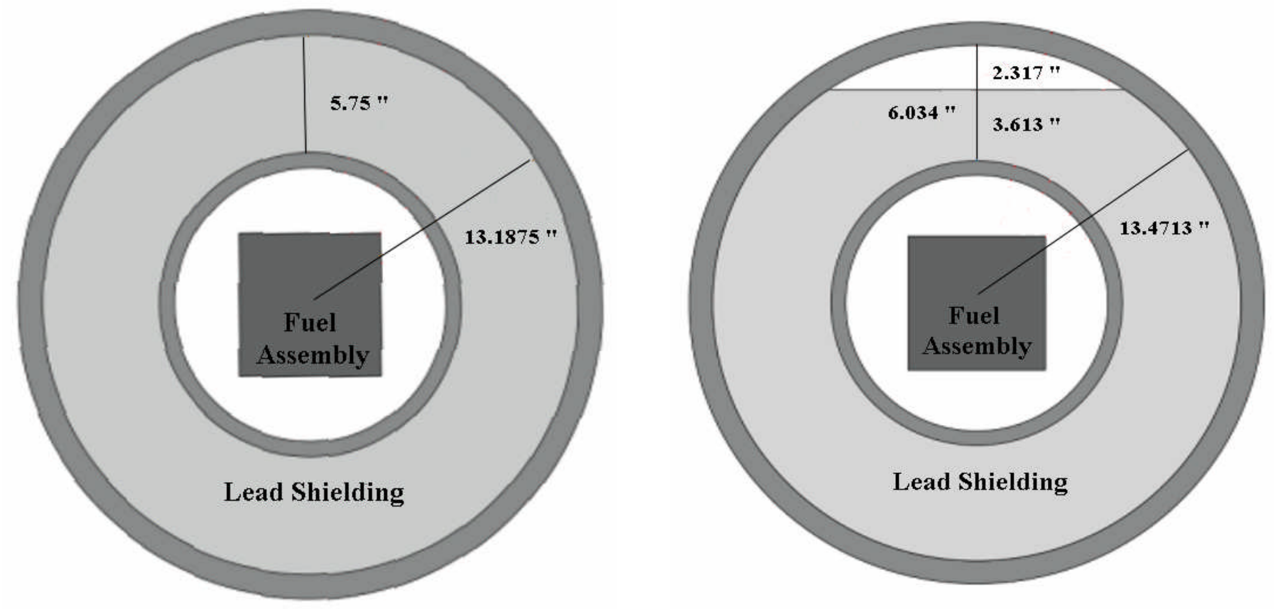
Calculations were performed by NRC staff to determine the size of this void space, taking into account the initial shrinkage gap between the lead and the enclosing steel, thermal expansion and phase-change expansion of the lead, and thermal expansion of the steel of the cask body. It was conservatively assumed that gravitational settling would result in the entire void space occupying a continuous volume within the annular cavity containing the lead shielding. For the horizontal orientation of the cask assumed in this fire scenario, this results in a void volume extending the full length of the upper edge of the annulus. Figure 9 shows a schematic representation of the configuration of the lead comprising the NAC LWT gamma shield before and after the fire, and includes conservative estimates of the change in dimensions of the cavity containing the lead shielding material.

An estimate of the potential radiation dose resulting from the maximum possible localized thinning of the lead shielding with the cask in a horizontal orientation is provided in Table 7. This dose rate does not exceed the accident limit of 1000 mrem/hr (10 mSv/hr) at one meter from the cask surface, as specified in 10 CFR 71 and 49 CFR 173.

Table 7. POTENTIAL DOSE RATE ESTIMATE FROM NAC LWT WITH REDUCED SHIELDING

<table>
<tr><th>Location</th><th>Intact Package
mrem/hr (mSv/hr)</th><th>After lead melt
mrem/hr (mSv/hr)</th><th>Regulatory Limit *
mrem/hr (mSv/hr)</th></tr>
<tr><td rowspan="3">Surface</td><td>Neutron: 7.09 (0.0709)</td><td>Neutron: 177.13 (1.773)</td><td rowspan="3"></td></tr>
<tr><td>Gamma: 48.62 (0.4862)</td><td>Gamma: 1216 (12.16)</td></tr>
<tr><td>Total: 55.71 (0.5571)</td><td>Total: 1393 (13.93)</td></tr>
<tr><td rowspan="3">1 m from surface</td><td rowspan="3">Total: 14.99 (0.1499)</td><td>Neutron: 50.93 (0.5093)</td><td rowspan="3">1000 (10)</td></tr>
<tr><td>Gamma: 331.3 (3.313)</td></tr>
<tr><td>Total: 382.2 (3.822)</td></tr>
</table>

*from 49CFR173 and 10 CFR 71.51(a)(2)



before lead melt **after lead solidification**

FIGURE 9. LEAD SHIELDING CONFIGURATION IN NAC-LWT BEFORE AND AFTER LEAD SOLIDIFICATION.

RISK PERSPECTIVE ON RAIL TRANSPORT IN THE UNITED STATES

As part of its investigation of the impact of the Baltimore tunnel fire on the transportation of spent nuclear fuel, NRC staff conducted a detailed survey of rail transportation accidents in the United States. The staff reviewed accident reports (particularly those of the NTSB), historical media accounts, and data from the Federal Railroad Administration (FRA) safety database, and from the Association of American Railroads (AAR). This review showed that severe rail fires, either in tunnels or open environments, are extremely infrequent events, as shown by the facts summarized below.

- In nearly 21 billion miles (33.8 billion km) of travel on American railroads between 1975 and 2005, there have been 1700 reported incidents involving release of hazardous materials.

- Many of the 1700 incidents involved minor releases of non-flammable hazardous materials. None of the incidents reviewed involved the release of any radioactive material.

- Of the 1700 incidents, there were 8 that involved a significant quantity of flammable material and that resulted in a long duration fire.

- Of these eight accidents, only one (the Baltimore tunnel fire) occurred in a tunnel.

Based on an examination of the NTSB accident reports on the seven accidents listed above that did not occur in a tunnel, the staff concluded that none of them could have provided a fully engulfing fire environment for a spent fuel cask, had one been involved in the event. This conclusion is based on three mitigating factors present in the accidents examined above:

(1) Proximity: Using diagrams of the rail car configurations in the seven accidents, as given in the NTSB reports, a rail car carrying a spent fuel cask and its required buffer cars could not have been located close enough to any tank cars that ruptured in these accidents. An SNF cask, had one been involved, would not have been positioned close enough to the burning flammable material in these accidents to be fully engulfed.

(2) Fuel for the fire: The flammable material involved in a majority of the accidents were gasses that resulted in localized pressure fires, so these accidents did not involve the pooling of flammable liquids. In those that did involve flammable liquids, pooling did not occur because of the nature of the track bed, which is elevated over porous media.

(3) Response time: The emergency response times were extremely rapid in these seven accidents (most were responded to within 1-2 hours), and response efforts included cooling the tank cars, effectively minimizing fire intensity and duration.

The Howard Street rail tunnel derailment and fire is unique in that none of the mitigating factors noted above (for non-tunnel fires) were acting to significantly limit the severity or duration of the fire. However, when the extremely low frequency of accidents involving hazardous material is coupled with the expected number of shipments of radioactive material in the future, the risk of an accident of this type still remains low. In addition, several factors could work to reduce the risk of this type of accident even further. These include:

(1) The intent of the Department of Energy (DOE) to ship the bulk of SNF and high level waste (HLW) to the Proposed Geological Repository for Disposal at Yucca Mountain via dedicated rail[4];

(2) FRA consideration of enactment of regulations that would require the use of dedicated trains[5] for the shipment of SNF and HLW;

(3) AAR enacting, at the recommendation of the NRC, a "no-pass" provision[6] in its rail practices for single bore dual-track rail tunnels. The provision specifies that trains carrying tank cars containing hazardous materials, such as flammable or combustible liquids, and trains carrying SNF or HLW may not pass one another within the same tunnel.

This investigation has shown that accidents involving hazardous materials and long duration fires on railroads in general and in rail tunnels in particular occur with extremely low frequency. As discussed above, DOE, FRA, and AAR have taken or are considering taking additional steps to further lessen the possibility of such an accident involving SNF or HLW and other hazardous (flammable or combustible) materials in a rail tunnel. Consequently, the frequency of any rail accident involving an SNF or HLW shipment in

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[4] Letter to Stakeholders from Paul M. Golan, Principal Deputy Director Office of Civilian Radioactive Waste Management, July 18, 2005.

[5] This consideration is mandated pursuant to Section 5105(b) of the Hazardous Materials Transportation Uniform Safety Act of 1990, As Amended.

conjunction with a long duration fire in a rail tunnel essentially approaches zero. Detailed conservative analyses of the Baltimore tunnel fire show that the potential consequences of such an accident, were it to actually occur, are minimal. The NRC staff therefore concludes that the risk to public health and safety posed by this type of transportation accident is close to nonexistent.

CALDECOTT HIGHWAY TUNNEL FIRE ANALYSIS

The staff also investigated how a fire similar to the Caldecott Tunnel fire might affect an NRC-approved over-the road spent fuel transportation cask design like the NAC-LWT.[12] The tunnel fire occurred shortly after midnight on April 7, 1982 in Bore No. 3 of the Caldecott Tunnel on State Route 24 near Oakland, California, as a result of an accident involving a tank truck and trailer carrying 33,310 liters (8,800 gal.) of gasoline [13]. This tunnel bore is 3,371 ft (1027 m) long, with a two-lane roadway 28 ft (8.5 m wide, with one-way traffic from east to west. Figure 10 shows a photograph[7] of the west portal of the tunnel; Bore No. 3 is the opening on the far left.

A diagram of a typical cross-section of Bore No. 3 of the tunnel is shown in Figure 11. The tunnel is actively ventilated by blowers with a total capacity of 1.5 million cubic feet per minute (42,500 cubic meters per minute) through ducting above the tunnel ceiling. (However, the blowers were not operating at the time of the accident.)

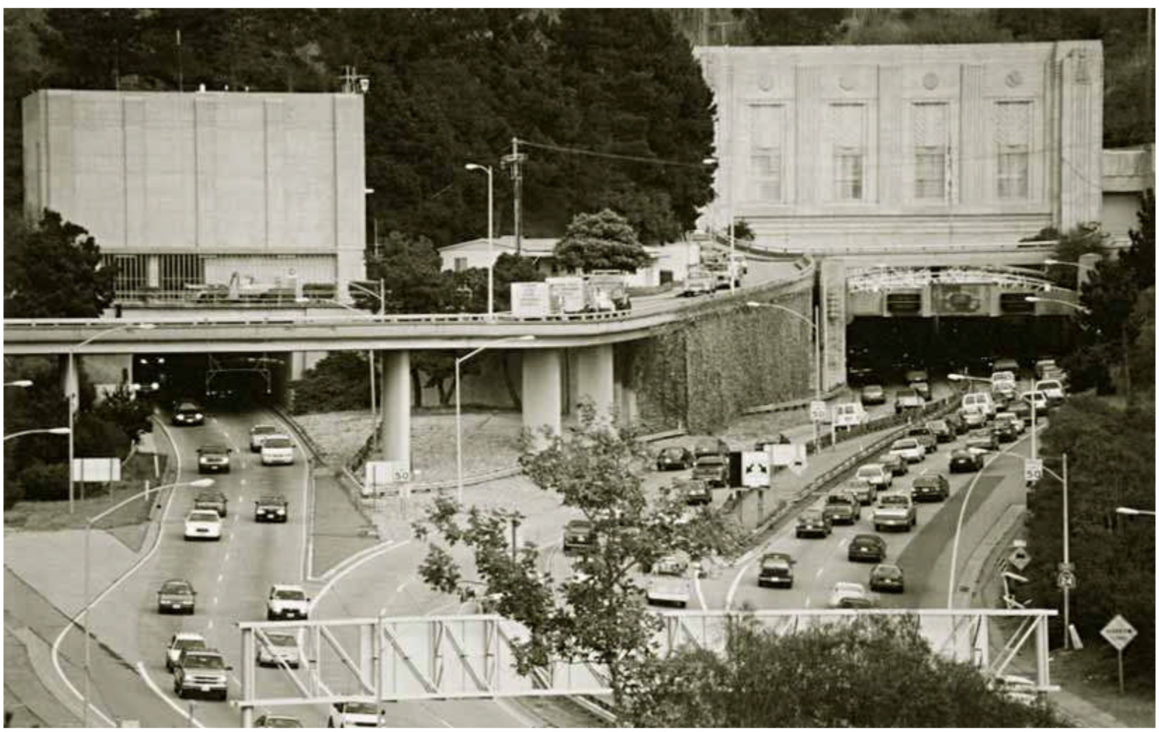

FIGURE 10. WEST PORTAL OF CALDECOTT TUNNEL.

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[6] Circular No. OT-55-I (CPC-1174), American Association of Railroads, July 17, 2006.

[7] From the Metropolitan Transportation Commission (MTC) newsletter, *Transactions OnLine*, June/July 2000 issue, http://www.mtc.ca.gov/news/transactions/ta06-0700/tunnel.htm. The MTC is the transportation planning, coordinating and financing agency for the nine-county San Francisco Bay Area.

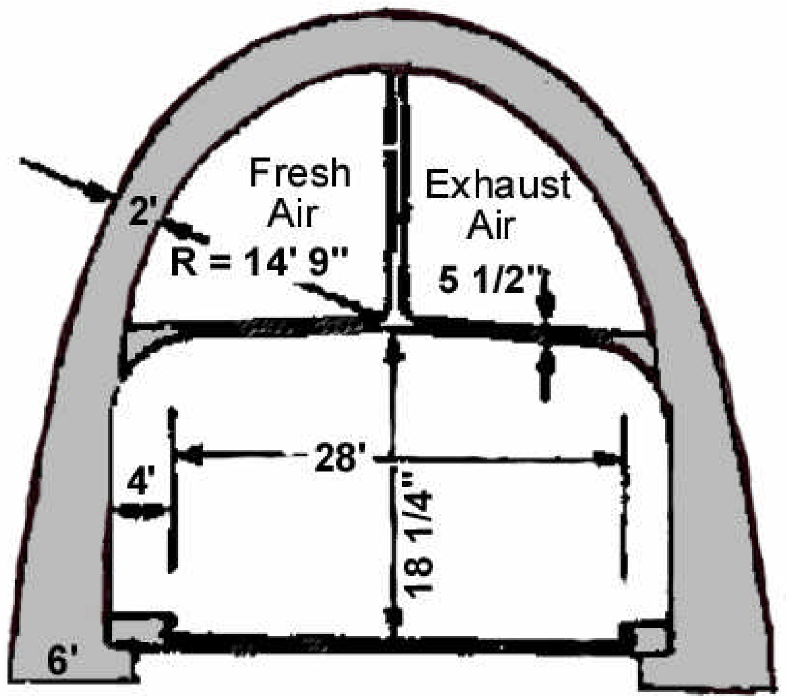

FIGURE 11. CROSS-SECTION DIAGRAM OF BORE No. 3 OF CALDECOTT TUNNEL.

In the accident, the tank trailer overturned, and gasoline that spilled onto the roadway subsequently caught fire. Within four minutes of the accident, heavy black smoke began pouring out of the east portal of Bore No. 3 of the tunnel. The tank truck, trailer, and five other vehicles in the tunnel were completely destroyed by the fire, seven persons were killed, and the tunnel incurred major damage. The overall duration of the fire is estimated at approximately 2.7 hours, but based on NTSB evaluations of the fire debris and interviews with emergency responders, the intensely hot gasoline-fueled portion of the fire is estimated to have lasted about 40 minutes. At about 46 minutes after the start of the fire, firefighters in protective gear entered the tunnel to search for survivors and were able to approach the location of the tanker truck.

NIST Tunnel Fire Model

The NIST model of the Caldecott Tunnel constructed with the FDS code consists of the section of the tunnel that experienced the most severe effects of the fire. This encompassed a length of about 623 ft (190 m), extending from about 1673 ft (510 m) to approximately 2297 ft (700 m), relative to the west portal of the tunnel. In the FDS simulation, the fire was located in the region between 1673-1706 ft (510-520 m) from the west portal, spanning a length nominally equivalent to the length of the truck tank and trailer. (The tank truck and trailer came to rest with the front of the truck approximately 1650 ft (503 m) from the west portal of the tunnel.) The FDS model consists of the tunnel over a length of 787 ft (240 m), extending from 1509 ft to 2297 ft (460 m to 700 m), relative to the west portal of the tunnel. The computational grid for the tunnel fire model consisted of a fully three-dimensional (3D) representation of this segment of the tunnel, in order to capture flame and gas behavior and the interaction of the fire with the tunnel walls, ceiling, and floor.

Based on boundary conditions that include information on the available fuel and air sources, the FDS code calculates the energy release from the combustion process, the resulting flow of air and hot combustion gases, and local air and surface temperatures throughout the tunnel. The FDS calculation simulated only the gasoline fire, and did not include the thermal energy released due to the burning vehicles. Which is negligible, compared to the energy released by the gasoline fire. In addition, these individual vehicle fires were located more than 600 ft (183 m) from the hottest region in the tunnel. The tank truck itself was 328 ft (100 m) away from the hottest location in the tunnel during the fire.

The maximum gas temperature calculated in the FDS model was 1965°F (1074°C). The maximum tunnel surface temperatures were predicted to be only about 1715°F (935°C). Maximum air temperatures in the upper and middle regions of the tunnel were predicted to exceed 1832°F (1000°C) in the first 5 to 6 minutes of the fire, and remained above this temperature until the end of the gasoline-fueled portion of the fire (at approximately 40 minutes.)

The FDS simulation was run out for a total transient time of three hours, which included the 40-minute gasoline-fueled fire and a 2.3 hr cool-down period. By the end of this three-hour period, the tunnel air temperatures predicted at the hottest location dropped to 154°F (68°C) or lower, and the tunnel surface temperatures were predicted to be less than 320°F (160°C).

Table 8 summarizes the peak temperatures predicted with FDS for the upper, middle, and lower regions of the tunnel. The hottest ceiling temperature and the highest air temperature near the ceiling both occur at 1969 ft (600 m). The hottest air temperature at the tunnel mid-line occurs at 1903 ft (580 m), but the hottest mid-line wall temperature occurs at 2100 ft (640 m), 197 ft (60 m) further 'downstream'. The peak air temperature near the floor also occurs at 2100 ft (640 m), but the peak surface temperature on the tunnel floor centerline occurs at 2165 ft (660 m).

TABLE 8. PEAK AIR AND SURFACE TEMPERATURES NEAR HOTTEST FIRE LOCATION

	Temperature, °F (°C)				
Location:	**1903 ft (580 m)**	**1969 ft (600 m)**	**2034 ft (620 m)**	**2100 ft (640 m)**	**2165 ft (660 m)**
Upper air	1902 (1039)	1965 (1074)	1904 (1040)	1805 (985)	1704 (929)
Mid-line air	1908 (1042)	1861 (1016)	1832 (1000)	1770 (982)	1711 (933)
Near-floor air	865 (463)	1040 (560)	1344 (729)	1513 (823)	1533 (834)
Ceiling centerline	1661 (905)	1715 (935)	1668 (909)	1596 (869)	1519 (826)
Wall mid-line	1452 (789)	1504 (818)	1551 (844)	1562 (850)	1542 (839)
Floor centerline	1256 (680)	1301 (705)	1377 (747)	1420 (771)	1405 (763)

In terms of the effect of the fire conditions on a cylindrical cask such as a spent fuel transportation cask positioned within the tunnel, the conditions at 2034 ft (620 m) represent the best estimate of the "hottest location" in the tunnel, in that it maximizes the temperatures and heat fluxes seen by *all* surfaces of the cask.

NAC LWT Transportation Package within the Tunnel

Boundary conditions for the model of the NAC LWT were taken from the results of the FDS analysis at 2034 ft (620 m) from the west portal, which is approximately 328 ft (100 m) down-stream of the fire source. This location was determined to be the hottest location in the tunnel (on average) during the fire. Two separate calculations were performed with ANSYS for the NAC LWT in this fire scenario; one assuming that the package was being shipped within an ISO container, the other assuming it was not within a shipping container. In both cases, the package was assumed to remain on the flatbed of the truck in a horizontal position with one end of the package facing the fire source. This orientation results in maximum possible exposure to the fire-driven flow of hot gas along the length of the package, and is the most adverse position for free convection cooling of the package during the post-fire cool down. It also results in the maximum exposure of package surfaces to tunnel surfaces for thermal radiation exchange. This is a particularly important consideration, since radiation heat transfer to the package is the most significant mode of heat transfer, by up to two orders of magnitude.

Based on the available fuel, air supply, and tunnel surface conditions, the FDS analysis of the fire predicted a duration of 40 minutes, which is consistent with the reported fire scenario. The FDS calculation was extended out an additional 2.3 hours beyond the end of the fire, to capture the post-fire cool down environment within the tunnel. The full analysis extended over a total simulation time of 3 hours.

To determine the package's complete transient temperature response, and to explore the effects of prolonged exposure to post-fire conditions in the tunnel, the ANSYS analysis further extended the transient to 30 hours. Tunnel wall and air temperatures predicted in the FDS analysis at 3 hours were extrapolated from 3 hours to 30 hours using a power function, to realistically model cool-down of the tunnel environment.

Model of NAC LWT Transportation Package

The model of the NAC LWT package constructed for ANSYS is essentially identical to that used for the Baltimore tunnel fire thermal analysis, except for the geometry describing the tunnel environment. The model consists of a detailed 3D representation of a symmetric half-section of the spent fuel package and a complete cross section of the surrounding tunnel wall. Because the package can be shipped uncovered or enclosed in an ISO shipping container, two models were constructed; one that included the ISO container, and one that did not. For both cases, the package is oriented horizontally within the tunnel. This orientation gives the package or ISO container outer surface the maximum exposure to the highest temperatures in the fire environment. This includes exposure to the tunnel surfaces for thermal radiation exchange and to the flow of hot gases generated by the fire, which results in significant convection heat transfer to the package during the fire transient. Diagrams of the package model and part of the tunnel are shown in Figure 12 (including the ISO container) and in Figure 13 (without the ISO container.)

NAC LWT Package Response to Fire Transient

The maximum temperature histories for package components obtained with the ANSYS model of the NAC LWT cask are shown in Figure 14 (within an ISO container), and in Figure 15 (without an ISO container.) Key component temperatures during the transient for both cases are summarized in Table 9. As in the Baltimore tunnel fire scenario, the thermal analysis for the NAC LWT cask shows that this cask design would also maintain the integrity of the fuel cladding during the Caldecott Tunnel fire scenario, and thus would maintain an important barrier to prevent the release of radioactive materials. The peak temperature of the fuel cladding is conservatively predicted to reach 535°F (279°C) in the cask without an ISO container, and 544°F (284°C) in the cask within an ISO container. In both cases, the peak clad temperature is far below the projected burst temperature of 1382°F (750°C) for Zircaloy cladding. This peak temperature occurs at approximately 7 hours after the start of the fire, in the case without the ISO container, and at 8 hours for the case with the ISO container (i.e., after the 40-minute fire and 6-7-hours into the cool down period.)

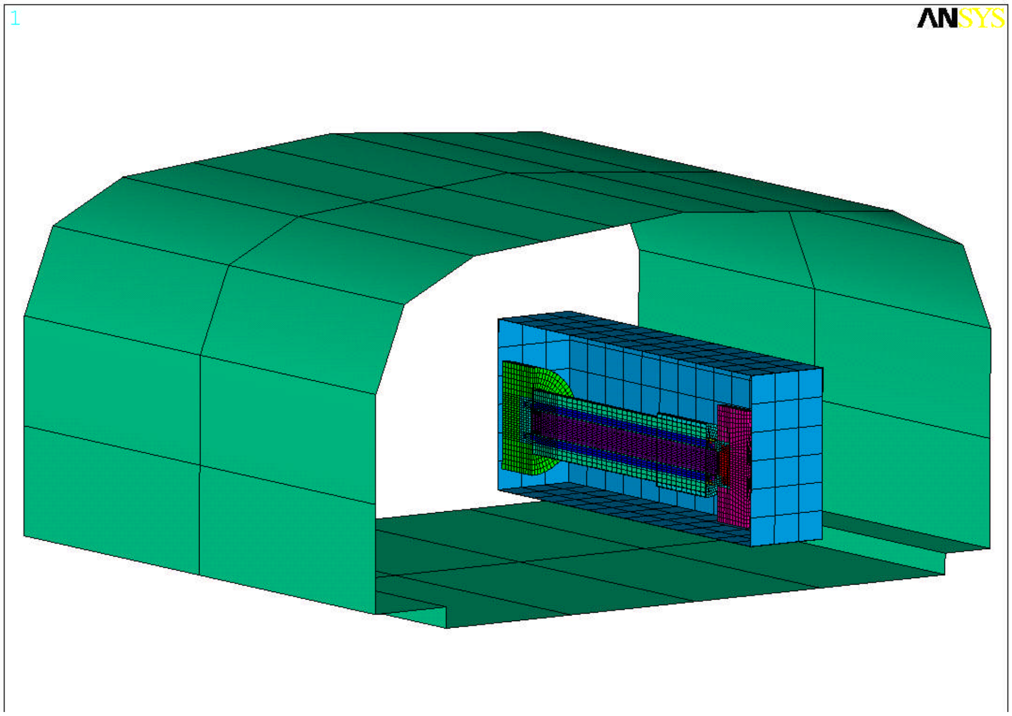

FIGURE 12. ANSYS NAC LWT PACKAGE ANALYSIS MODEL ELEMENT PLOT (with ISO)

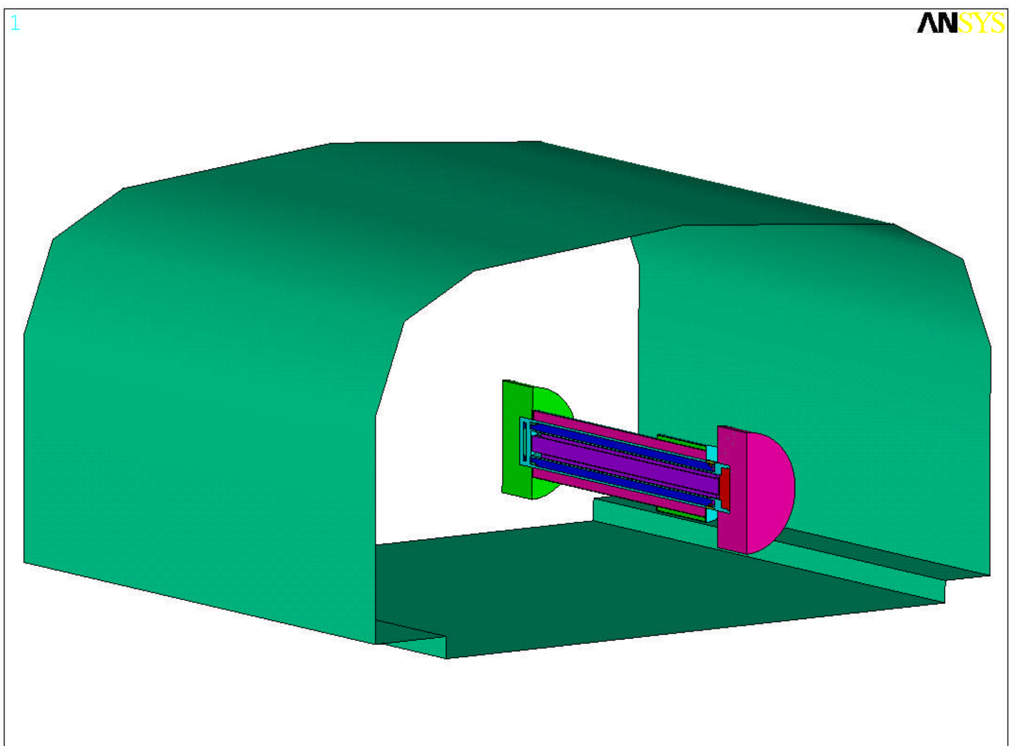

FIGURE 13. ANSYS NAC LWT PACKAGE ANALYSIS MODEL ELEMENT PLOT (without ISO)

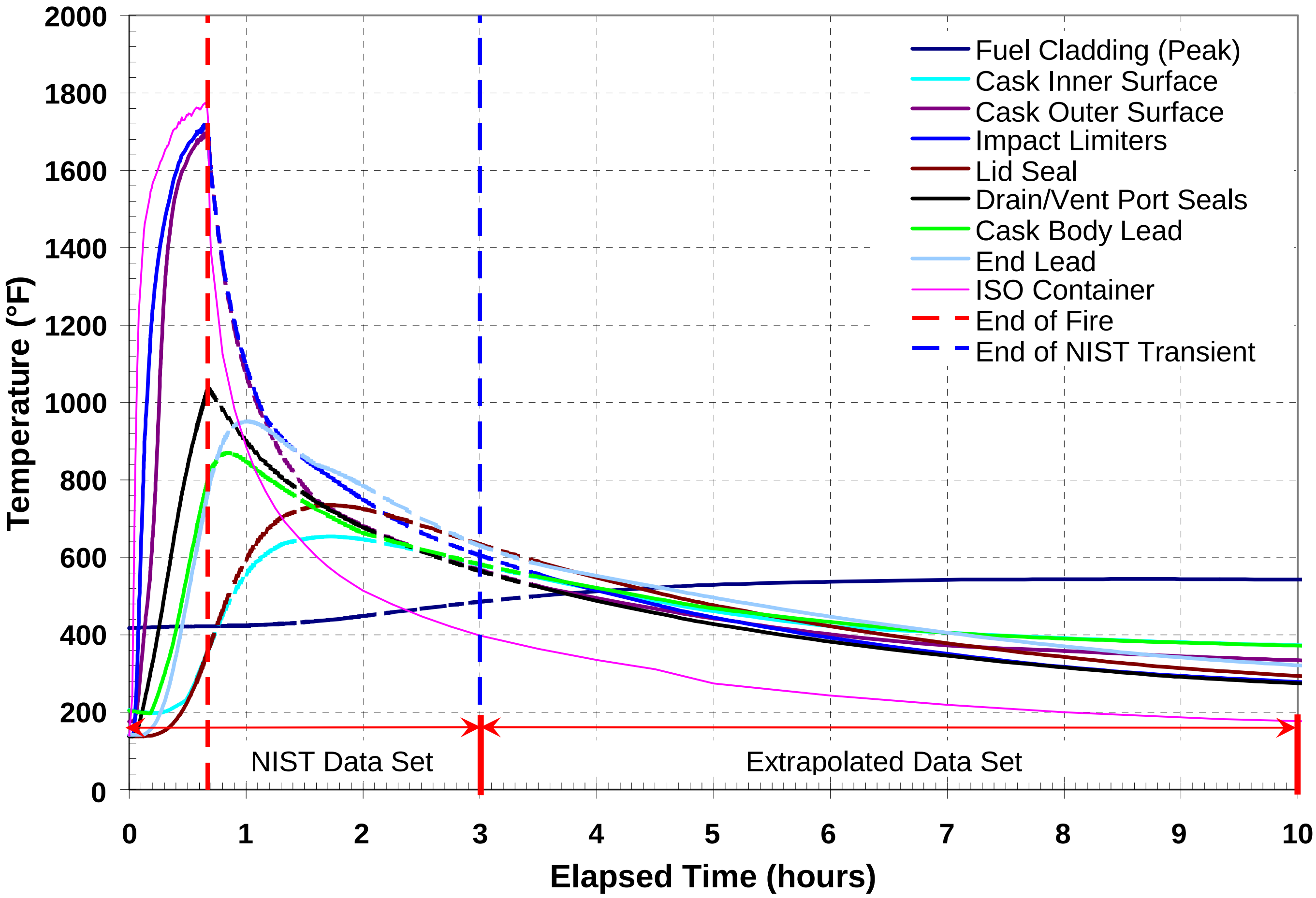

FIGURE 14. NAC LWT (WITH ISO CONTAINER): MAXIMUM TEMPERATURE HISTORIES IN CALDECOTT TUNNEL FIRE SCENARIO.

The maximum temperature predicted for the Teflon and metallic helicoflex seals used on the NAC LWT lid peaks at about 0.67-0.68 hours elapsed time, reaching 794°F (423°C) in the case without the ISO container, and 735°F (391°C) in the case with the ISO container. These values approach or exceed the continuous-use rated service temperature limits of 735°F (391°C) for the Teflon seals and 800°F (427°C) for the metallic helicoflex seals. Similarly, the peak temperatures experienced by the vent and drain port seals (1288°F (698 °C) and 1035°F (557 °C) without and with the ISO container, respectively, at approximately 0.67-0.68 hours elapsed time) exceed the rated long-term service temperature of the Teflon seal material.

Even though the rated service temperature of the seals on the NAC-LWT cask lid is exceeded, it is still unlikely that any radioactive material would be released to the environment. As discussed above in the analysis of the NAC LWT and the TN-68 cask in the Baltimore tunnel fire scenario, the potential release path is restricted, and because the fuel cladding remains intact, any potential release from the cask would consist exclusively of CRUD particles that could flake off from individual fuel rods. A potential release analysis based on the same assumptions as those used in the analysis presented above for the NAC LWT in the Baltimore tunnel fire scenario shows that the corresponding potential release from this cask in the Caldecott Tunnel fire scenario is approximately 0.10% of an A_2.

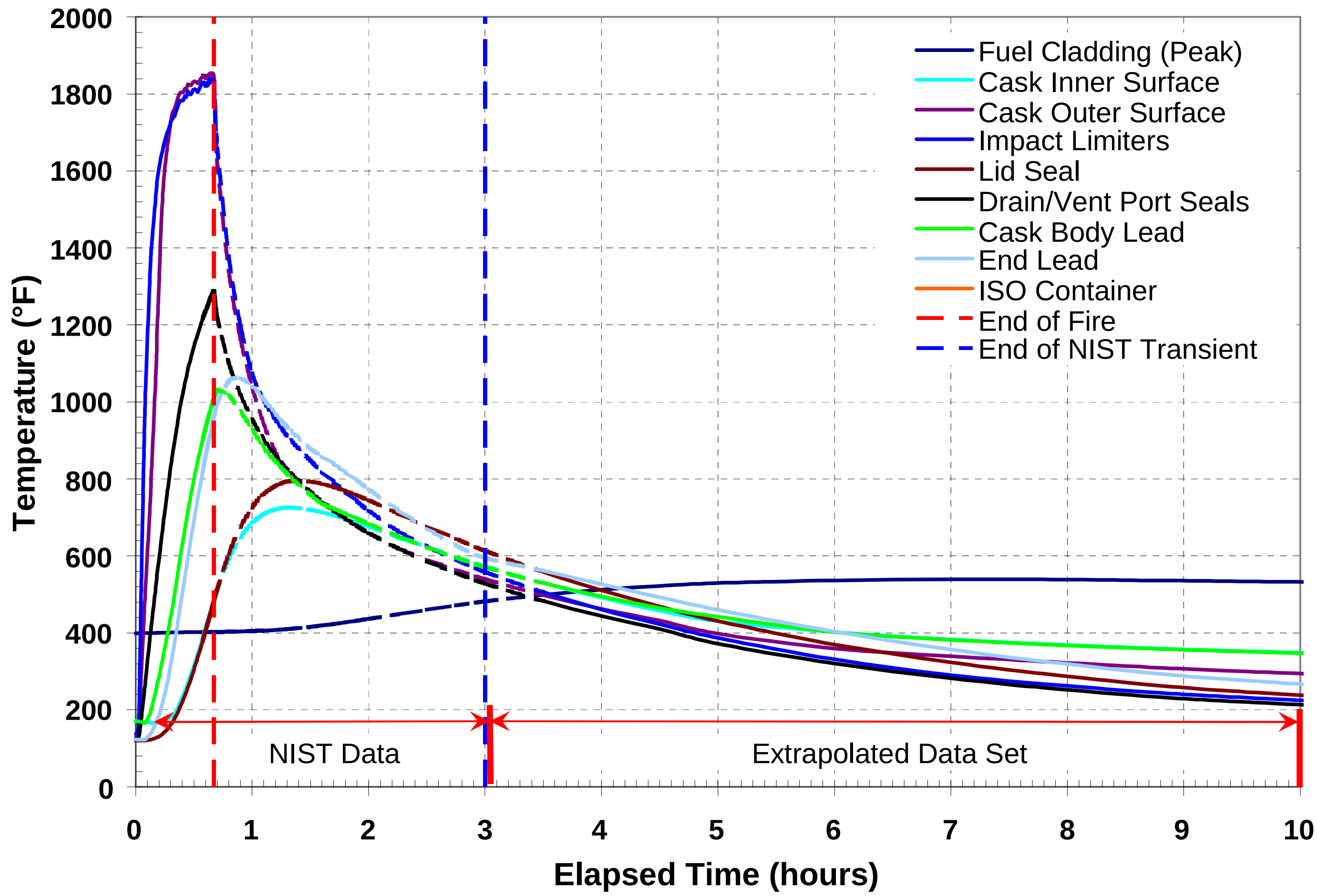

FIGURE 15. NAC LWT (WITHOUT ISO CONTAINER): MAXIMUM TEMPERATURE HISTORIES IN CALDECOTT TUNNEL FIRE SCENARIO.

TABLE 9. KEY RESULTS FOR THE NAC-LWT TRUCK CASK IN CALDECOTT FIRE SCENARIO

<table>
<tr><td>Peak Cladding Temperature</td><td>Cladding Burst Temperature</td><td>Temperature Margin</td><td rowspan="3">► No release from spent fuel rods</td></tr>
<tr><td>Without ISO:
535°F (279°C)</td><td rowspan="2">1382°F (750°C)</td><td rowspan="2">>838 °F (>466 °C)</td></tr>
<tr><td>With ISO:
544°F (284°C)</td></tr>
<tr><td>Peak Temperature in Seal Region</td><td>Outer Seal Temperature Limit</td><td>Inner Seal Temperature Limit</td><td rowspan="3">► Minor release of CRUD possible</td></tr>
<tr><td>Without ISO:
1288°F (698°C)</td><td rowspan="2">391°C (735°F)</td><td rowspan="2">800°F (427°C)</td></tr>
<tr><td>With ISO:
1035°F (557°C)</td></tr>
</table>

Potential Consequences of Loss of Shielding in Caldecott Tunnel Fire Scenario

USNRC staff evaluated the potential for increased neutron and gamma radiation dose rates from the NAC LWT as a result of exposure to conditions in the Caldecott Tunnel fire scenario. As with the similar analysis conducted for the Baltimore tunnel fire scenario, this analysis indicates that the regulatory dose rate limits specified in 10 CFR 71 for accident conditions would not be exceeded by this cask in the Caldecott fire scenario, even though the package would be expected to lose neutron shielding, and could experience some loss of gamma shielding. This cask is designed to meet the regulatory limits with an assumed loss of neutron shielding in all licensing accident scenarios.

The effects of the Caldecott Tunnel fire scenario on the lead gamma shielding is not expected to be severe enough to degrade gamma shielding performance. Although there could be some localized melting of the lead shielding in the course of this fire transient, the fire duration is too short to entirely melt the lead material. The evaluation for the NAC LWT in the Baltimore tunnel fire (where the entire lead shielding is predicted to melt, without adverse consequences for gamma shielding) conservatively bounds the potential for reduced gamma shielding in the Caldecott Tunnel fire scenario.

SUMMARY

USNRC staff evaluated the radiological consequences of the package responses to the Baltimore and Caldecott tunnel fires. The results are summarized in Table 10. The results of these evaluations strongly indicate that neither spent nuclear fuel (SNF) particles nor fission products would be released from a spent fuel shipping cask involved in a severe tunnel fire such as the rail tunnel fire that occurred in the Howard Street Tunnel in Baltimore or the fire that occurred in the Caldecott highway Tunnel. None of the three cask designs analyzed for the Baltimore tunnel fire scenario (HI-STAR 100, TN-68, or NAC LWT) or the truck cask (NAC LWT) analyzed for the Caldecott tunnel fire scenario experienced internal temperatures that would result in rupture of the fuel cladding. Therefore, radioactive material (i.e., SNF particles or fission products) would be retained within the fuel rods.

TABLE 10. SUMMARY OF KEY RESULTS

Cask Model	Fire Scenario	Potential Releases (calculated)	Comments	Number of A_2's released
HI-STAR 100	Baltimore tunnel fire	None	Releases prevented By Inner Canister.	0
TN-68	Baltimore tunnel fire	3.4 Ci of ^{60}Co	Potential release due to CRUD. Cladding remains intact.	0.3
NAC-LWT	Baltimore tunnel fire	0.02 Ci of ^{60}Co	Potential release due to CRUD. Cladding remains intact.	0.002
NAC-LWT	Caldecott tunnel fire	0.01 Ci of ^{60}Co	Potential release due to CRUD. Cladding remains intact.	0.001

For the Baltimore tunnel fire, there would be no release from the HI-STAR 100, because the inner welded canister remains leak tight and all seals remain intact. The potential releases calculated for the TN-68 rail cask (in the Baltimore tunnel fire scenario) and the NAC LWT cask (for both the Baltimore and Caldecott tunnel fire scenarios) as a consequence of exceeding seal temperature limits, indicate that any potential release of CRUD from either cask would be very small - less than an A_2 for radionuclides of greatest concern. Releases of this magnitude would not pose a significant health risk to either first responders or the public. Similarly, none of these casks in either fire scenario would experience significant degradation of neutron and gamma shielding, and would not exceed radiation dose rate limits for accident conditions.

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