The Performance of Spent Fuel Casks in Severe Tunnel Fires

C.S. Bajwa, E.P. Easton, A. Hansen
United States Nuclear Regulatory Commission
Washington, DC 20555

ABSTRACT

The Nuclear Regulatory Commission (NRC), working with the National Institute of Standards and Technology (NIST), Pacific Northwest National Laboratory (PNNL), and the National Transportation Safety Board (NTSB), performed analyses to predict the response of various spent fuel transportation cask designs when exposed to a fire similar to that which occurred in the Howard Street railroad tunnel in downtown Baltimore, Maryland on July 18, 2001. The thermal performance of three different spent fuel cask designs (HOLTEC HI-STAR 100, TransNuclear TN-68, and NAC-LWT) was evaluated with the ANSYS® and COBRA-SFS analysis codes, utilizing boundary conditions for the tunnel fire obtained using NIST's Fire Dynamics Simulator (FDS) code. NRC Staff evaluated the potential for a release of radioactive material from each of the three transportation casks analyzed for the Baltimore tunnel fire scenario. The results of these analyses are described in detail in *Spent Fuel Transportation Package Response to the Baltimore Tunnel Fire Scenario, NUREG/CR-6886,* published in draft for comment in November 2005. Comments received by the NRC on NUREG/CR-6886 will be addressed in the final version of the report.

INTRODUCTION

The Howard Street Tunnel fire occurred when 11 rail cars of a 60-car freight train derailed as the train was passing through the tunnel. The freight train, pulled by 3 locomotives, 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 2-inch (5.08 centimeter) 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] To validate the FDS code for tunnel fire applications, NIST benchmarked the code against a series of fire experiments conducted by the Federal Highway Administration and Parsons Brinkerhoff, Inc. as part of the Memorial Tunnel Fire Ventilation Test Program.[3] NIST modeled both a 6.83×10^7 BTU/hr (20 MW) and a 1.71×10^8 BTU/hr (50 MW) unventilated fire test from the Memorial Tunnel Test Program, and achieved results using FDS that were within 100°F (56°C) of the recorded data.[4]

Figure 1 depicts the positions of the rail cars used to model the Howard Street tunnel fire. The spacing of the rail cars was selected based on the Department of Transportation's requirement that spent fuel casks

be separated from other rail cars carrying hazardous materials by a buffer car. The source of the fire was a pool of burning liquid tri-propylene positioned below the approximate location of the hole punctured in the tri-propylene tank car. The duration of the fire was assumed to be 7 hours, based on the amount of tri-propylene in the derailed tank car (approximately 29,000 gallons), followed by a cool down period of 23 hours.

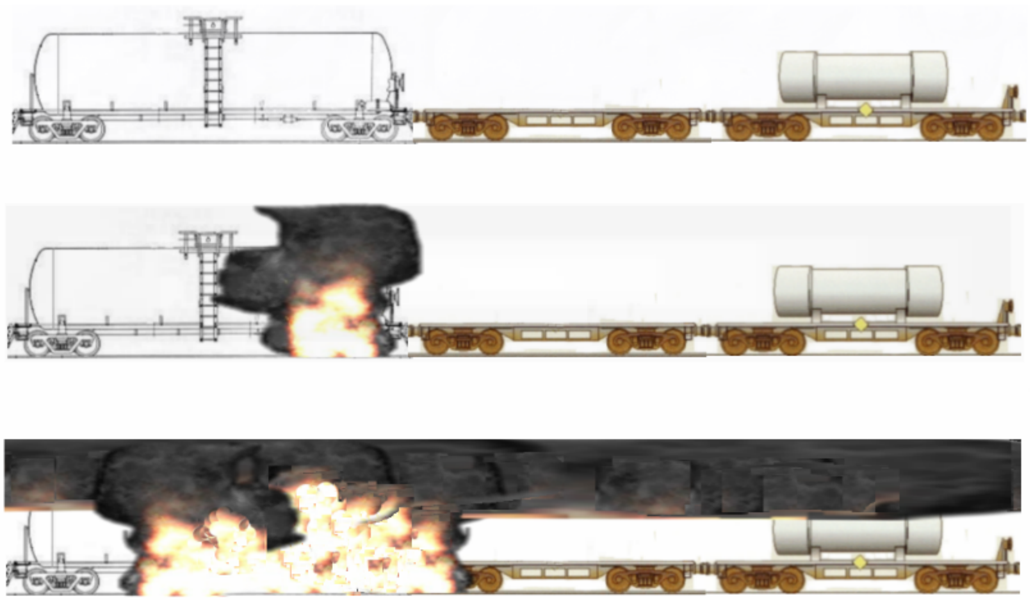

Fig. 1. Representation of a spent fuel cask in the Baltimore Tunnel Fire. Top: Normal spacing of rail cars. Middle: Fire begins at site of tank car leak. Bottom: Fully developed tunnel fire.

Maximum flame temperatures calculated by the FDS model were approximately 1832°F (1000°C). The model indicated that the hot gas layer above the railcars within three rail car lengths of the fire was an average of 932°F (500°C). Temperatures on the tunnel wall surface were calculated to be in excess of 1472°F (800°C) where the fire impinged directly on the ceiling of the tunnel. The average tunnel ceiling temperature, within a distance of three rail cars from the fire, was 752°F (400°C).

Staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA), along with staff from NRC, NIST, and NTSB, 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 box and tank cars inspected. By performing different 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 tri-propylene tank car, the CNWRA was able to estimate the 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.[5]

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. These 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 be likely to 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 was used in

the Department of Energy’s rail shipments of foreign reactor fuel. Overall design features for these casks are given in Table I.

Table I. Spent Fuel Casks Analyzed in the Baltimore Tunnel Fire Study

Cask Model	Transport Mode	Loaded Weight, lbs	Contents	Cask Closure Design Features
HI-STAR 100 (cask on rail car)	Rail	277,300	68 BWR 32 PWR	Bolted Lid with O-rings, Inner Welded Canister
TN-68 (cask on rail car)	Rail	260,400	68 BWR	Bolted Lid with O-rings
NAC-LWT (cask in ISO container on rail car)	Truck	52,000	1 PWR	Bolted Lid with O-rings

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® code,[6] and the TN-68 cask was modeled using the COBRA code.[7] 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.[8] Decay heat loads of 68,240 BTU/hr (20kW) for the HI-STAR 100 cask, 72,334 BTU/hr (21.2kW) for the TN-68 cask, and 8,530 BTU/hr (2.5kW) for NAC-LWT cask were applied with appropriate peaking factors, over the active fuel region.

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.

Results for the HI-STAR 100 Cask

The thermal analysis shows 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 adhering to the outside of the fuel rods. The temperature of the fuel cladding peaks at about 887°F (475°C), 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 1177°F (636°C) predicted for the cask’s metallic O-rings is below the rated continuous-use service temperature of 1200°F (649°C). Thus, the O-rings would not be expected to significantly degrade. The key results for the HI-STAR 100 rail cask are summarized in Table II.

Table II. Key Results for the HI-STAR-100 Rail Cask

<table>
<tr><td>Peak Cladding Temperature</td><td>Cladding Burst Temperature</td><td>Temperature Margin</td><td rowspan="2">► No release from spent fuel rods</td></tr>
<tr><td>887° F</td><td>1382° F</td><td>495° F</td></tr>
<tr><td colspan="3">Inner Canister remains intact</td><td>► No release from cask</td></tr>
<tr><td>Peak Temperature in Seal Region</td><td>Outer Seal Temperature Limit</td><td>Inner Seal Temperature Limit</td><td rowspan="2">► No release from cask</td></tr>
<tr><td>1177° F</td><td>1200° F</td><td>1200° F</td></tr>
</table>

Results for the TN-68 Cask

The thermal analysis for the TN-68 cask shows that during the Baltimore tunnel fire scenario, this cask design would maintain the integrity of the fuel cladding. 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 reach a maximum temperature of 811°F (433°C) by the end of the fire (at 7 hours elapsed time.) This exceeds the seals' rated service temperature of 536°F (280°C) by 275°F (153°C). The key results for the TN-68 rail cask are summarized in Table III.

Table III. Key Results for the TN-68 Rail Cask

Peak Cladding Temperature	Cladding Burst Temperature	Temperature Margin	► **No release from spent fuel rods**
845° F	1382° F	537° F	
Peak Temperature in Seal Region	Outer Seal Temperature Limit	Inner Seal Temperature Limit	► **Minor release of CRUD possible**
811° F	644° F	644° F	

Even through 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. The potential for a 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 (more than eight times as tight as the typical automobile wheel lug). As depicted in Figure 2, the TN-68 lid is bolted to the cask body using forty-eight, 9-inch long, 2-inch diameter bolts. This close spacing of the bolts provides a significant closing force on the lid that assures that the cask lid remains securely fastened during severe transportation accidents.

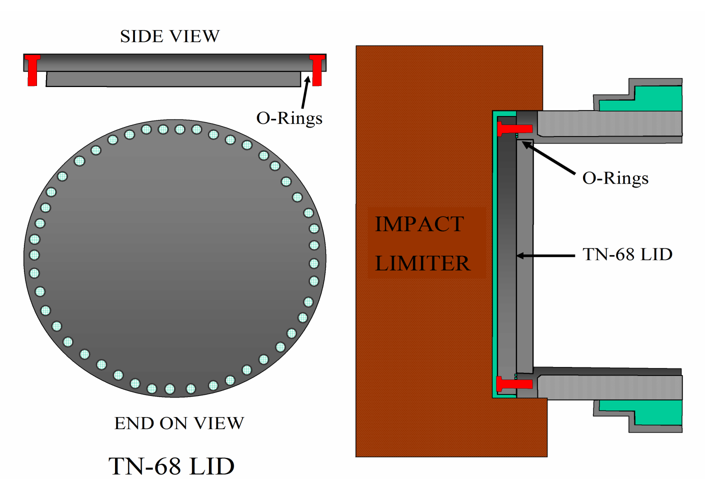

Fig. 2. The TN-68 cask lid showing end on and side views, and attachment to cask body.

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 3. In order to be released outside the cask, a CRUD particle would have to transit a narrow convoluted pathway approximately 12 to 14 inches in length. 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.

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 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 TN-68 cask was estimated using data developed by Sandia National Laboratory (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. An estimate of the maximum "spot" CRUD activity shows that for 90% of BWR spent fuel rods the maximum activity is 300µCi/cm^2 or less [see ref. 9, Table I-17]. The ratio of the peak to average concentration on the rod surface (i.e., the maximum "spot" CRUD activity over the average value) varies by a factor of two for BWR fuel rods [see ref. 9, Table I-17].

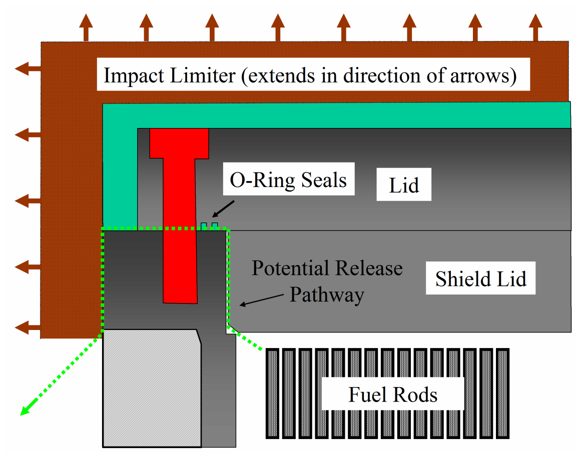

Fig. 3. Schematic of the potential release pathway for TN-68 rail cask

The CRUD activity estimates [9] are based on newly discharged spent nuclear fuel. The CRUD activity is expected to decay by a factor of one-half for five-year cooled fuel, based on the decay rate for Co^{60}. This proves to be a good approximation because 98% of the activity for five-year cooled BWR fuel comes from Co^{60}. Based on this data, the average CRUD activity for a BWR rod with a surface area of 348 in^2 (1600 cm^2) is about 0.12 Ci for five-year cooled fuel. The average CRUD activity for a typical 7 x 7 BWR assembly is about 5.9 Ci.

The amount of CRUD that might flake from the surface of a BWR rod due to thermal stresses induced by temperature change in the fuel rods is estimated to be a maximum of 15% [see ref 9, Table I-10]. 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. This yields a conservative estimate of the temperature change.

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. It is also consistent with the values used in other studies [9]. The major assumptions used to estimate the potential CRUD release are given in Table IV.

Table IV. 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	300μCi/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

To estimate the potential release from the TN-68 cask, a methodology similar to that developed by SNL (for NUREG-6672 [9]) was used. 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 estimated release is given by the relationship

$$R = C_I S(1-D)\left(1-\frac{T_i}{T_p}\right)$$

where

R = release (curies)
C_I = amount of CRUD on fuel assemblies (curies)
S = fraction of CRUD released due to heating
D = deposition factor
T_p = peak internal temperature (°R)
T_i = initial internal temperature (°R)

The potential release from the TN-68 cask based on five-year cooled fuel is estimated to be approximately 3.4 curies of Co^{60}. Since the A_2 value for Co^{60} is 11 curies, the potential release is about 0.3 of an A_2 quantity. An A_2 quantity 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 quantity/week after being subjected to the hypothetical accident conditions in 10 CFR Part 71 [8].

Results for the NAC LWT Cask

The thermal analysis for the NAC LWT cask shows that this cask design would also maintain the integrity of the fuel cladding during the Baltimore 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 1099°F (593°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 1350°F (732°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. The key results for the NAC LWT cask are summarized in Table V.

Table V. Key Results for the NAC-LWT Truck Cask

Peak Cladding Temperature	Cladding Burst Temperature	Temperature Margin	► **No release from spent fuel rods**
1099° F	1382° F	283° F	
Peak Temperature in Seal Region	Outer Seal Temperature Limit	Inner Seal Temperature Limit	► **Minor release of CRUD possible**
1350° F	735° F	800° F	

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 - in the case of the NAC-LWT cask of about 250 ft- lbs. 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 4. In order to be released outside the cask, a CRUD particle would have to transit a narrow convoluted pathway approximately 15 inches in length. 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.

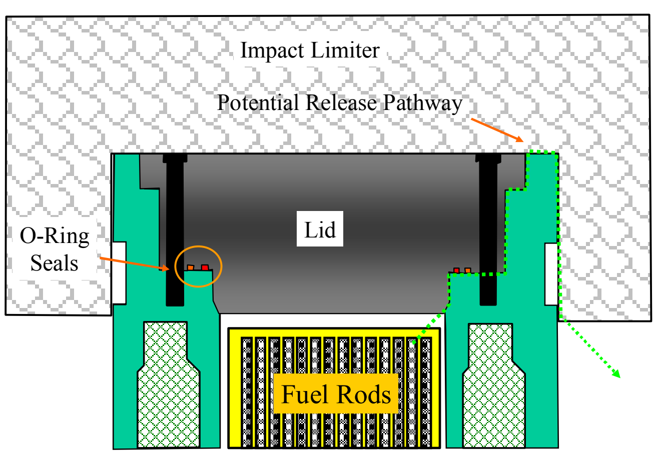

Fig. 4. Schematic of the potential release pathway for NAC-LWT truck cask

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 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. An estimate of the maximum "spot" CRUD activity shows that for 90% of PWR spent fuel rods the maximum activity is $20\mu Ci/cm^2$ or less [see ref. 9, Table I-15]. The ratio of the peak (i.e., the maximum "spot" CRUD activity) to average concentration on the rod surface varies by a factor of two for PWR fuel rods [26, Table I-12]. The CRUD activity estimates [9] are based on newly discharged spent nuclear fuel. The CRUD activity is expected to decay by a factor of one-half for five-year cooled fuel, based on the decay rate for Co^{60}. This proves to be a good approximation because 92% of the activity for five-year cooled PWR fuel comes from Co^{60}.

Based on these data, the average CRUD activity for a PWR rod with a surface area of 186 in^2 (1200 cm^2) is about 0.006 curies for five-year cooled fuel. The average CRUD activity for a 17 x 17 PWR assembly is therefore about 1.73 Ci. The amount of CRUD that would flake or spall from the surface of a PWR rod due to temperatures calculated for the fuel rods in the thermal analysis is estimated to be a maximum of 15% [see ref. 9, Table I-10]. Finally, a deposition factor of 0.90 was used to account for the deposition of CRUD particles on cask surfaces and fuel assemblies.

The major assumptions used to estimate CRUD release are given in Table VI. The potential release from the NAC LWT cask can be estimated from the same equation 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.

Table VI. 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

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 of Co^{60}. Since the A_2 value for Co^{60} is 11 curies, the potential release is about 0.002 of an A_2 quantity.

SUMMARY

USNRC staff evaluated the radiological consequences of the package responses to the Baltimore tunnel fire. The results are summarized in Table VII.

Table VII. Summary of Key Results

Cask Model	Potential Releases (calculated)	Comments	Number of A2's released
HI-STAR 100	None.	Releases prevented by Inner Canister	0
TN-68	3.4 Ci of Co^{60}	Release due to CRUD. Cladding remains intact.	0.3
NAC-LWT	0.02 Ci of Co^{60}	Release due to CRUD. Cladding remains intact.	0.002

The results of this evaluation 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 Howard Street Tunnel fire in Baltimore. None of the three cask designs analyzed for the Baltimore tunnel fire scenario (HI-STAR 100, TN-68, or NAC LWT) 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. 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 and the NAC LWT cask (as a consequence of exceeding seal temperature limits) indicate that any release of CRUD from either cask would be very small - less than an A_2 quantity, and would not pose a significant health risk to either first responders or the public.

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