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Spent Fuel Transportation Package Response Analyses to Severe Fire Accident Scenarios

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This paper summarizes studies of truck and rail transport accidents involving fires, relative to regulatory requirements for shipment of commercial spent nuclear fuel (SNF). These studies were initiated by the U.S. Nuclear Regulatory Commission (NRC) in response to a 2006 National Academy of Sciences review of NRC's procedures and regulations. The fire accident scenarios were based on the most severe historical railway and roadway fires in terms of their potential impact on SNF containers.

The accident scenarios that were analyzed include one railway tunnel fire, two roadway tunnel fires, and one roadway with enclosed overpass fire. Analyses of the accident scenario fire conditions were performed with the Fire Dynamics Simulator (FDS) code. The fire conditions predicted with FDS for the various scenarios were then applied as thermal boundary conditions to numerical simulations of SNF packages. The peak temperatures of fuel cladding, containment seals, and other key packaging components are summarized, and dose and release consequences are discussed for each fire accident scenario.

The combined summary of this work on fire accidents demonstrates that the current U.S. Nuclear Regulatory Commission regulations and packaging standards provide a high degree of protection to the public health and safety against release of radioactive material in real-world transportation accidents, were such events to involve SNF containers.

1. Introduction

This paper summarizes studies of truck and rail transport accidents involving severe fires relative to regulatory requirements for shipment of commercial spent nuclear fuel (SNF). While no such accidents involving SNF have been documented, for shipments either by rail or truck, accidents resulting in fires do occur in both modes of transport and, however unlikely, plausible arguments can be made for the possibility of SNF containers being involved in some future accidents. A regulatory framework for SNF containers is in place in the United States to ensure that risk due to such accidents is small and that the danger to the public is within accepted standards. Specifically, the requirement is survivability (meaning no release above regulatory limits) in an 800°C fire for 30 minutes [1]. This fire temperature and duration bounds a broad range of possible fire exposures for a transportation package, but surveys of rail and roadway accidents involving fires show a small number of severe fires in which the peak fire temperature and duration have exceeded these regulatory values.

The adequacy of regulations for managing SNF transportation risks has been reviewed by the National Academy of Sciences (NAS) [2]. Among the materials reviewed by the NAS was an early and very conservative analysis by the NRC based on the 2001 Howard Street Tunnel fire in Baltimore (also known as the Baltimore tunnel fire). The reviewers at the NAS acknowledged the significant conservatisms contained in the earlier analysis. One of the recommendations of the NAS report was that NRC "undertake additional analyses of very long-duration fire scenarios that bound expected real-world accident conditions."

After completing analysis of a more realistic scenario for the Baltimore Tunnel fire [3], the NRC followed with analyses of three additional severe fire scenarios: Caldecott Tunnel fire [4], MacArthur Maze fire [5] and Newhall Pass fire [6], which represent extraordinary hypothesized accident conditions for road and railway transport of SNF. As part of these analyses, NRC has investigated: (a) types and quantities of fuel available in actual fires, (b) possible ranges of temperatures in realistic and idealized fires, (c) duration of fire in real accidents, (d) effect on packages (size and mass of the package), (e) behaviour of important-to-safety components (e.g., fuel cladding, containment seals, neutron shield and gamma shield), and (f) additional actions, if any, that may be needed to address real-world fire accidents. NRC investigated the response and potential consequences if an SNF package had been involved in these accidents, and compared this with existing requirements of SNF containers. The results of these four studies are discussed in this paper.

In a study summarizing the collective results of these NRC investigations into severe fires [7], surveys of historical rail accidents were reviewed showing a very low frequency of accidents on railways involving severe fires. This, coupled with regulatory changes (e.g., limit 2-track tunnels to single train with SNF) and planned procedural actions to minimize or exclude involvement of transportation of other hazardous materials, make accidents such as the one analyzed in the Baltimore Tunnel fire scenario a very low probability event. This finding is supported by the Department of Energy (DOE) plans to move SNF by rail [8].

This study also reviewed surveys of historical roadway accidents and considered the safety of truck transport of SNF on public roadways. While the incidence of roadway accidents involving fires is higher than with railway transport, regulations for transport of SNF including pre-planned route selection and coordination are part of Federal requirements. Consideration should also be given for pre-planned administrative controls (e.g., temporary lane closure) and alternate routes to address the impact of current conditions (e.g., including seasonal weather changes, tunnel activity, or construction activity) that may impact the risk of an accident.

2. Thermal Models

The Fire Dynamics Simulator (FDS) code [9], developed by the National Institute of Standards and Technology, was used to predict the fire conditions for the various scenarios using available information on fuel sources, geometry of the fire, and actual fire duration, based on reports and photographs from first responders at the scene. The fire conditions, predicted by FDS, were then provided as boundary conditions for thermal models of SNF transportation packages. Conservative assumptions made in each fire analysis include: (a) fire is fully oxygenated and burned until the entire fuel supply is fully consumed, and (b) for tunnel fires, peak gas temperatures in tunnel zones and peak surface temperatures on tunnel floor, walls and ceiling are used as boundary conditions for the thermal-hydraulic analysis.

Thermal analyses were performed using two codes. COBRA-SFS [10], developed by Pacific Northwest National Laboratory, and ANSYS [11]. COBRA-SFS was used to perform the thermal-hydraulic analysis and predict detailed flow and temperature distributions in fuel assemblies inside the transportation package during fire and extended post-fire cooldown. ANSYS was used for the same purpose although fuel assemblies are treated in less detail. ANSYS models were developed for many of the fire accident scenarios and was the sole model created for two of the casks. Conservative assumptions used in the thermal analyses include: (a) conveyance and package support structure are neglected to allow maximum heat transfer into the package during the fire, (b) forced convection is applied during the fire and natural convection is used during the post-fire cooldown, (c) impact limiter and neutron shield retain nominal properties during the fire and degrade during the post-fire cooldown, and (d) maximum design basis heat load is used for packages.

3. SNF Packages

Four transportation packages were selected as being representative of rail and transport casks for the severe fire studies: TransNuclear TN-68, HOLTEC HI-STAR 100, NAC-LWT and General Atomics GA-4. Of these, the TN-68 and HI-STAR 100 are large capacity transport packages designed for rail transport. They were both modeled along with the NAC-LWT in the Baltimore Tunnel accident scenario. The NAC-LWT is a single-assembly capacity package that is licensed for use on rail and roadways. It can be transported within an International Organization for Standardization (ISO) shipping container. Both packaging options were investigated for this cask in the Caldecott Tunnel accident scenario. The GA-4 package can carry a relatively large payload for an over-the-road transportation package; up to four PWR assemblies. The GA-4 was the package used in the MacArthur Maze and Newhall Pass accident scenarios. The maximum heat loads of TN-68, HI-STAR 100, NAC-LWT and GA-4 packages are 21.2 kW, 20.0 kW, 2.5 kW, and 2.468 kW, respectively.

4. Severe Fire Accidents

The fire accident scenarios were based on four historical accidents, none of which involved radioactive material.

Baltimore Tunnel Fire
The Baltimore tunnel fire was a railway accident in which a freight train carrying hazardous (non-radioactive) materials derailed and caught fire while passing through the Howard Street Tunnel in Baltimore (Figure 1-a). A tank car containing liquid tripropylene had a hole punctured in it by the car's brake mechanism during the derailment. Ignition of the tripropylene led to the ensuing fire. Based on interviews of emergency responders, it was determined that the most severe portion of the fire lasted approximately 3 hours. Less severe fires persisted longer. Approximately 12 hours after the fire started, the tank car was no longer burning. Investigation of the fire afterward revealed that the tunnel ventilation was turned off at the time of the accident. Because of this the fire was oxygen starved, thus limiting its burn rate and maximum temperature. For the accident scenario analysis, the fire was assumed to be fully oxygenated.

Caldecott Tunnel Fire
The Caldecott Tunnel fire occurred in a roadway accident (Figure 1-b) involving a tank truck and trailer carrying gasoline. In the accident, the tank trailer overturned and gasoline spilled onto the roadway and caught fire. The tank truck, trailer, and five other vehicles in the tunnel were completely destroyed by the fire, and the tunnel walls incurred major damage.

MacArthur Maze Fire
The MacArthur Maze fire was a roadway accident in which a tanker truck and trailer carrying gasoline overturned and caught fire in the interchange located in Oakland, California. The intense heat from the fire weakened the steel girders of the roadway above, collapsing two adjacent spans of the elevated roadway onto the section of freeway below (Figure 1-c). While not strictly a "tunnel" fire, the fire in the MacArthur Maze interchange provided some of the confinement characteristics of a tunnel fire without the constraint of tunnel walls to restrict the flow of air to the fire. Therefore, it was well oxygenated throughout the timeframe of active burning of the fuel source, producing high fire temperatures for the full duration of the fire, and in addition, added the unique effect of the collapse of an elevated roadway onto the wreckage and fire below. For the accident scenario, the major consequence of the collapsed roadway was to limit post-fire cooling of the blanketed cask.

Newhall Pass Fire
The Newhall Pass fire was a roadway accident consisting of a chain reaction accident involving 33 semi-trailer trucks, 24 of which were trapped inside this relatively short, downslope underpass tunnel (Figure 1-d), rather than a single-vehicle accident with a pool fire surrounding a fuel transport vehicle. None of the trucks involved carried liquid fuel, except for the diesel fuel in their on-board tanks. The fire started in the pile-up of trucks near the tunnel exit, and was carried back through the tunnel from vehicle to vehicle, eventually engulfing all of the tractor-trailer rigs trapped within the tunnel. As an accident scenario, the worst-case fire conditions for a hypothesized SNF package was not obvious, so package location and burn rate were considered as parameters in the analyses.

5. Analyses and Consequences

Loss of shielding was not an issue in these fire accident scenarios. This is because SNF transport packages with liquid or hydrocarbon resin neutron shields are generally designed to be able to lose this shielding and still meet regulatory accident dose limit requirements. Loss of gamma shielding is discussed for each scenario below, but other than the lead shielded NAC-LWT, this component is generally unaffected by these scenarios due to the high melting point of the material of the shield. As discussed for each scenario below, the significant consequence in these fire accidents is the potential for release of radioactive material (gases and particulate) due to the potential for containment boundary failures.

Baltimore Tunnel Fire
FDS analysis of a fully-oxygenated fire suggested that the available fuel would allow the fire to burn for 7 hours. The SNF cask was assumed to be located 60 m downstream of the burning rail car, this distance being the closest allowed by the one rail car spacing requirement. With the peak temperature history computed by FDS as boundary conditions, thermal models for each cask were used to calculate the response of fuel and cask components over the 7-hour fire and subsequent cooldown transient. The temperature history for the NAC LWT package (with ISO container) for the first 30 hours of the transient

is displayed in Figure 2. Note that the peak cladding temperature is not reached until 3 hours after the fire ends. This is due to the limited rate of heat transfer away from the cask to the still hot environment while the fuel continues to be heated by radiolytic decay. A summary of peak component temperatures for all three of the packages is given in Table 1. Peak cladding temperatures remain below the limit of 1058°F (570°C), so no fuel failure is predicted. However, containment seal temperature limits are exceeded for both the TN-68 and NAC-LWT, and the conservative assumption is made that in each case the seals retain no sealing function. For both packages, evaluations showed that the potential release due to surface deposits detaching from the fuel rods is less than an A_2 quantity[1].

There is no adverse impact on gamma shielding for the TN-68 and HI-STAR 100, because these components consist of layers of steel. For the NAC-LWT, analyses showed there were no dose consequences due to portions of the lead gamma shielding exceeding 622°F (328°C), the melting temperature of this material. Therefore, the SNF packages survive the severe rail fire with fuel integrity maintained and radiation dose below regulatory limit per 10 CFR 71 [1].

Table 1.Temperature Ranges of Package Important to Safety components in Baltimore Tunnel Fire

	TN-68	HI-STAR 100	NAC-LWT	
Peak Cladding Temperature (PCT) (Limit – 1058°F (570°C))	845°F (452°C)	930°F (499°C)	1001°F (539°C)	
Peak Lead Gamma Shield (melting at 622°F/328°C)	NA	NA	1369°F (743°C) – pkg. body 1413°F (767°C) – end billet	
Containment Seals	Closure Port	Lid/Drain/Vent Ports	Lid	Drain/Vent Ports
Seal Materials	Helicoflex	Metallic	Metallic & Teflon	Teflon
Continuous-use Limit of Seal Materials	536°F (280°C)	1200°F (649°C)	800°F (426°C)	735°F (391°C)
Max. Seal Temperature	811°F (433°C)	1181°F (638°C)	1356°F (735°C)	1407°F (764°C)
PCT = Peak Cladding Temperature				

<u>Caldecott Tunnel Fire</u>

In the Caldecott Tunnel fire, the FDS code predicted a fire duration of approximately 40 minutes, based on the available fuel. The package was assumed to be located in the hottest location, 100 m downstream of the fire, where the thermal response of the airflow and tunnel walls determined the post-fire cooldown boundary conditions. The predicted peak temperatures of fuel cladding, containment O-rings, and gamma shield, per thermal analyses using ANSYS for the NAC-LWT package without the ISO container, are 544°F (284°C), 1288°F (698°C), and 622°F (328°C), respectively. The NAC-LWT package component maximum temperature histories for this case are shown in Figure 3. The thermal analysis showed that the peak temperatures in the lead shielding are above the operating limit of 600°F (316°C) for both cases with and with ISO container, however the complete melting of the lead gamma shielding is not expected and the locally molten lead is well contained within the steel cavity.

The peak temperatures of 1035°F (557°C) with an ISO container and 1288°F (698°C) without an ISO container in the drain and vent port seal regions exceed the continuous-use limits of the package seals. Although the lid peak temperatures of 735°F (391°C) for the package with an ISO container and 794°F (423°C) without an ISO container remain below the continuous-use limit for its metallic seal, it exceeds the limit for its polymeric seal. Therefore, this seal is assumed to fail. The fuel cladding temperatures are not high enough to expect fuel rod failure. Therefore, any potential release would only involve a release of Chalk River Unknown Deposit (CRUD) detaching from the fuel rods. Evaluations showed that the potential release would be less than an A_2 quantity. Therefore, the radiological hazard associated with an accident similar to the Caldecott Tunnel fire, if it were to involve an SNF package, is small.

<u>MacArthur Maze Fire</u>

[1] An A_2 quantity of radioactive material, as defined in 10 CFR 71, Appendix A [1] would not be expected to result in a significant radiological hazard to first responders even if it were released from the package due to a transportation accident.

Analysis of this fire accident scenario involved a number of conservative assumptions to maximize potential adverse consequences to the GA-4 package. These included choosing the most adverse position of the cask for the roadway segment drop in the structural evaluations, and positioning the cask in the worst case location within the pool fire for the thermal analysis. Based on the FDS analysis for this fire, a bounding flame temperature of 2012°F (1100°C) was assumed for the 37 minute pre-collapse portion of the fire and a flame temperature of 1652°F (900°C) was assumed for the 71 minute post-collapse portion of the fire. The fire was treated as fully engulfing in both fire duration intervals for the thermal models developed with COBRA-SFS and ANSYS.

Initial conditions for the fire transient were assumed to correspond to NCT for the package. In the thermal response to the fire scenario, the COBRA-SFS analysis predicted a maximum peak cladding temperature of 1388°F (753°C). The peak fuel region temperature predicted with the ANSYS model was higher, at 1433°F (779°C). Since these predicted temperatures are well above the limit, fuel failure is expected in this scenario. Based on the predicted fuel cladding temperatures from the COBRA-SFS model, fuel performance was evaluated using the FRAPTRAN-1.4 code [12] with a burst stress/strain model. Burst rupture is a potential failure mode for spent fuel at high temperatures and creep rupture is considered a possible alternative mechanism of failure for spent fuel rods. To evaluate this possibility, an additional analysis was performed using the FRAPCON-3.4 code [13] in conjunction with the DATING code [14].

Based on the temperature history and characteristics of the fuel, the calculated cladding hoop stress is 50 MPa at the start of the fire and reaches a peak of 121 MPa just prior to predicted cladding rupture at 1098°F (592°C), as predicted with the burst strain model in FRAPTRAN-1.4. The cladding failure temperature predicted with the creep model in the DATING code is 1229°F (665°C). Table 2 summarizes the elapsed time and time duration that the hottest rod peak temperatures are predicted to exceed the calculated burst rupture temperatures of 1098°F (592°C) by the burst strain model and 1229°F (665°C) by the creep model.

Table 2. Time above Predicted Rod Rupture Temperatures in the MacArthur Maze Fire Scenario

		COBRA-SFS Model		ANSYS Model	
		Max PCT in fire transient	1388°F (753°C)	Max PCT in fire transient	1433°F (779°C)
Rod Condition	PCT at Time of Rupture	Elapsed Time (hours)	Time Above Rupture Temperature (hours)	Elapsed Time (hours)	Time Above Rupture Temperature (hours)
rod rupture (burst strain model)	1,098°F (592°C)	0.8	16	0.69	>14.5
rod rupture (creep model)	1,229°F (665°C)	1.15	10.5	0.97	11.5
PCT = Peak Cladding Temperature					

Based on the burst strain model, the fuel rods are expected to rupture before the end of the fire. Based on the creep rupture model, the fuel rods would also be expected to begin rupturing before the end of the fire, but slightly later in the transient. As noted in Table 2, the peak fuel cladding temperatures remain significantly above these predicted rupture temperatures for more than 10 hours. Based on these results, it is assumed that all of the rods in each of the four assemblies in this package would rupture and release some fraction of their radioactive content into the canister. The integrity of the containment boundary then becomes the controlling factor in any release.

GA-4 package seal locations are shown to exceed all seal temperature limits during the fire and far into the post-fire cooldown period. Leakage between closure lid and body flange was assumed to be the dominant leak path. Release was estimated using the release fractions into the package at a conservative upper bound pressure, and the leak rate through the lid gap based on lid bolt tension. This release model conservatively assumed no particulate settling and no filtration of particulate by the gap. The calculated total release from the package is estimated as less than an A_2 quantity. Therefore the potential release of this extremely challenging hypothetical fire accident is still within regulatory limits.

Newhall Pass Fire

Conditions for the five cases evaluated for the Newhall Pass fire scenario are listed in Table 3. Peak cladding temperatures calculated for each case with ANSYS and COBRA-SFS are shown in Figure 4. For the peak fuel temperature histories predicted with the ANSYS model, the FRAPTRAN analysis predicted burst rupture at 1038°F (559°C). Based on the ANSYS model results, the predicted maximum fuel temperatures exceed the calculated burst temperature obtained in the FRAPTRAN analysis for three cases evaluated at the hottest location in the tunnel (near the center of the tunnel). Predicted maximum fuel cladding temperatures did not exceed the calculated burst temperature in any of the five cases at the “longest fire” location (near the tunnel entrance). For the COBRA-SFS results, the predicted maximum fuel cladding temperature does not exceed the calculated burst temperature in any of the cases considered, although clad ballooning is predicted to occur for the most severe case (NIST-06). For the purpose of calculating the potential release, it is assumed that all rods in the package fail. This is consistent with the assumptions for the hypothetical accident conditions (HAC) fire in NRC guidance, and effectively bounds the maximum possible release from the GA-4 package.

The seal regions on the GA-4 package are predicted to exceed temperature limits for several hours in all cases. Again the lid seal is considered as the bounding leak path.

Table 3. FDS Cases Modeling Newhall Pass Tunnel Fire

Case	Fuel Load	Burn Rate	Fire Spread Rate
NIST 01	typical fuel budget for each modeled vehicle	1.36 kg/s	0.01 m/s (slow)
NIST 02			0.015 m/s (moderate)
NIST 03			0.022 m/s (fast)
NIST 04	typical fuel budget for each modeled vehicle, but with burn rate doubled	2.72 kg/s	0.01 m/s (slow)
NIST 05	same as NIST 01 – sensitivity study on concrete spalling model in FDS		
NIST 06	fuel load based on actual cargo (if known), typical cargo (if not known); no cargo for empty vehicles	1.36 kg/s	0.01 m/s (slow)

Potential release from the GA-4 package in the Newhall Pass fire scenario can be estimated using the leak rate model and the equivalent gap width approach used for MacArthur Maze fire scenario analysis. The conditions of pressure and temperature inside the package in the MacArthur Maze fire scenario effectively bound the conditions of the Newhall Pass Tunnel fire scenario. This is illustrated in Figure 5 with a comparison of the bounding cavity gas pressure calculated for the MacArthur Maze fire scenario, compared to the cavity gas pressure predicted for the bounding cases defining the Newhall Pass Tunnel fire scenario. Therefore, it is concluded that the potential release for the Newhall Pass fire accident is within regulatory limits.

6. Conclusions

The severe fire studies resulted in the following conclusions:

- The severe fire case studies showed that an important factor driving a potential release is not the fire itself, but rather the impediment to getting decay heat out of the package during the fire and post-fire cooldown.
- These analyses confirmed that failure of shielding is not an issue in fire accident scenarios for SNF packages. The packages were designed to meet regulatory requirements in any credible loss-of-neutron shielding scenario, including fire accidents.
- Packages are shown to be extremely robust in their response to severe, real-world fire accident scenarios.
- Analyses of conservative, bounding representations of severe fire accident scenarios are predicted to have less than an A_2 quantity release.

The combined summary of work demonstrates that current NRC regulations and packaging standards provide a high degree of protection to the public health and safety against releases of radioactive material during real-life transportation accidents, if a spent fuel transportation package is involved.

7. References

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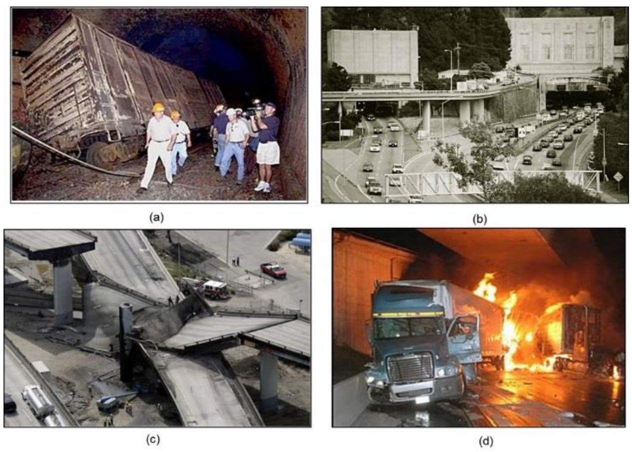

Figure 1. Severe Fire Accidents: (a) Baltimore Tunnel Fire, (b) Caldecott Tunnel Fire, (c) MacArthur Maze Fire and (d) Newhall Pass Fire

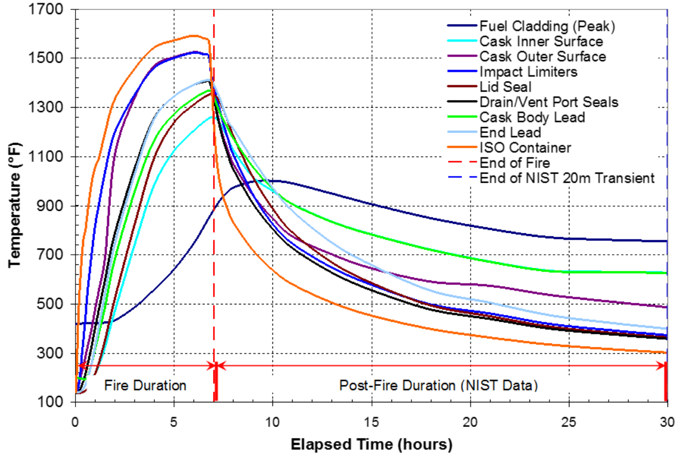

Figure 2. NAC LWT (with ISO Container) Maximum Temperature Histories – Baltimore Tunnel Fire Scenario

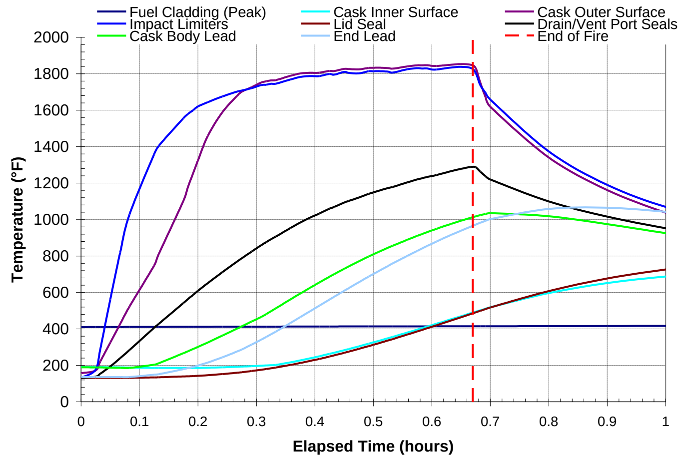

Figure 3. NAC LWT Package (without ISO Container) Maximum Component Temperature Histories – Caldecott Tunnel Fire Scenario

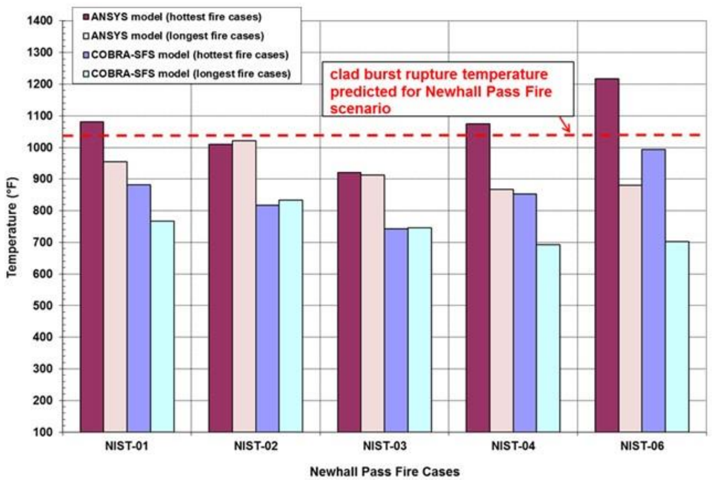

Figure 4. Predicted Burst Rupture Temperature Compared to Maximum Fuel Temperatures for GA-4 Package – Newhall Pass Fire Scenario

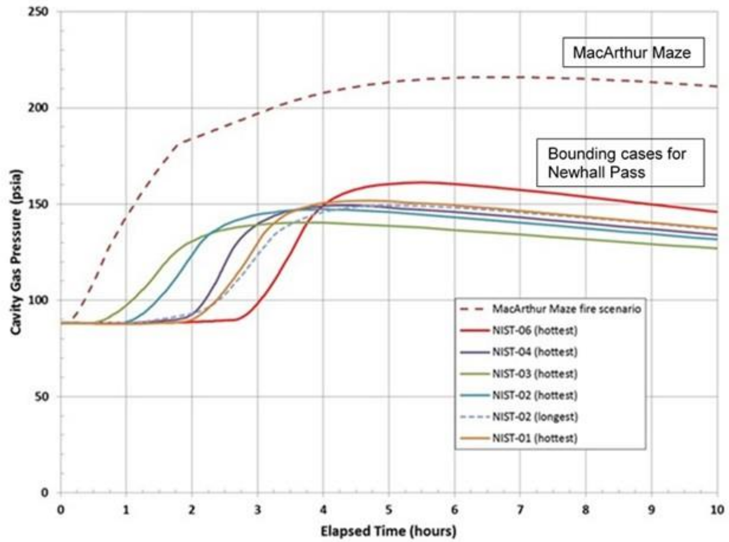

Figure 5. Cavity Gas Pressure for Newhall Pass Tunnel Fire Scenario Compared to Bounding Value from the MacArthur Maze Fire Scenario