Simulated Response of a One-PWR Truck Package to the Caldecott Tunnel Fire Scenario – 11573

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ABSTRACT

The US Nuclear Regulatory Commission has performed an analysis to predict the response of a currently-certified legal-weight-truck spent-nuclear-fuel package assuming it was in proximity to the 1982 Caldecott Tunnel fire. In that event, 33 m^3 (8800 gallons) of gasoline burned for 22-40 minutes near the middle of a 1000-m-long tunnel bore that had a 4% slope. The objective of the current work is to perform an analysis using different computational methods to assess the validity of the NRC analysis results. In the current work Container Analysis Fire Environment (CAFE) computational fluid dynamics simulations of the Caldecott Tunnel fire event were performed to calculate the tunnel ceiling temperatures and gas speeds. Those simulations used a 200-m^2 fuel pool and did not include endothermic concrete ablation of the tunnel walls. The simulated wind speed 110 m uphill of the fire was 14 m/s (30 miles/hr), and the ceiling temperatures near the fire were higher than those estimated to exist by an accident investigation. This difference may be because the simulations did not include concrete ablation. A finite-element thermal model of the package was then constructed and linked to the CAFE tunnel fire model. The temperatures of four containment components were monitored during and after 40-minute tunnel fires, with the package centered over the fuel pool, and 20, 30, 40, 60, 80, 100 and 120 m uphill. The highest temperatures were observed with the package between 40 and 60 m uphill of the fire. At some package locations the seals of the package lid, vent port, and drain port exceeded their limit temperatures. However, in agreement with the NRC analysis results, under no condition examined in this work will the fuel cladding exceed its containment integrity temperature limit.

NOMENCLATURE

H_T	Tunnel domain height
L_T	Tunnel domain length
Q	Combustion heat release rate
s	Gas speed
t	Time after fire ignition
T	Temperature
T_C	Ceiling line temperature
T_G	Gas line temperature
T_P	Peak or maximum temperature within a package component
W_T	Tunnel domain width
z	Axial tunnel location relative to the fuel pool center
Z_C	Location of the package center relative to the fuel pool center

CAFE	Container Analysis Fire Environment
CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator
FE	Finite Element
LWT	Legal Weight Truck
NAC	Nuclear Assurance Corporation
NCT	Normal Conditions of Transport
NRC	US Nuclear Regulatory Commission
SAR	Safety Analysis Report
SNF	Spent Nuclear Fuel

INTRODUCTION

Spent nuclear fuel (SNF) is transported away from reactor sites in thick-walled packages [1]. Before a transport package can be used it must receive a Certificate of Compliance from US Nuclear Regulatory Commission (NRC). To do this, the manufacturer must demonstrate that the package will maintain its containment, shielding and criticality control functions after a series of severe events [2]. These events include a 9-m drop onto an unyielding flat surface, a 1-m drop onto a steel puncture bar, full engulfment in an 800°C-(1472°F)-fire for 30 minutes, and water submersion.

Transportation risk studies assess the response of certified packages to all possible types of accidents, as well as the likelihood that packages will be involved in those events [3, 4]. In order to assess the ability of SNF packages to withstand specific historically-severe long-duration fires, the NRC conducted analyses that predict the response of SNF transport packages assuming they were in proximity to accidents that took place in the Caldecott roadway tunnel near Oakland, California in 1982 [5, 6], and the Howard Street rail tunnel in 2001 [7].

The Caldecott Tunnel fire was the only long-duration high-temperature roadway tunnel fire in the US between 1949 and 2005 [8]. In that fire, a tanker truck and trailer carrying 33 m^3 (8800 gallons) of gasoline was in an accident in one of the tunnel's three bores. It overturned roughly midway through the 1000-m-long bore, and the gasoline fueled an intense fire that lasted 22 to 40 minutes. The tunnel has a 4% slope, and flames were periodically observed at the uphill portal. The cement tunnel walls were severely spalled uphill from the flames, but the downhill half of the tunnel was essentially undamaged. Roughly 0.55 m^3 (200 gallons) of gasoline flowed into a drain, but the rest was assumed to have been vaporized. Some fraction of the vaporized gasoline fueled the fire. An investigation of the accident indicated that the maximum temperature during the fire was roughly 1000ºC (1832 ºF) and was located near the fuel source.

In the NRC analysis of the Caldecott Tunnel fire, the Fire Dynamics Simulator (FDS) computer program [9] was used to predict the thermal environments that existed during and after the fire [10]. That simulation included the effect of endothermic concrete ablation of the tunnel walls. It predicted that the hottest location in the tunnel was roughly 100 m uphill of the fuel source. A thermal finite element model of a NAC LWT truck package [11] was then constructed, which included the effects of high temperature damage to the package impact limiters and liquid-filled neutron shield [8]. The package model was subjected to a conservative version of the environment that was calculated to exist 100 m downwind of the fuel supply. The simulated response predicted the temperature of key internal components, including the fuel cladding, and package seals and radiation shields. The analysis concluded that the Caldecott Tunnel fire environment would not have caused the fuel cladding to reach temperatures that challenge its containment integrity.

The objective of the current work is to predict the response of the NAC LWT truck package to the Caldecott Tunnel fire using different computational methods than were used by the NRC, and to assess the validity of the NRC's study conclusions.

Container Analysis Fire Environment (CAFE) Simulations

The Container Analysis Fire Environment (CAFE) computer code was developed at Sandia National Laboratories to predict the response of SNF transport packages to severe accident conditions [12]. CAFE links a computational fluid dynamics (CFD) and radiation heat transfer fire simulator with a finite element (FE) package model. The fire and package model use separate computational meshes and they do not run simultaneously. The CFD code runs for a user-defined fire time, such as 1 second, to calculate the fire behavior and heat transfer to surfaces of the package. The package surface temperature is a boundary condition of the fire simulation. The FE model then calculates the package temperature response to the heat transfer from the fire for another user-defined period of time. The new FE package surface temperature is then used to update the temperature boundary condition of the fire simulation. The two components run alternately until the fire/post fire simulation is complete.

CAFE's fire simulator employs a number of physics-based fuel evaporation, turbulent transport, reaction chemistry, and radiation heat transfer models. These models allow the fire simulator to accurately predict heat transfer to objects even when relative coarse (and fast running) computational meshes are employed. Parameters of these models (such as the combustion kinetics constants, and the products-of-combustion mass-fraction used to define the edge of the diffusely-radiating fire region) are determined based on comparison of CAFE simulation results with measured data acquired in large fire experiments [13, 14].

Large-scale outdoor fire tests have been performed to acquire data to benchmark CAFE [15, 16]. In these experiments, truck- and rail-package-sized pipe calorimeters were suspended over JP8 jet fuel fires. The calorimeter interior surface temperatures and external wind conditions were measured during and after a series of roughly 30-minute fires. CAFE simulations were performed using computational domains that modeled the experimental facility, and the measured wind conditions as boundary conditions [17-20]. These simulations were performed with different values for the model parameters. The calorimeter temperature results from these simulations were compared to the experimental data to determine the most appropriate model parameter values, and to benchmark the simulation methods.

The behavior of tunnel fires can be quite different from unenclosed fires [21]. For example, outdoor fires generally lose heat to the cool environment. In contrast heat from a fire to tunnel walls may be conducted into the walls, or it may be reflected or absorbed and re-radiated. Moreover, tunnel fires may have less access to oxygen than outdoor fires. This is especially true in long tunnels and if the fire lasts long enough to consume the oxygen in its immediate vicinity. This can significantly reduce the fire heat release rate compared to outdoor fires. The buoyancy induced flow of fresh air to the fire, which is affected by the flow of combustion products away from it, must be accurately calculated to predict fire effects. In some tunnels, blowers and vents are used to ventilate the tunnel. If buoyancy is the main driver of fresh air to the fire then it may be necessary to model the entire tunnel length to accurately simulate fire effects. This can be computationally intensive since some tunnels are kilometers in length. Before simulations can be used with confidence to predict tunnel fire behavior, they must be benchmarked against relevant experimental data.

A series of 98 tunnel fire experiments were performed in the Memorial Tunnel, an 850-m-long decommissioned highway tunnel in West Virginia with a 3.2% slope [22]. Gas temperature and speed were measured at several axial locations in the tunnel at different elevations. However, these tests did not measure heat transfer from the fire to objects engulfed in or near the fires. CAFE simulations have been benchmarked against data acquired in one forced and one naturally ventilated fire of the Memorial test sequence [23]. The CAFE simulations predicted the air temperatures and speed more accurately for the forced-ventilated fire test than it did for the naturally-ventilated one. The FDS code, which was used in the NRC study, was also benchmarked against data from these experiments [24, 25]. The accuracy of the FDS simulations was similar to that of the CAFE calculations.

The next section describes the construction and benchmark of the FE thermal model of the Nuclear Assurance Corporation’s (NAC) Legal Weight Truck (LWT) SNF transportation package [11] used in this work. The CAFE computational model of the Caldecott Tunnel fire is then described. Fire simulations are preformed in that domain first without the package, and then with the package at different locations within the tunnel. Package internal component temperatures are determined as functions of time during and after the fires.

NAC LWT MODEL

Figure 1 shows a finite-element thermal model of an NAC LWT transport package [11] constructed using PATRAN commercial software. A single square-cross-section pressurized water reactor assembly is at the center of the package. It is within a cylindrical aluminum support basket. Outside the basket are a stainless steel package body, a lead gamma shield, a stainless steel outer body, and a liquid-filled neutron shield tank with an outer stainless steel skin. A liquid overflow tank surrounds a portion of the package body, and aluminum honeycomb-filled impact limiters are at both ends. There are spacer fittings at each end of the fuel assembly. On the right hand side of Figure 1a is a stainless steel base that is permanently attached to the package body. A cylindrical lead shield is within the base. On the left-hand side a collar is attached to the body, and a removable lid fits into it. An O-ring seals the gap between the collar and lid. The dimensions and material properties used in this model were taken from the Safety Analysis Report (SAR) for the NAC LWT package [11].

In the current work we assume the void spaces within the package are filled with helium gas. Within the fuel region, the individual fuel rods and helium gas are replaced with homogenized solid elements with an effective thermal conductivity and an effective specific heat. These temperature-dependent effective properties were taken from the package SAR [11]. The fuel assembly total heat generation rate is 2500 Watts. In the current work we determine

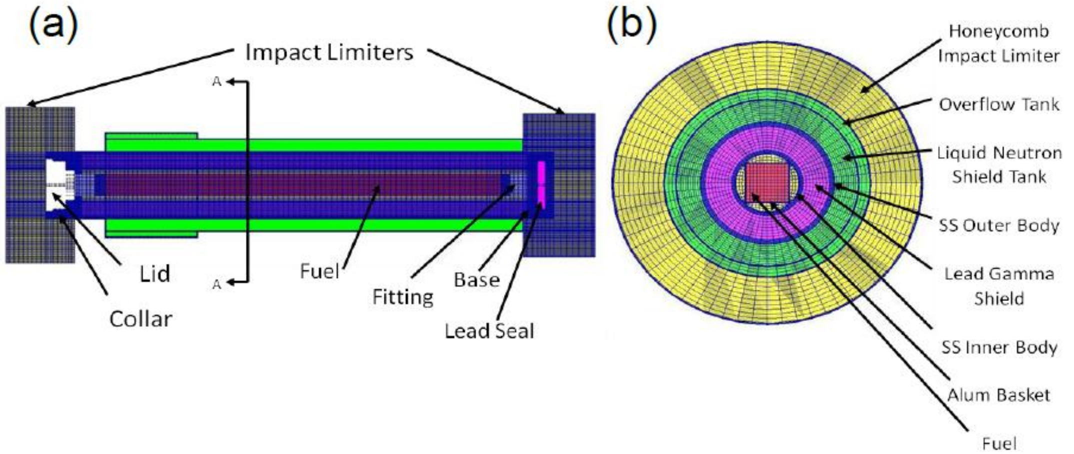

Figure 1 Finite Element Model of an NAC LWT Package (a) Axial cross section (b) View A-A, as seen in part (a)

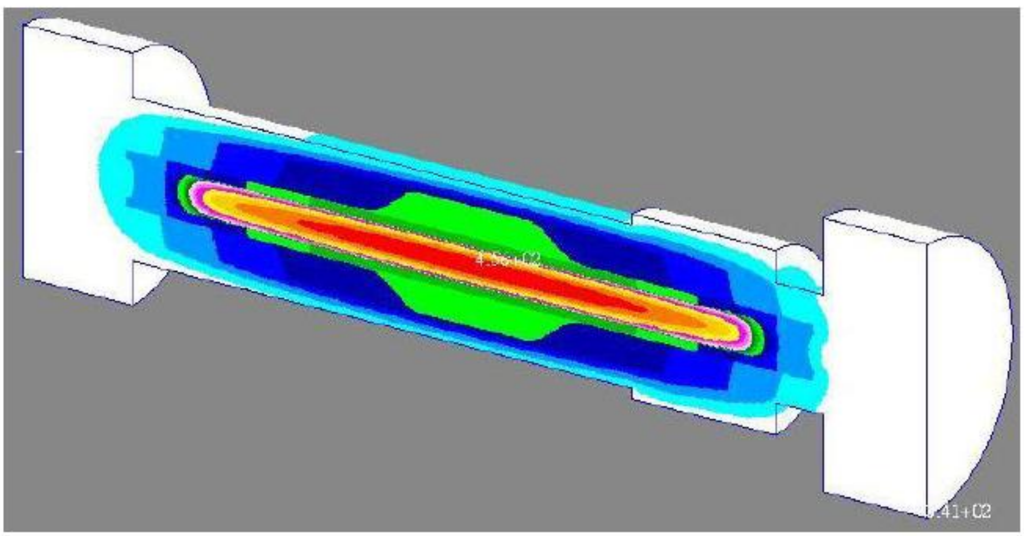

Figure 2 Normal Conditions of Transport Temperature Contours in an axial cross section

the maximum temperatures caused by the fire within the fuel cladding, the seal between the package lid and collar, and the seals of the package vent and drain ports. The drain and vent ports are near the left side of Fig. 1a. They are on the package body surface between the impact limiter and neutron shield tank. We assume that they are 45° from the top center of the package body.

The package steady state temperatures were first determined for Normal Conditions of Transport (NCT) [2]. Figure 2 shows temperature contours on an axial cross-section within the package. Table 1 reports the NCT maximum or peak temperatures within several package components from the current work. The NCT temperatures presented in the NRC study [8] are included in Table 1, and the difference between the current work and NRC results are also reported. The temperatures of all components from the current simulations are within 13°C (23°F) of those calculated by NRC, except for the peak fuel cladding.

The temperature difference between the peak fuel cladding and basket is 75°C (135°F) in the current work, but 101°C (182°F) in the earlier NRC simulations. To get a better understanding of this difference, we performed simulations of a single fuel element within isothermal basket walls using the effective thermal conductivity

Table 1 Comparison of Normal Conditions of Transport maximum component temperatures calculated in the current study with those calculated by Adkins et al. [8]

Peak Normal Conditions of Transport Temperatures [ºC]			
Component	Current Work	NRC [8]	ΔT
Fuel Cladding	171	210	39
Basket	96	109	13
Inner Shell	79	88	9
Gamma - Radial	78	87	9
NS - Skin	74	70	-4
Neutron Shield	76	73	-3
Steel Lid	67	55	-12
Impact Limiters	65	56	-9

method in the fuel region. When we use the conductivity given in the SAR [11] that assumes helium is the cover gas, we get a maximum temperature difference between the basket and fuel of 75°C (135°F). When we use the conductivity that assumes air is the cover gas we get a temperature difference of 101°C (182°F). This may indicate that air was used as the fuel cover gas for the NRC study.

The current model of the NAC LWT does not include the effect of permanent high-temperature damage to the liquid neutron shield and impact limiters. These permanent damage effects were included in the NRC package model [8].

CALDECOTT TUNNEL MODEL

Figure 3 shows the Caldecott Tunnel computational domain used in the current work. Figure 3a shows an end view cross section and includes the tunnel roadway, sidewalks, walls, ceiling, and the x- and y-axes. The domain length in the direction normal to Fig. 3a is L_T = 1000 m. One end of the transport package is shown and its center is 2 m above the roadway. A package on a truck trailer would be at roughly that elevation (the trailer is not included in this model). In the current work, the gas and ceiling temperatures are reported along a “Gas-Line” and a “Ceiling-Line.” The labeled dots in Fig. 3a show the lines are centered between the side walls, and their elevations above the roadway are indicated. Both lines run the full tunnel length. Lines in the walls of Fig. 3a show the computational mesh used in this work. It is more highly refined near the elevation and transverse location of the package than away from it. The same wall thermal conductivity, density and specific heat used in the NRC study are employed in the current work [10]. However, concrete ablation is not included in the current work.

Figure 3b shows a three-dimensional view of a tunnel region roughly halfway between the two portals. The roadway, one tunnel wall, both sidewalks and the outer surface of the package are shown. The tunnel roof and one of its walls have been removed for clarity. A black rectangle on the roadbed represents a 200-m^2 area that is used to model the fuel source. The center of the fuel pool is halfway between the tunnel portals. The origin of the z-coordinate is at the center of the fuel pool, and z increase (is positive) toward the uphill portal. The fuel pool is within the region z = ±10 m and x = ±5 m. The gravitation vector is in the y,z-plane, but is tilted by a 1.83° relative to the negative y-direction to model the tunnel’s 3.2% slope.

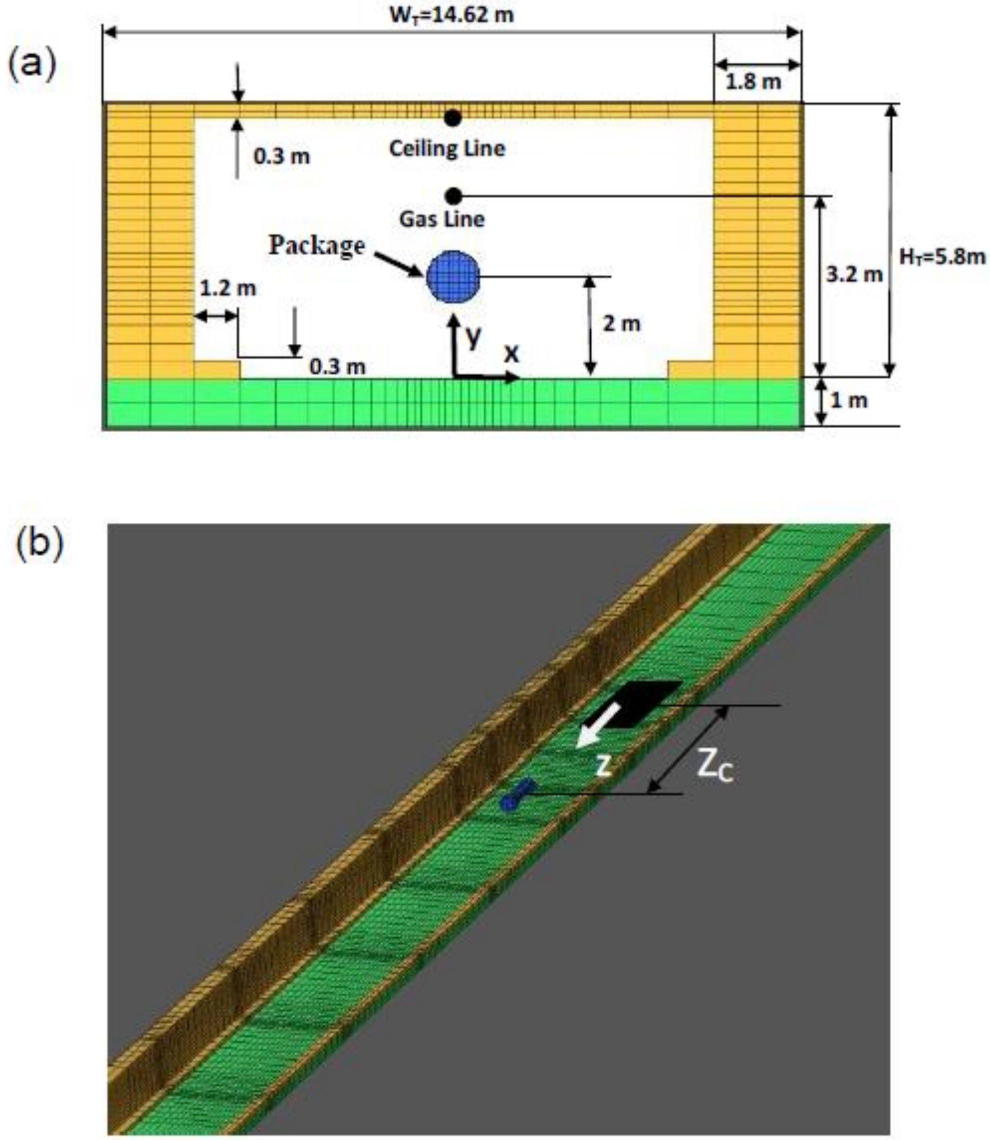

Figure 3 Caldecott Tunnel computational domain. (a) End view showing rectangular tunnel cross section, roof, walls, roadway, two sidewalks, dimensions and locations of the package and axial lines in the gas and wall surfaces (b) Three-dimensional view showing the roadway, sidewalks, and one wall. The exterior surface of the NACLWT package is shown. The Grid is more highly refined near the package than in the surrounding regions. Outside the frame of this view, the mesh is even less fine.

In the current work, simulations are performed with the package centered over the pool, and at seven other locations uphill of that location. The distances between the centers of the pool and package are Z_C = 0, 20, 30, 40, 60, 80, 100 and 120 m. Simulations are also performed with no package in the tunnel.

The mesh in Fig. 3b is more refined in the region between z = -50 m and 130 m, which includes the fuel pool and all 8 package locations, than it is outside. The same mesh is used for all package locations. Figure 3a shows that some axial-locations have a higher mesh density than others. The dense mesh lines accommodate the locations of the package ends, impact limiters and overflow tank, for each package location. Outside z = -50 to 130 m the axial dimension of the grid cells expands based on a power law distribution. The minimum mesh separation is 0.3 m near the package, and the maximum separation is 59 m near the tunnel portals. Two mesh refinements are used in this work. The nominal mesh, which is used for most results reported in this work, has 24, 22 and 198 cells in the x, y and z-directions for a total count of 104,544. In the refined mesh the cell counts in the x, y and z directions are 32, 32, and 198, for a total of 202,752. It is used to check mesh sensitivity of the calculation.

In the current simulations, the properties of JP8 jet fuel are used to model the gasoline. The fuel is injected uniformly from the 200-m^2 fuel pool for forty minutes at a constant rate of 0.064 kg/m^2s. The simulations continue after fuel injection ceases to model the cool down of the tunnel walls, gases and package. The timescale used in this work, t, begins when the fire is ignited. Hydrostatic boundary conditions are used at the two portals to allow room temperature fresh air and products of combustion to flow in and out of the tunnel.

"No-package" simulations are used to calculate the conditions during the Caldecott Tunnel fire without a transport package in the tunnel. They use the CAFE computational domain described in this section, and are not linked with the package finite element model. Initially the tunnel gas is at room temperature and zero velocity. Simulations using the nominal and refined grids require roughly 5 and 13 days, respectively, to calculate the behavior of a 40 minute tunnel fire.

In "Package Response" simulations, the tunnel fire computational domain is linked to the package finite element model discussed in the previous section. Initially the package temperatures are those from the NCT calculation. The fire and package simulations run alternately for one second each. The nominal tunnel mesh is used for these calculations. The linked package/fire calculation simulates 40-minute fires and roughly 4-hour post fire periods, and they require roughly 11 days.

RESULTS

No-Package Simulations

This subsection presents tunnel fire simulations that do not include the package. Simulations using the nominal and refined grid were performed for a 40 minute fire, but post-fire cool-down simulations were not carried out.

Figure 4a shows the fire heat release rate within the tunnel domain versus time. This heat release rate is directly related to the total reaction rate within the domain. Results from simulations using the nominal and refined computational grids are shown. They are essentially identical, especially early in the fire. This indicates the simulation results are mesh-independent. The heat release rate jumps to 250 MW within seconds of fire ignition. Over the next 1.4 minutes it increases to roughly 430 MW and oscillates around that value for another minute. It then decreases to 300 MW, increases slowly for the next ten minutes, and levels out at roughly 380 MW. To understand the time-dependent heat release rate we must consider the masses of oxygen and fuel available for combustion.

Figure 4b shows the total masses of oxygen (O_2) and fuel (JP8) within the tunnel versus time. For the first 2.5 minutes of the fire the oxygen mass decreases rapidly because the rate of consumption by the reaction is far greater than the rate it enters the tunnel through its portals. It appears that the high heat release rate at the beginning of the fire (seen in Fig. 4a) is caused by the availability of oxygen in the vicinity of the fuel supply. After the oxygen is depleted the reaction rate decreases. The oxygen mass in Fig. 4b then becomes steady. This indicates there is a balance between the rate at which oxygen is being consumed and is flowing out of the uphill portal with the rate it is entering through the downhill portal. The mass of fuel in the tunnel increases at the beginning of the fire. This is because the fuel, which enters at a constant rate from the pool, is flowing into the domain at a higher rate than it is consumed by the fire or flowing out of the uphill portal. After t = 2.7 minutes, the accumulated fuel mass begins to decrease, and it reaches a steady value at roughly t = 15 minutes.

Figure 5 shows the axial component of the gas speed w, at the center of the tunnel cross section 110 m (360 feet) uphill of the fuel, at location (x, y, z) = (0, 2.75 m, 110 m). Buoyancy forces and gas expansion, both caused by fire heating, accelerate the gas for the first 20 minutes of the fire. At that time, a balance between buoyancy forces and drag against the tunnel walls causes the velocity component to reach a steady state level of 14 m/s (31 miles/hr). This fast flow of air uphill of the fire induces air to enter the downhill portal. Even though the heat release rate in Fig. 4a decreased at t = 2.4 minutes because the oxygen in its immediate vicinity was depleted, it was replenished by the incoming flow from the downhill portal. This causes the increase in heat release rate.

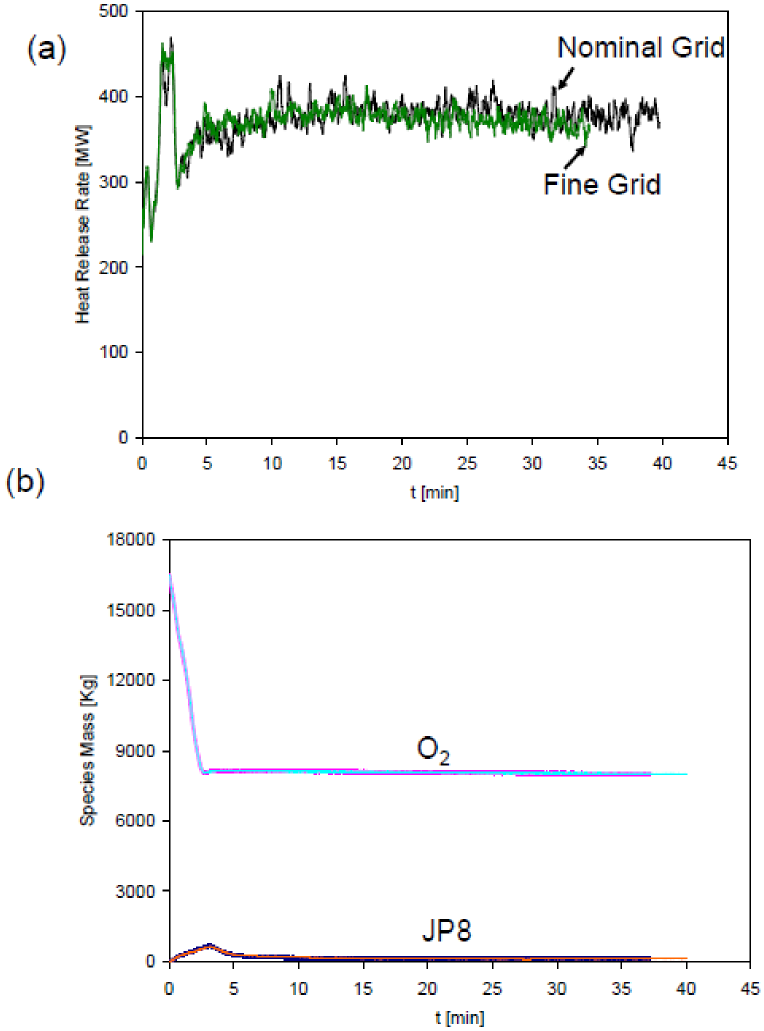

Figure 4 Time-dependent quantities intigrated over the tunnel volume for no-package simulations. (a) Fire heat release rate from simulations using two different grids (Z_C = 0 and 40 m). (b) Total mass of oxigen and fuel for a simulation using Z_C = 0.

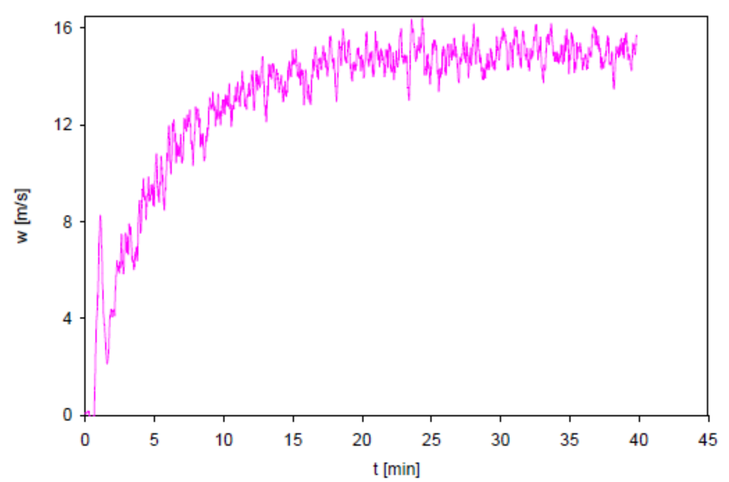

Figure 5 Axial speed component at (x, y, z) = (0 m, 2.75m, 110m) versus time for the no-package simulation using the nominal mesh

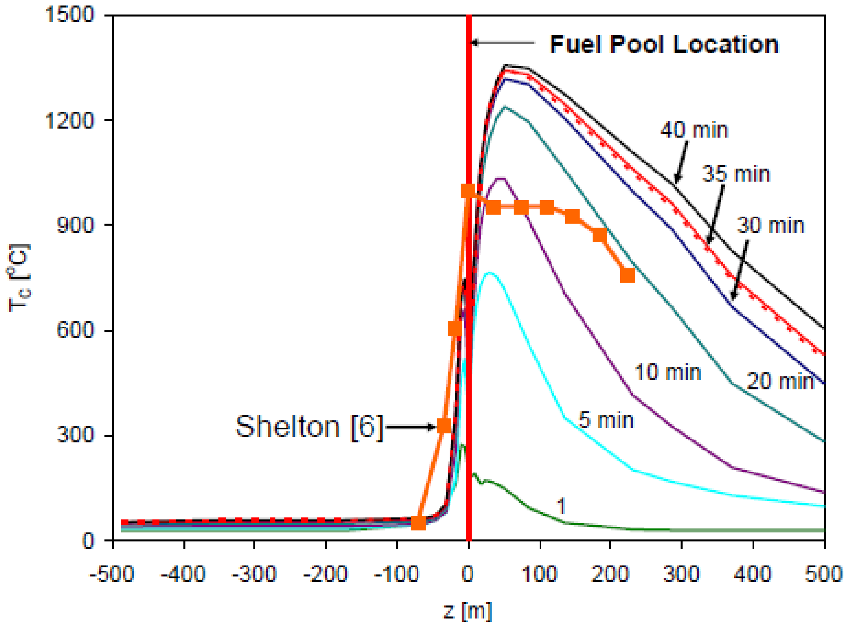

Figure 6 Ceiling temperature versus axial location at seven different times during the fire for the no-package simulation. The solid lines are from a simulation using the nominal mesh, while the dashed line is from a refined mesh simulation.

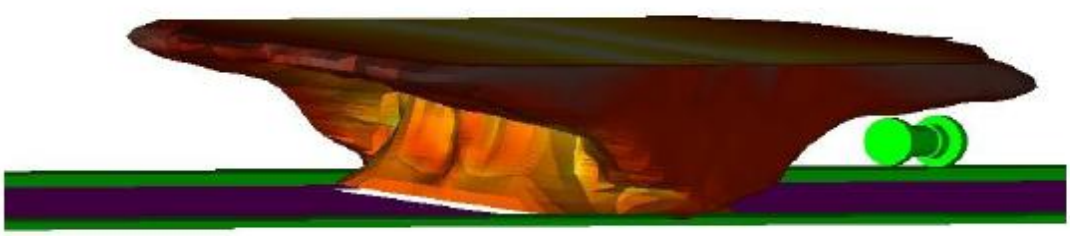

Figure 7 Fire surface temperature contour 10 seconds after the beginning of a simulation with a package in the tunnel at Z = 40 m. The fire surfaces in this figure are at the tunnel ceiling, wall, and at locations where the products of combustion mass fraction is 0.07.

Figure 6 shows the temperature along the ceiling-line in Fig. 4a versus axial location. A vertical line shows the location of the fuel pool. Results are given at 7 times during the fire. The solid lines show results from the nominal mesh, while a dashed line shows a result from the refined grid at t = 35 minutes. Good agreement between the nominal and refined simulation results indicates the simulations are essentially grid-independent. The ceiling is near room temperature far downhill of the fuel, but increases sharply at z = ~-45 m. It reaches a local peak lat z = -10 m and then dips to a minimum over the pool. This dip may be because the gas mixture is fuel rich over the pool and so there is insufficient oxygen for combustion. The temperature increases further uphill of the fuel (where the mixture is less fuel rich) and reaches a maximum between z = 20 and 51 m. The location of the maximum temperature moves away from the fuel (further uphill) as time increases. The temperature decreases as distance from the fuel increases, but is above 600°C at the tunnel exit at the end of the fire.

The tunnel temperature versus location for the actual Caldecott Fire, estimated based on the oxidation behavior of materials collected after the fire [6], are included in Fig. 6. The maximum estimated temperature was 1000°C (1832°F) near the fuel source. It was roughly 950°C (1742°F) between z = 0 and 110 m (0 and 360 feet), and dropped off further uphill of the fuel. The temperatures were much lower downhill of the fire, and were close to atmospheric conditions at z = -70 m. These data are presented for comparison with the simulated ceiling temperatures. However, the relationship between the material-based temperature estimates and the ceiling temperature is not immediately clear, and the uncertainty of the temperature estimates has not been quantified. There was also uncertainty about the actual fire duration, which was estimated to be between 22 and 40 minutes.

The maximum simulated ceiling temperature for the 40 minute fire was located 50 m downhill from the fuel source, and was roughly 350°C (662°F) hotter than the value based on the material samples. At t = 20 minutes, the simulated fire temperature is roughly 240°C (464°F) hotter than the estimated temperature. The simulated temperature may be hotter than the estimated values because endothermic concrete ablation is not included in the current computational model.

Package Response Simulations

This subsection presents simulations with the package in 40 minute tunnel fires. The post-fire cool-down period, after fuel injection into the domain ceases, is also calculated. The nominal mesh was used to calculate temperatures in the tunnel ceiling and gas temperatures as well as the package, with the package at 8 different locations.

Figure 7 shows a three-dimensional plot of the fire surface at t = 10 sec with the package at Z_C = 40 m. The fire surface is defined as the locations where it contacts the tunnel ceiling or walls, and the locations inside the domain where the mass-fraction of the products-of-combustion is 7%. The surface is colored according to its local temperature. The figure shows the fire volume emanates from the fuel pool on the roadbed, and it spreads near the tunnel ceiling. At the time shown in the figure the high temperature region has not yet engulfed the package.

Figure 8 shows 11-second window averages of the simulated heat release rate versus time for all 8 package locations. The results for each location are very similar to each other, and to the no-package simulations in Fig. 4a. However, when the package is present the period of time at the beginning of the fire when the heat release rate is 450 MW lasts longer than when there is no package. Moreover, Fig. 8 shows that even after injection of fuel into the domain ends, combustion continues for roughly another minute. This is because fuel vapor that accumulated in the domain continues to burn.

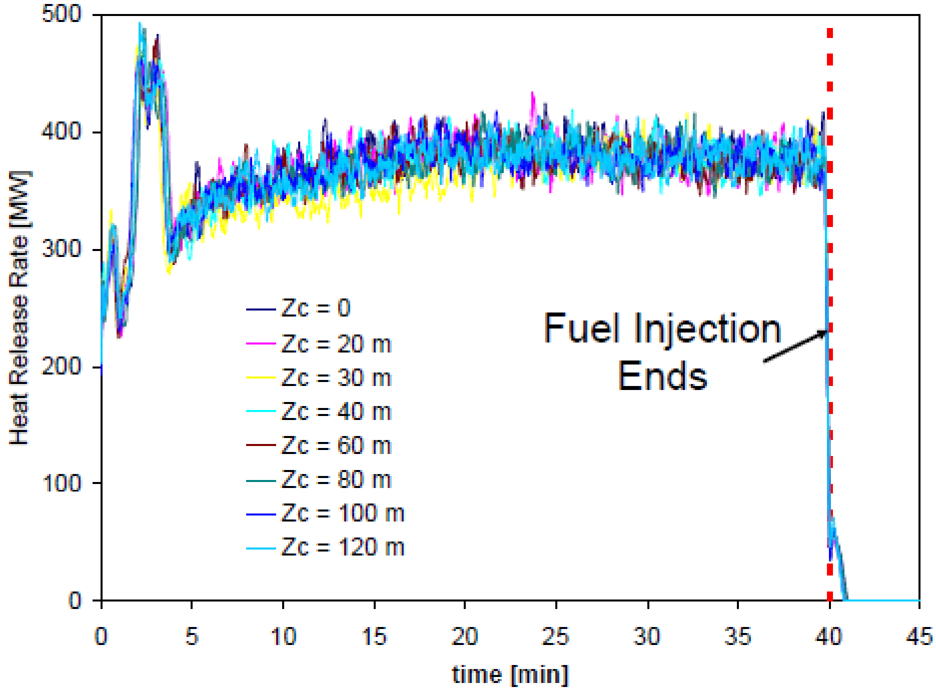

Figure 8 10-second window-average of the heat release rate versus time for simulations with the package at 8 different locations.

Figure 9 shows the simulated gas-line temperature versus axial location during the fire with the package at Z_C = 60 m. Figures 9a and 9b cover time periods t = 1 – 3 minutes, and t = 5 – 40 minutes, respectively. Vertical lines show the location of the fuel supply. Figure 9a shows that at t = 1 minute the gas line temperature near the pool is much greater than atmosphere conditions. The edge of the hot zone extends between z = -160m – 260 m. At t = 2 and 3 minutes, the induced draft in the tunnel causes the downhill edge of the hot zone to move closer to the fuel pool, and the downhill edge to propagate further away. For t = 5 – 40 minutes, Fig. 9b shows that the temperature profile downhill of the fuel remains essentially constant. The maximum gas temperatures increase and their locations move uphill as time after ignition increases. At the end of the fire the gas line temperature at the uphill portal is greater than 670°C (1238°F).

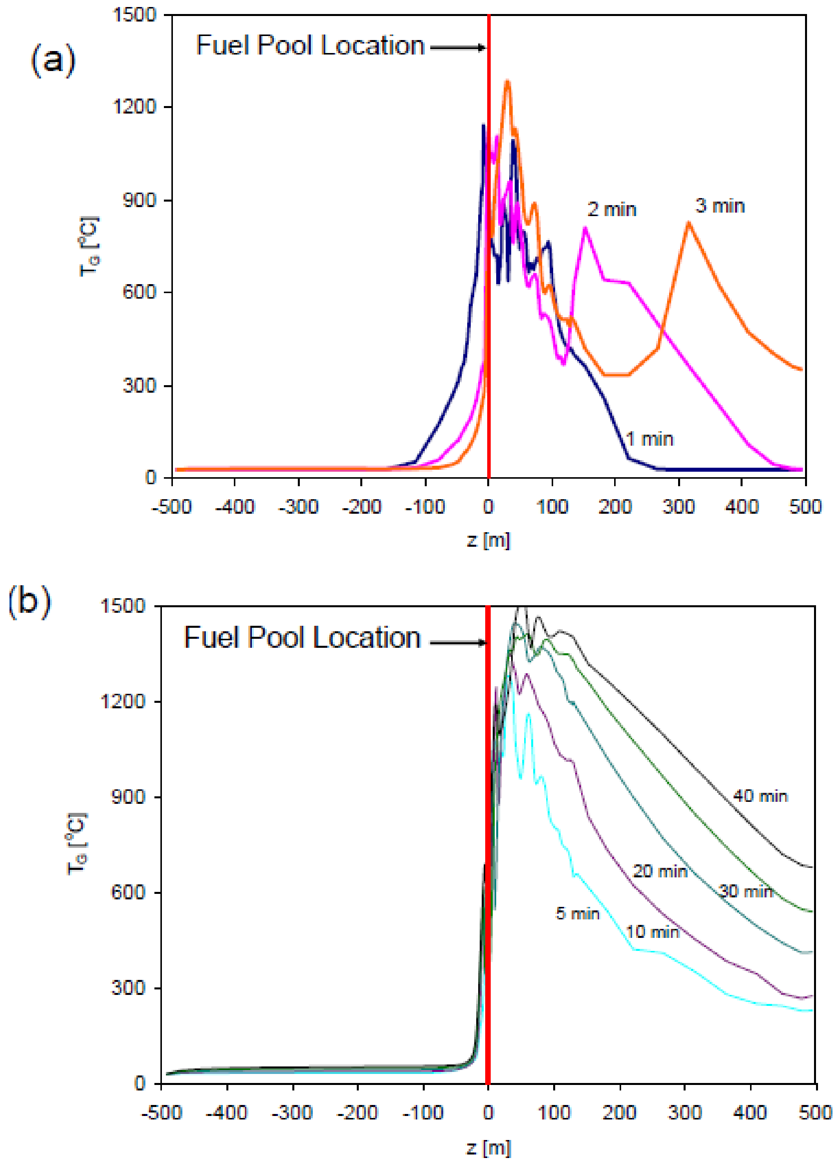

Figure 9 Gas line temperature versus axial location at different times during a fire with the package at Z_C = 60 m. (a) t = 1 – 3 minutes. (b) t = 5 – 40 minutes.

Figure 10 shows the ceiling gas line temperature versus axial location with the package at Z_C = 60 m. Solid lines show results for times during fuel injection ($t \leq 40$ minutes), and dashed lines are for the cool down period (T > 40 minutes). The fuel pool location is also indicated. The shapes of the temperature profiles during the fire are very similar to those for the no-package simulations (Fig. 6). The result for t = 41 minutes shows that the ceiling temperature between z = 50 – 300 m decreases significantly one minute after the fire is extinguished. The ceiling temperature continues to decrease as time increase, but it is still roughly 170°C (338°F) near the package location Z_C = 60 m two-hours after the fire is extinguished.

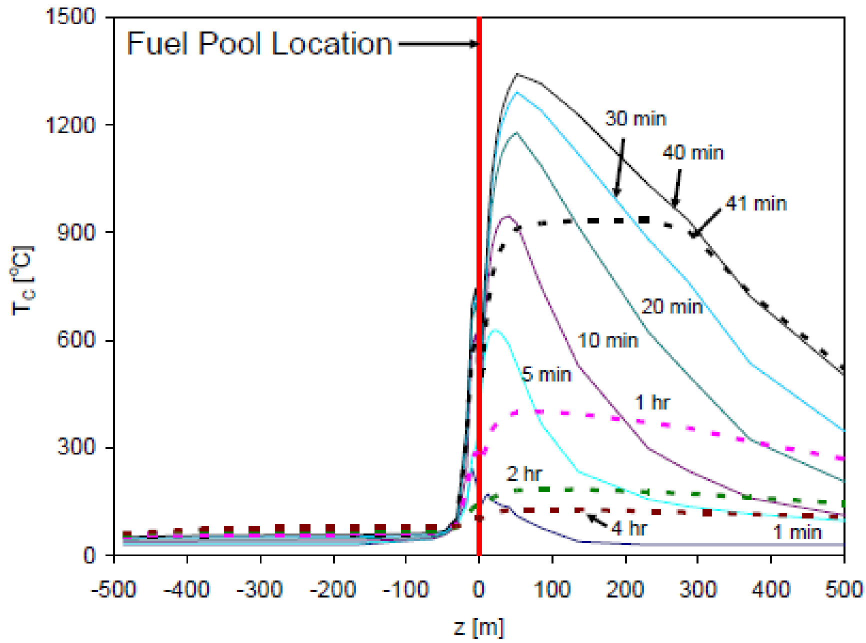

Figure 10 Ceiling temperature versus axial locations at different times during a fire with a package at Z_C = 60 m.

Figure 11 is a plot of the *maximum* ceiling-line temperature versus time. Results are given from the package response simulation with Z_C = 60 m, and the no-package calculation. While the ceiling-line temperature profile shapes in Figs. 6 and 10 are similar, the maximum ceiling-line temperatures are not the same. Figure 11 shows that when the package is present, the maximum ceiling temperatures are up to 80°C lower than when it is absent. This may be because the large and thermally massive package is relatively cool compared to the fire. It absorbs energy from the fire and slows the heating of the tunnel environment.

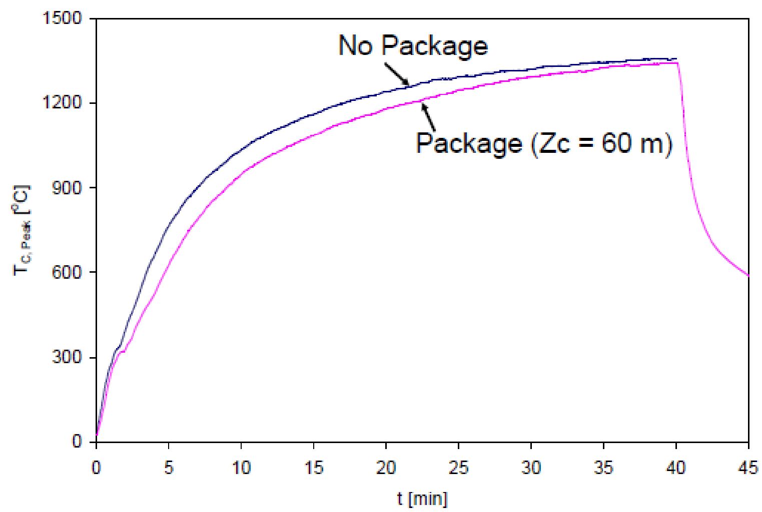

Figure 11 Maximum ceiling temperature versus time for simulations with no package, and with a package at Z_C = 60 m.

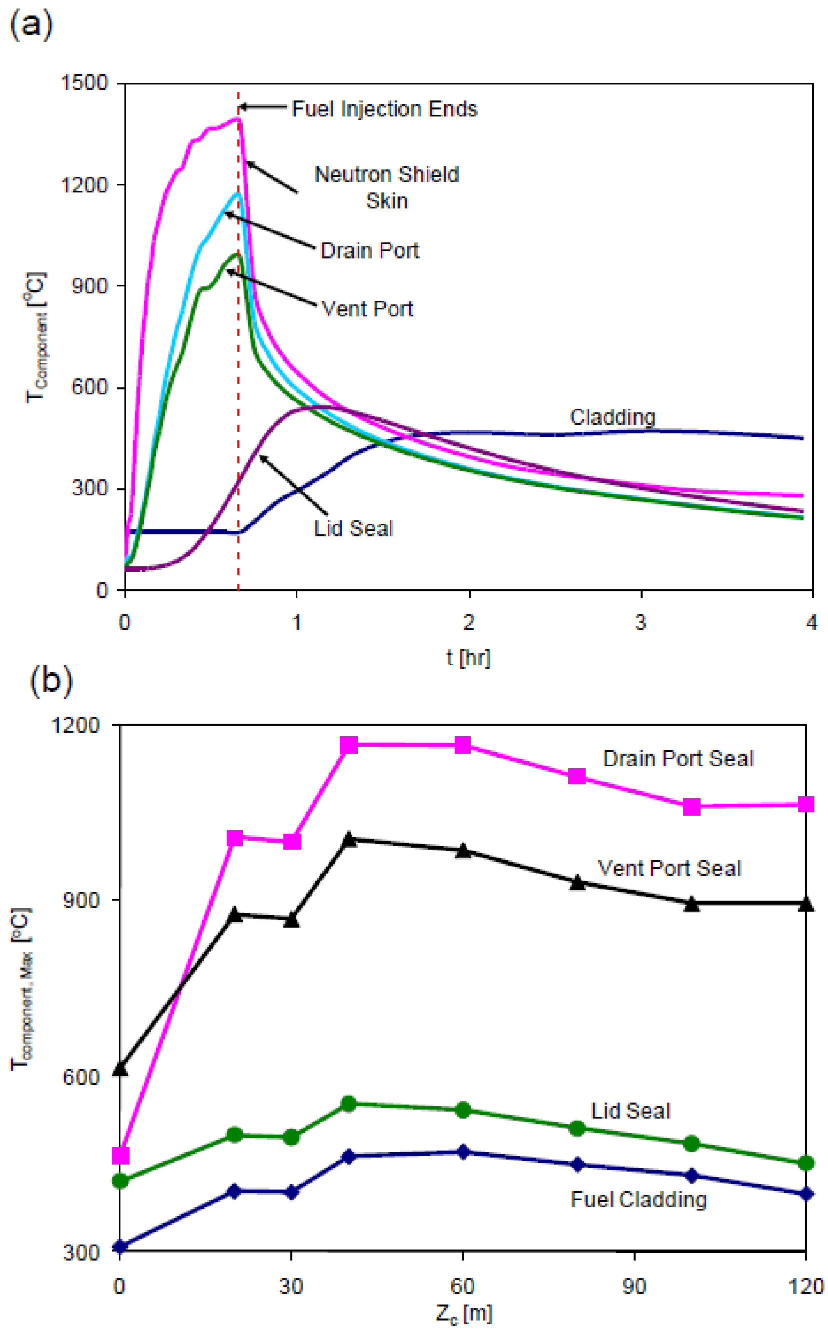

Figure 12 Package component temperature response to the Caldecott Tunnel fire scenario. (a) Component temperature versus time for a package at Z_C = 60 m. (b) Maximum component temperature caused by the fire versus package location.

Figure 12 shows the temperature response of different package component during and after the fire. Figure 12a shows the maximum temperatures within the neutron shield skin, drain port seal, vent port seal, lid seal and fuel cladding versus time with the package at Z_C = 60 m. The first three of these components are near or at the package outer surface. Their temperatures begin to rise soon after the fire begins and they all peak at t = 40 minutes, when fuel injection ends.

The lid seal and fuel cladding are further from the package surface. There is a delay between the beginning of the fire and the time when the temperature of those components begin to rise. Their temperatures continue to rise after the fire is extinguished because heat continues to diffuse to these locations from the hotter outer portions of the package. At this package location, Z_C = 60 m, the lid seal and cladding temperatures peak at times t = 1 hr and 2.7 hr, respectively.

Figure 12b shows the peak temperatures caused by the fire in the four containment components (fuel cladding, and the seals of the drain port, vent port and lid) versus package location. These peak temperatures are relatively low when the package is directly over the fuel pool (Z_C = 0). Figures 9 and 10 show that the gas-line and ceiling-line temperatures above the fuel pool are relatively low. They also show that the gas and ceiling temperatures increase further uphill, reach a peak and then decrease. The same behavior is observed in the peak temperatures shown in Fig. 12b. The seals of the drain port, vent port and lid all experience their highest temperature at Z_C = 40 m. The highest fuel cladding temperature is observed at Z_C = 60 m.

The limit temperature for the seals of the drain and vent ports is 391°C (735°F) whereas the limit temperature for the metallic seal in the lid seal region is 427°C (800°F). The fuel cladding may experience fuel cladding creep deformation, or burst rupture if its temperature is above 570°C (1058°F) or 750°C (1382°F), respectively. The vent and drain port seals exceed their limit temperatures at all package locations considered in this work. The lid seal also exceeds its limit temperature at all package locations except Z_C = 0. However, under none of the circumstances examined in this work does the cladding temperature exceed either of its limit temperatures.

Table 2 summarized the limit temperature for each containment component. The hottest temperature for each component predicted by the current work and the NRC analysis are also included. The current work predicts higher component temperatures than the NRC analysis. This may be because the current work does not include endothermic concrete ablation of the tunnel walls. The current work and the NRC analysis both predict that the drain and vent port seals exceed their limit temperatures. While the NRC analysis does not predict the Caldecott Tunnel fire scenario would cause the lid seal to exceed its limit temperature, the current work does. Neither the current work nor the NRC analysis predicts the fuel cladding temperature will exceed its limit temperature.

Table 2 Limit and Peak Temperatures for Containment Components for the Caldecott Tunnel Scenario Predicted by the NRC Analysis [8] and the Current Work

Containment Component	Limit Temperature [°C]	Peak Temperature [°C]	
		Current work	NRC [8]
Drain Port Seal	391	1167	698
Vent Port Seal	391	1005	698
Lid Seal	427	552	423
Fuel Cladding	570	471	279

SUMMARY

Spent nuclear fuel (SNF) transport packages must be able to withstand a series of severe events before they receive a Certificate of Compliance from the US Nuclear Regulatory Commission. This series includes a 10-m-drop onto an unyielding surface, a 1-m-drop onto a puncture bar, a 30-minute-engulfment in an 800-ºC-fire, and water submersion. The NRC conducted an analysis to predict the response of a certified SNF legal weight truck transport package assuming it was in proximity to the 1982 Caldecott roadway tunnel fire, and found that the cladding temperature would not have exceeded its limit temperatures. The objective of the current work is to perform a similar analysis using different methods to assess the validity of those results.

In this work a finite element thermal model of the same legal weight truck package assessed in the NRC analysis was constructed using the PATRAN finite analysis package. The model employed a homogenized fuel region model with temperature-dependent effective thermal conductivities and specific heats. It did not include permanent high-temperature damage to the impact limiters or neutron shield. The package model was linked to Container Analysis Fire Environment (CAFE) simulations of the Caldecott Tunnel fire. The tunnel model was 1000 m long and had a 4% slope. Fresh air and products of combustion were allowed to flow into and out of the portals at each end. Fuel was injected into the domain at a constant rate for 40 minutes from a 200-m^2 pool at the midpoint of the domain. The tunnel mesh was more highly refined in the region that included the fuel injection pool and package than it was uphill or downhill of those objects. Endothermic ablation of the concrete walls was not included.

Simulations *without* the package indicate that the fire heat release rate was 450 MW during the first 3 minutes of the fire when oxygen near the fuel was abundant. After the oxygen in the immediate vicinity of the fuel was consumed the heat release rate decreased to 300 MW, but it rose to 380 MW after the fire induced a flow of fresh air through the tunnel. After fire durations of 20 and 40 minutes, the maximum ceiling temperatures of 1240°C and 1350°C, respectively, were located 40 m uphill of the fuel pool center. The maximum temperature estimated in an investigation of the Caldecott accident, based on corrosion of samples acquired after the fire, was 1000°C. This difference may be due to the current simulations neglecting concrete ablation.

Fire and post-fire simulations were then performed with the package centered above the fuel pool, and 20, 30, 40, 60, 80, 100 and 120 m uphill. Even though fuel injection ceased after forty minutes, the heat release rate did not reach zero for another minute due to reaction of fuel vapor that had accumulated in the tunnel. The time dependent temperatures of four containment components (the seals for the package vent port, drain port and lid, as well as the fuel cladding) were determined during and after the fire. The lid seal and fuel cladding, which are significantly inside the package surfaces, reached their maximum temperatures well after the fire was extinguished. This delay was due to heat continuing to diffuse to these locations from the hotter outer regions of the package. The maximum temperature for each package component reached its highest level when the cask was located 40 to 60 m uphill of the fuel. The vent and drain port seals exceed their limit temperatures at all package locations considered in this work. The lid seal also exceeds its limit temperature when the package was not directly over the fuel. However, under none of the circumstances examined in this work does the cladding temperature exceed its limit temperature.

FUTURE WORK

The size of the fuel pool in the actual Caldecott Tunnel fire is not known. Future simulations will be conducted with a 30 m^2 pool to determine if the results are different from the current simulations, which used a 200 m^2 pool. The concrete walls of the actual Caldecott Tunnel were severely spalled after the fire. Future simulations will include endothermic concrete ablation, which may reduce the simulated temperatures. Finally, a model for permanent high-temperature damage to the impact limiters and liquid neutron shield will be incorporated into the package model.

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