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Severe Transportation Accidents: Do Used Nuclear Fuel Transportation Packages Survive Real World Accidents?

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ABSTRACT

In 2007, a severe transportation accident occurred near Oakland, California, on a section of Interstate 880 known as the "MacArthur Maze," involving a gasoline tanker truck which impacted an overpass support column and burst into flames. The fire caused the collapse of portions of the Interstate 580 overpass onto the remains of the tractor-trailer. The U.S. Nuclear Regulatory Commission, with assistance from Pacific Northwest National Laboratory, the Center for Nuclear Waste Regulatory Analyses, the Southwest Research Institute, and the National Institute of Standards and Technology, examined the accident conditions in order to characterize the fire and collapse that occurred, analyzed material samples from the collapsed I-580 overpass as well as the gasoline tanker truck, and developed a fire model of the accident. This was followed by development of a finite element analysis model to determine the impacts of this accident on the thermal and structural performance of a spent nuclear fuel (SNF) transportation package. The analysis results will be used to determine any potential regulatory implications related to the safe transport of SNF in the U.S. This paper provides a summary of this effort and presents some preliminary results and conclusions.

NOMENCLATURE

AST – adiabatic surface temperature
Caltrans – California Department of Transportation
CHP – California Highway Patrol
CFR – Code of Federal Regulations
FDS – Fire Dynamics Simulator
HAC – Hypothetical Accident Condition
LWT – Legal Weight Truck (package)
NIST – National Institute of Standards and Technology
NRC – United States Nuclear Regulatory Commission
PNNL – Pacific Northwest National Laboratory
PWR – pressurized water reactor
SNF – spent nuclear fuel
SwRI® – Southwest Research Institute®

BACKGROUND

The primary objectives of the work described in this paper are two-fold. The first objective is to assess the severity of the MacArthur Maze fire by evaluating the highway structure and other materials exposed to the fire and to estimate the maximum temperatures experienced by those materials during the event. The second objective is to compare the accident with the hypothetical accident condition (HAC) fire exposure defined in Title 10 of the Code of Federal Regulations (CFR), Part 71, "Packaging and Transportation of Radioactive Material" [1] to assess the potential impact of this type of accident on a spent nuclear fuel (SNF) transportation package.

The accident occurred on Sunday morning, April 29, 2007, in an area commonly known as the "MacArthur Maze," a network of connector ramps that merge highways I-80, I-580, and I-880 in Oakland, California. The fire started at about 3:38 a.m. after a gasoline tanker truck carrying 32,500 liters [8,600 gallons] of gasoline, heading south along I-880 and nearing the I-580 overpass, lost control, rolled onto its side, and slid to a stop on the 21-foot-high ramp connecting westbound I-80 to southbound I-880. The fire eventually led to the collapses of two sections of the I-580 overpass.

The main portion of the fire, fueled by gasoline leaking from the tanker, spread along a section of the I-880 roadway, and encompassed an area of roughly 30 m [100 ft] in length by 10 m [33 ft] in width. Some of the gasoline went through the scupper drain on I-880 and burned on the ground around an I-880 roadway support pillar. The fire on the I-880 roadway heated the steel girders on the underside of the I-580 overpass to temperatures at which the steel strength was reduced and was insufficient to support the weight of the elevated roadway. A portion of the I-580 overpass (between Bents 19 and 20[1]) completely collapsed onto

[1] The transverse support locations for the elevated roadway are referred to as "Bents" and are labeled in Figures 1 and 2.

the I-880 roadway about 17 minutes after the fire started, based on surveillance video taken from a water treatment plant adjacent to the highway interchange. At the same time, a second portion of the I-580 overpass (between Bents 18 and 19) began to sag heavily and eventually partially collapsed approximately 40 minutes after the fire began. Due to the collapse of the two I-580 spans, the fire was significantly reduced in size for the remaining 60 minutes of the fire duration. An image captured from the video at 16.7 minutes, just before the collapse of the first overhead span, is shown in Figure 1. A photograph of the scene after the fire was extinguished (from later that day) is shown in Figure 2 [2].

Figure 1. MacArthur Maze fire at +16.7 minutes (video image at 03:54:24.61 PDT)

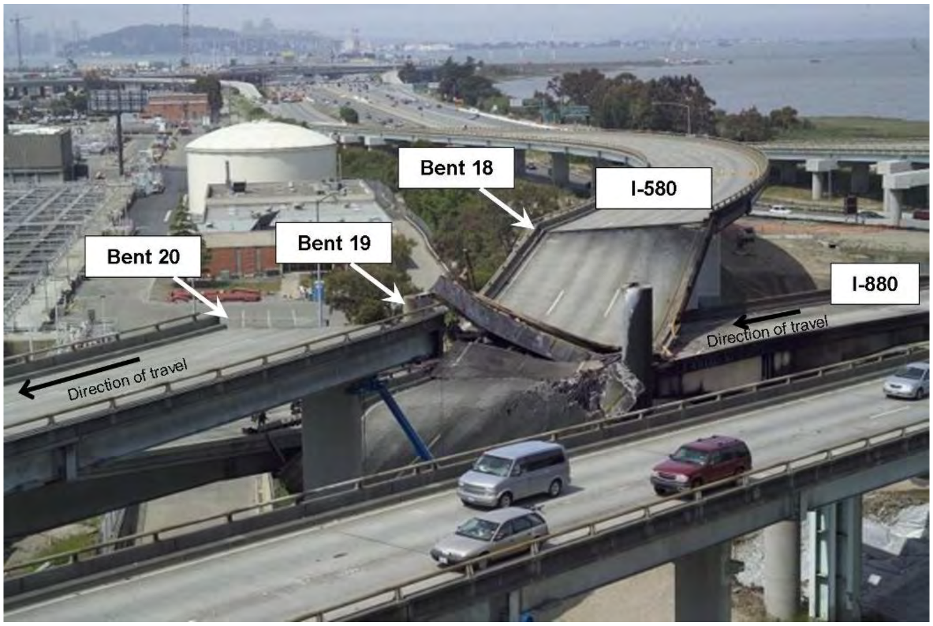


Figure 2. Post-fire aerial view of the collapsed section of I-580 looking west.

DETERMINING FIRE TEMPERATURES: THE MACARTHUR MAZE FIRE

Examining Physical Evidence

Initial media reports of the MacArthur Maze accident suggested that the fire could have reached temperatures as high as 1,650°C [3,000°F]; however, no direct temperature measurements were taken of the fire. This estimate fails to take into account two crucial factors: (1) the maximum temperatures achievable in an open hydrocarbon-fueled pool fire and (2) the temperature-dependent nature of the strength of structural steel. Based on experimental and analytical evaluations of large pool fires [3], a consistent estimate of the bounding flame temperature for these types of fires is approximately 1,000ºC (1,832ºF). Higher temperatures may be achievable if the fire is confined in a manner that does not restrict the flow of oxygen to the fire or remove significant heat from the fire by means of conduction, evaporation, or ablation (spalling). However, the upper limit is only about 1,350ºC (2,462ºF), based on tunnel fire testing [4, 5].

Review of the documentation compiled by Caltrans during the demolition and repair of the overpass, as well as examination of the I-580 overpass girders after the demolition, revealed no indications that any of the steel girders were exposed to temperatures where melting would be expected. Other items that aided in determining the fire temperature included: (1) melting of alloys used on the tanker truck, (2) solid-state phase transformations in the steel girders, (3) spalling of concrete, and (4) damage to paint. NRC and SwRI® staff collected and analyzed material samples from the steel girders and the tanker truck to estimate exposure temperatures. Spalling of the concrete was observed on the upward facing surface of the I-880 roadbed, the physical extent of which was measured by Caltrans. Damage to the paint of the steel girders also served as a useful indication of exposure temperature, especially with the extensive photographic documentation available from Caltrans [2].

MacArthur Maze (I-580 Overpass) Samples

Samples of steel girders collected from the collapsed I-580 overpass underwent metallurgical analyses to determine the effect of the fire temperature on the microstructure of the materials. The approximate locations of the samples collected from the collapsed structure are shown in Figure 3 [2]. Table 1 provides a list and a brief description of the samples that the staff collected during a visit to the accident site in June, 2007.

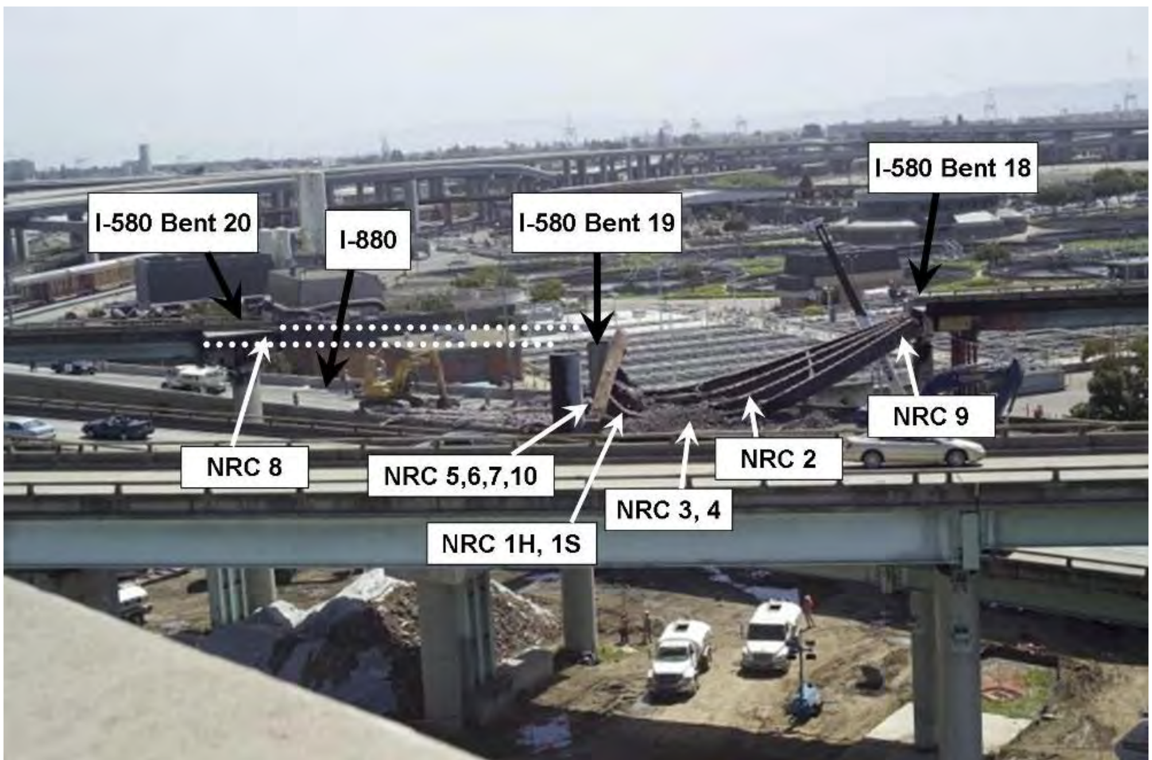


Figure 3. MacArthur Maze during demolition (Viewed from the southwest)[2]

[2] Bents 18 - 20 and approximate locations of samples are shown. Dotted lines represent pre-accident overpass structure that was demolished and removed prior to this photograph.

Table1: Description of Samples Collected

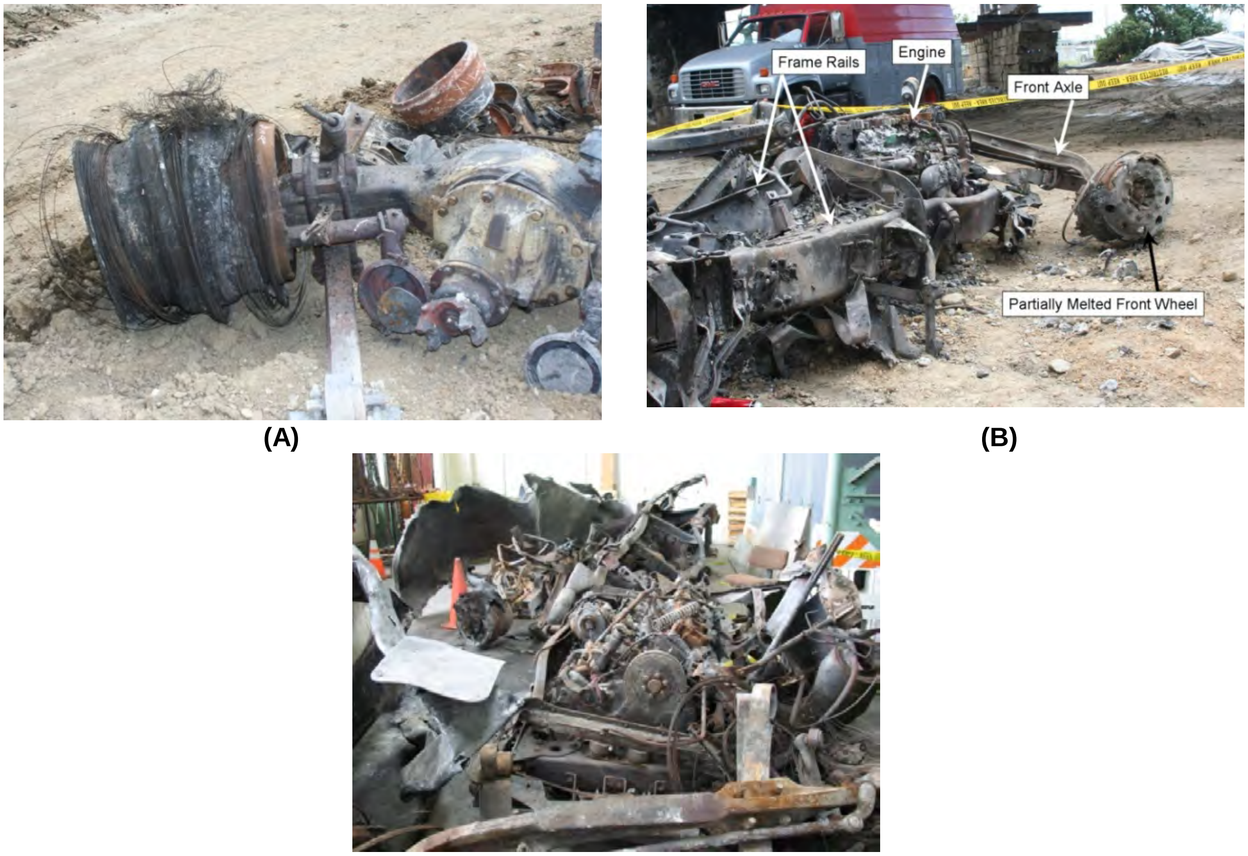
Sample Number	Description
NRC 1H	Plate Girder 3 at Bent 19 end with rivet holes. Specimen did not contain weld metal.
NRC 1S	Plate Girder 3 with stiffener near Bent 19. Specimen contained weld metal.
NRC 2	Plate Girder 4 with Butt Weld. Specimen contained weld metal.
NRC 3	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener heavy distortion. Specimen contained weld metal.
NRC 4	Plate Girder 5 likely located between Bent 18 and Bent 19 with stiffener medium distortion. Specimen contained weld metal.
NRC 5	Box Beam Cap 7 lower plate with side and weld. Specimen contained weld metal.
NRC 6	Plate Girder found attached to Box Beam Cap 8 with reduction in area.
NRC 7	Rivet head located in Box Beam Cap 8.
NRC 8	Plate Girder 10 Near Bent 20 Web and plate with weld. Specimen contained weld metal.
NRC 9	Plate Girder 12 with stiffener near Bent 18. Specimen contained weld metal.
NRC 10	Flakes peeled off of plate girder angles on Box Beam Cap 8.

Analysis of the Tanker Truck Samples

In March, 2008, staff from SwRI® and NRC were given access to the Caltrans storage facility where the remains of the tanker truck involved in the accident were stored, and collected several samples for metallurgical analysis. At the time of the accident, the tanker truck was engulfed in fire, prior to the overpass collapse, and the staff sought to characterize the exposure temperatures in the vicinity of the tanker truck. In order to accomplish this, a variety of materials were collected including glass, aluminum alloys, steel, copper, brass, and stainless steel. Descriptions of the samples collected are provided in Table 2. Photographs of the truck remains are shown in Figure 4.

Table 2: Description of Collected Tanker Truck Samples

Sample Identification Number	Description
1	Front tire cord from left side of vehicle
2	Tire cord from #5 axle on right side of vehicle
3	Brake pad located near rear of vehicle
4	Rim component sample from #5 axle
5	Spring located near rear of truck
6	Large bolts (3) located on frame and near engine
7	Grade 5 bolt located on frame
8	Copper wire ground strap located on frame
9	Copper wire battery cable
10	Copper wire electrical system wiring located on frame and melted aluminum
11	Fitting with brass located on engine
12	Bolt from engine passenger side with steel wire and melted aluminum
13	Aluminum screen from radiator
14	Aluminum rim from dual wheel axle
15	Aluminum tank section
16	Glass mirror from passenger side
17	Stainless steel mirror support bracket



(A) (B)

(C)

Figure 4. Photographs of the tanker truck remains at the accident site (A) Rear axle of the truck; (B) Engine and frame; and (C) Collected remains of the vehicle at the Caltrans storage facility.

The MacArthur Maze Fire: Materials Analysis Conclusions

Based on the samples collected and analyzed and the results of thermal exposure tests, the temperature of the fire below the I-580 overpass was estimated to have ranged from 850°C [1,562°F] to approximately 1,000°C [1,832°F]. Near the truck, the maximum exposure temperature was estimated to have been between 720°C [1,328°F] and 930°C [1,706°F]. Results obtained from the analysis of the overpass and truck samples are consistent with modeling results (discussed below), indicating the hottest gas temperatures during the fire were located above the I-880 roadway near the steel girders of the I-580 overpass. An extensive discussion of the materials analyses completed for the samples collected are provided in previous papers [6], as well as in NRC NUREG/CR-6987, *Analysis of Structural Materials Exposed to a Severe Fire Environment* [7].

The insights gained from the materials analyses from the MacArthur Maze fire have been utilized by the staff to verify computer models of the fire and roadway collapse. This has allowed for further evaluation of the potential effects that a fire of this magnitude and duration, followed by a roadway collapse, could have on an NRC certified over-the-road SNF transportation package. Preliminary results of these investigations are discussed below.

CFD MODELING OF THE MACARTHUR MAZE FIRE

A preliminary model of the MacArthur Maze fire was developed for NRC using the FDS code [8, 9] by the CNWRA, at SwRI®, San Antonio, Texas, under contract NRC-02-07-006. This model provided an initial scoping analysis of the fire. NIST then refined the model and performed final calculations. A diagram of the structural elements and roadways as represented in the FDS model is shown in Figure 5.

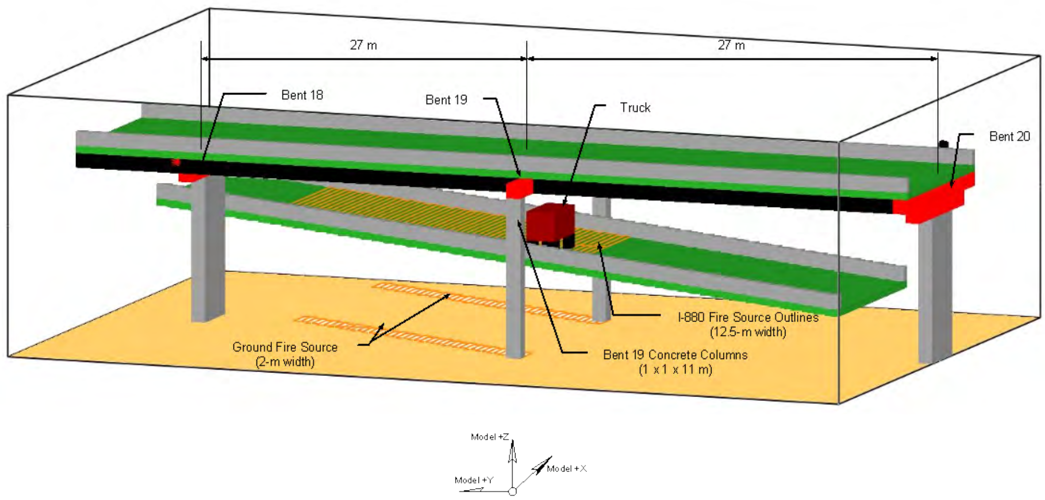
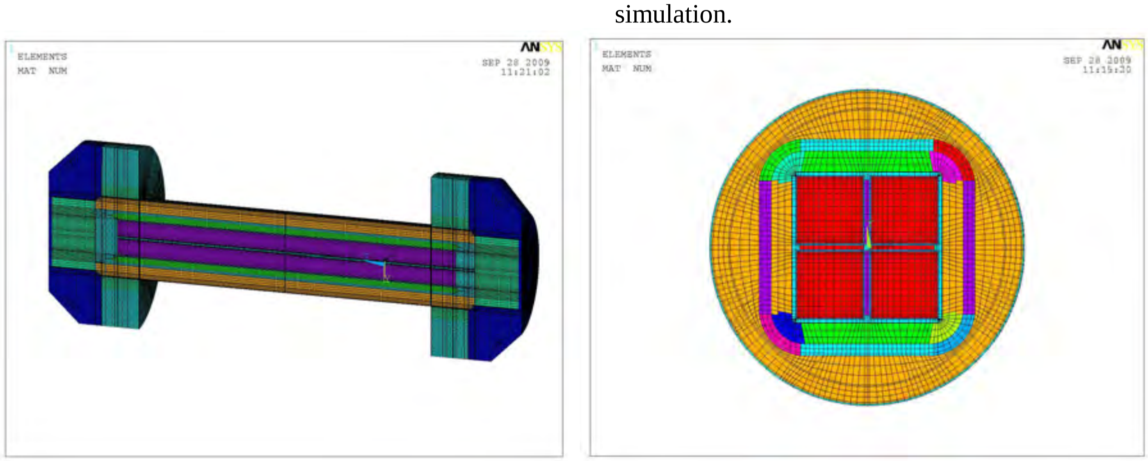


Figure 5. Diagram of FDS model of MacArthur Maze Geometry for Fire Simulation

The FDS analysis was limited to the fire prior to the collapse of the overpass (basically the first 17 minutes of the fire). The upper bound on the peak fire temperature during this first phase of the fire is 1,100ºC (2,012ºF), based on predicted Adiabatic Surface Temperatures (ASTs) at points in the fire near the final position of the tanker truck, at elevations of 1 m (3.3 ft) above the roadway and 1 m (3.3 ft) below the girders of the overhead I-580 span. The results of the FDS analysis were used to determine appropriate boundary conditions for the analyses presented below of the thermal effects of the fire on a typical LWT SNF package, and the structural effects of the lower roadway dropping onto the package. For these analyses, the General Atomics GA-4 LWT SNF package [10] was selected, based primarily on its ability to carry up to 4 spent PWR fuel assemblies.

MODELING OF THERMAL EFFECTS OF THE MACARTHUR MAZE FIRE

Simulation of the GA-4 package in the MacArthur Maze fire consisted of imposing three sets of boundary conditions in succession, representing: (1) the large (pre-collapse) fully engulfing fire at 1,100ºC (2,012ºF), (2) a smaller (post-collapse) fully engulfing fire at 900ºC (1,652ºF), and (3) the post-fire cooldown with the package beneath the fallen upper roadway. PNNL developed two independent models for this analysis, one using the ANSYS finite element code [11] and the other using the COBRA-SFS thermal-hydraulics finite difference code [12]. These models were developed in parallel to expedite cross-checking and verification between the codes. Figure 6 shows a cross-section of the model geometry developed for the simulation with ANSYS. Figure 7 shows a cross-section of the model developed for the COBRA-SFS simulation.



(A) Axial Cross-Section (B) Mid-Plane Cross-section

Figure 6. Diagram of ANSYS model of GA-4 Package

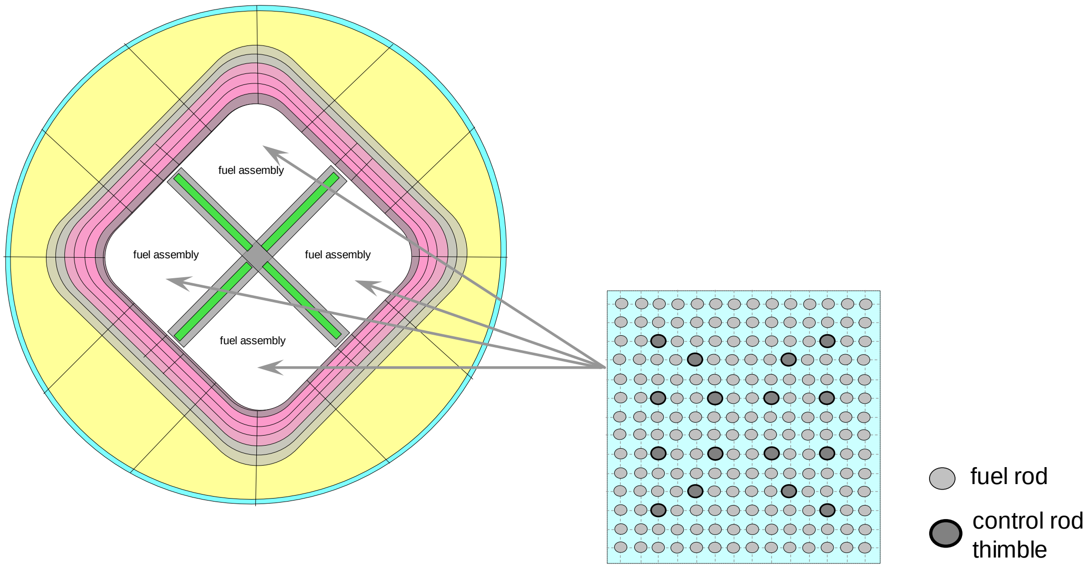


Figure 7. Diagram of COBRA-SFS model of GA-4 Package

To simulate the pre-collapse fire, the package model was subjected to an ambient boundary temperature of 1,100ºC (2,012ºF) for 37 minutes, to conservatively represent the fire conditions before and during the collapse of the two overhead spans. Therefore, in this case, the term "pre-collapse' actually includes the collapse of both spans of the I-580 overpass. To simulate the smaller post-collapse fire, the fire boundary temperature was reduced to 900ºC (1,652ºF) for the remaining 71 minutes of the transient, for a total fire duration of 108 minutes. Figure 8 shows the bounding fire temperatures assumed for the MacArthur Maze fire, compared to the prescribed fire boundary temperature for the HAC fire described in 10 CFR 71.

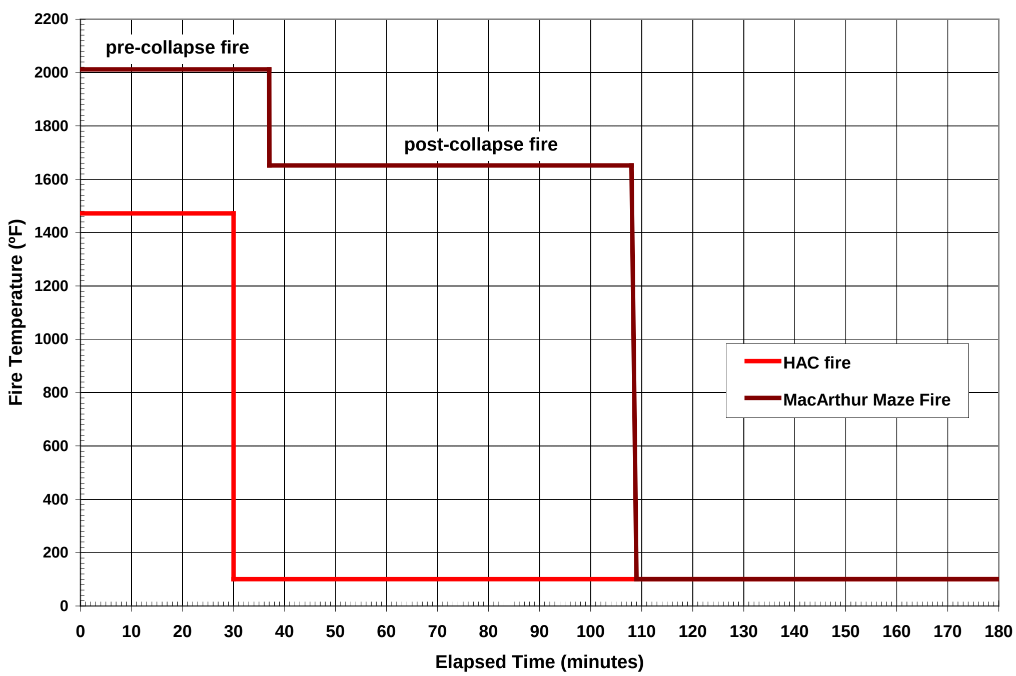


Figure 8. Fire Temperatures as a function of Time

Preliminary Results of Thermal Analysis with ANSYS Model

The temperatures predicted with the ANSYS model simulation of the MacArthur Maze pre-collapse fire scenario at 1,100ºC (2,012ºF) are shown in Figure 9. This color thermograph shows the temperature distribution in the package cross-section at 37 minutes (end of the pre-collapse portion of the fire scenario.) Figure 10 shows the temperature distribution predicted at the end of the fire, at 108 minutes, after the additional 71 minutes of the post-collapse fire at 900ºC (1,652ºF).

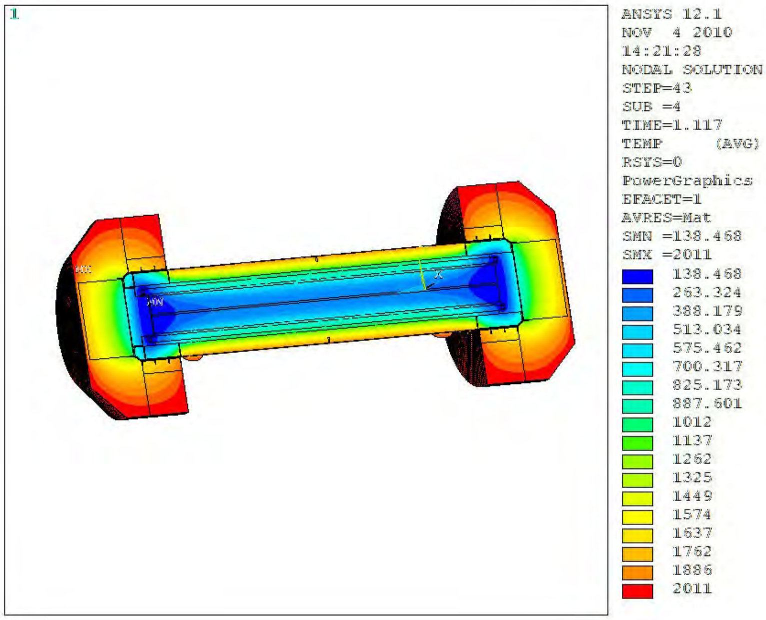


Figure 9. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of Pre-collapse 1,100ºC (2,012ºF) Fully Engulfing Fire (37 minutes)

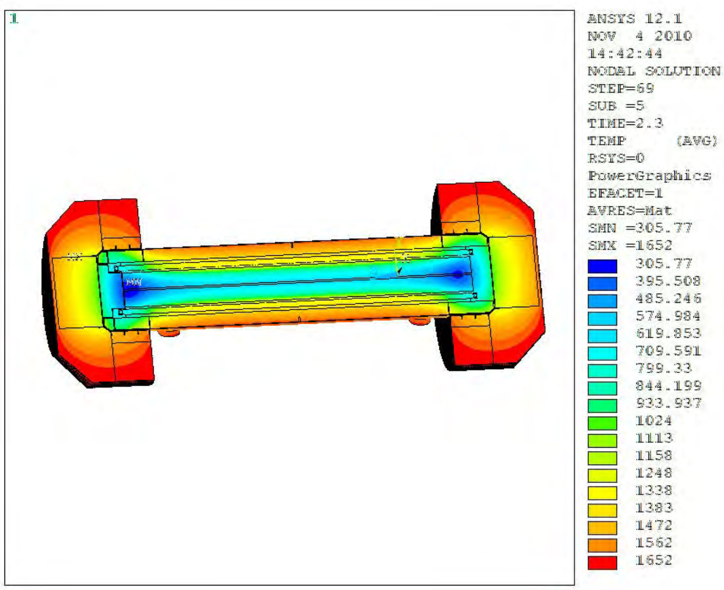


Figure 10. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of fire (108 minutes), after Post-collapse 900ºC (1652ºF) Fully Engulfing Fire

The peak clad temperature predictions for SNF in the GA-4 package in the MacArthur Maze fire were obtained with the COBRA-SFS and ANSYS models and are shown in Figure 11. The peak cladding temperature predicted with the ANSYS model follows the peak temperature curve predicted with the

COBRA-SFS model for the axial center of the package, despite the inclusion of the impact limiters in the ANSYS model and their omission from the COBRA-SFS model. The higher peak cladding temperature predicted with the COBRA-SFS model occurs at the end of the rod, where the steel lid of the package is exposed directly to the fire. Without the thermal insulation provided by the impact limiter, the fuel cladding temperature is predicted to approach or exceed experimentally observed Zircaloy burst temperature values [13].

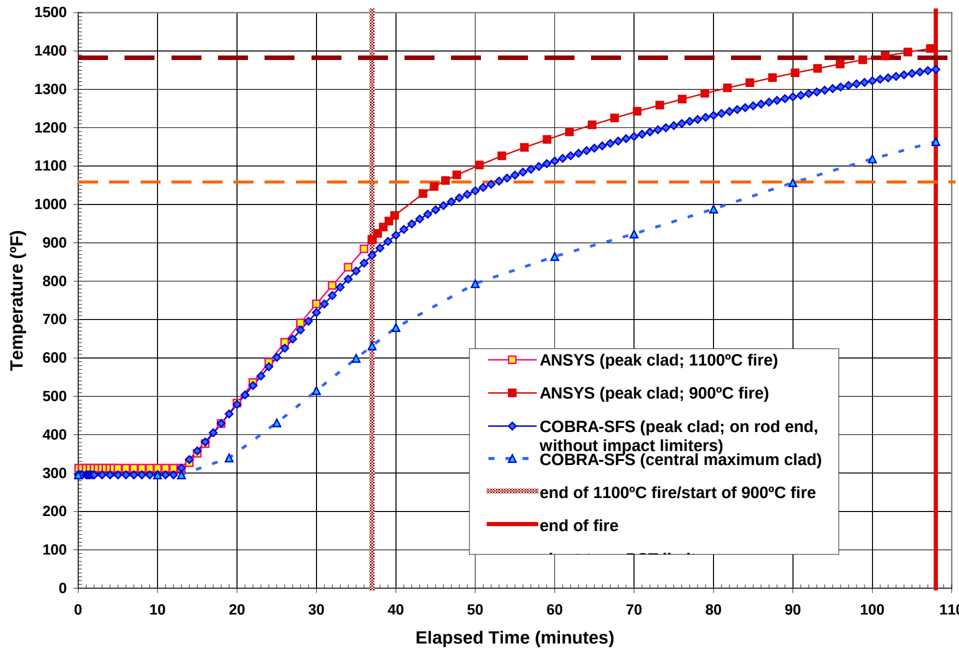


Figure 11. Peak clad temperature predictions with ANSYS and COBRA-SFS models for the complete MacArthur Maze fire scenario

The effect of the impact limiters on the thermal response of the package is illustrated in Figure 12. The external surface temperature on the exposed surface of the package (between the impact limiters) is essentially the same for the two models, but the temperatures predicted with the ANSYS model are much lower in regions covered by the impact limiters. As a result, the cladding temperature at the rod ends predicted with the ANSYS model during the fire is much lower than the peak cladding temperature predicted with the COBRA-SFS model. However, the insulating effect of the impact limiters also slows the predicted cooldown rate of the package in the post-fire scenario. Preliminary results show that the peak fuel cladding temperature predicted with the ANSYS model continues to rise for several hours after the end of the fire, due to the decay heat load within the package that is not removed during the fire and is removed only at a rate below the required design rate during the post-fire cooldown. For the conditions in the MacArthur Maze fire, the cooldown rate is further slowed by the assumption that the SNF package is buried under the fallen span of the upper roadway after being subjected to the long-duration fully engulfing fire.

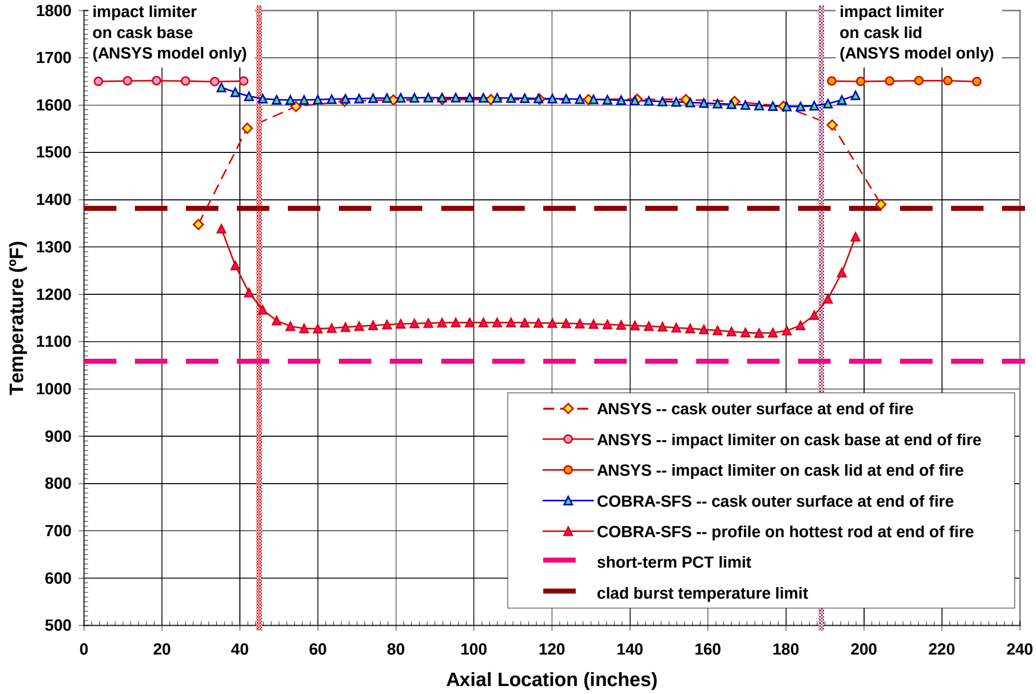


Figure 12. Peak external surface temperature predictions with ANSYS and COBRA-SFS models for the complete MacArthur Maze fire scenario

The complete transient calculations for both models are still in progress, therefore, this paper will not report the overall peak temperatures for the internal components of the SNF package, including the peak fuel cladding temperatures; however, experience with long post-fire cooldown transients with other fire models suggest that the final peak temperatures could be higher than those predicted during the fire.

Preliminary Results of Structural Analysis with LS-Dyna

PNNL developed a model of the I-580 roadway and GA-4 package in LS-Dyna [14] for analyzing the potential effects of the upper roadway dropping onto the SNF package. The model of the span between Bent 19 and Bent 20 was constructed using the original roadway assembly plate girder design drawings. The plate girders are the most important components of the overpass system for the impact modeling because, under the most damaging assumptions, these are expected to contact the package body directly. The concrete and rebar structure of the I-580 roadway is simply modeled as a homogenized elastic material with a low modulus of elasticity. The falling span was subjected to a constant gravity force and given a velocity of 7.671 m/s (25.12 ft/s) at the point of impact, which corresponds to a 3-m (9.8 ft) drop. This is based on possible geometric conditions that could have existed prior to release of the span.

The sequence of events in this accident scenario is the reverse of the postulated order of a package drop followed by a fully engulfing fire, as specified in 10 CFR 71 (see Ref. 1). In contrast to the package drop scenario prescribed in the regulations, which occurs at normal ambient temperatures, the temperature distribution on the I-580 overpass in the MacArthur Maze fire scenario is a key factor in determining the potential severity of the impact of the collapsing roadway on the package. The stiffness of the girders, and therefore the magnitude of the force that can be imparted to the SNF package by the drop impact, is primarily a function of the girder temperatures. A conservative estimate of 982ºC (1,800ºF) was obtained for the girder temperatures in the drop scenario, based on the material data analyses previously discussed, and thermal modeling of the effect of the fire on the girder temperatures at the time of the complete collapse of the first overhead span at 17 minutes (1020 seconds) into the fire. This value was applied uniformly along the axial length of the steel girders for the drop evaluation.

The position assumed for the SNF package beneath the falling upper roadway has a significant influence on the potential damage to the package, and a range of possible orientations of the package on the lower roadway were evaluated. These included: (1) the package oriented perpendicular to the axis of the girders so that the main impact was across the center of the package, (2) the package oriented parallel to the axis of the girders so that one girder would strike the cask along its full axial length, and (3) the package oriented such that the main impact would be localized on the package closure. The structural model of the package excluded the impact limiters and the thin neutron shield shell on the outer surface of the package, as these components were considered superficial to the overall structural integrity of the package.

The preliminary results of the scenario modeled in LS-Dyna indicated that the steel plate girders of the overhead roadway would undergo significant plastic strains and, therefore, tend to deform under the impact, while the SNF package would be relatively unaffected by the impact force. Limited plastic strains are predicted in the package wall and the depleted uranium (DU) gamma shield; however, these strains are substantially less than those predicted for the girders. Figure 13 shows the geometry of the perpendicular impact scenario. The deformation of the girders is clearly visible in the graphic (the roadway concrete has been removed from this image, for clarity).

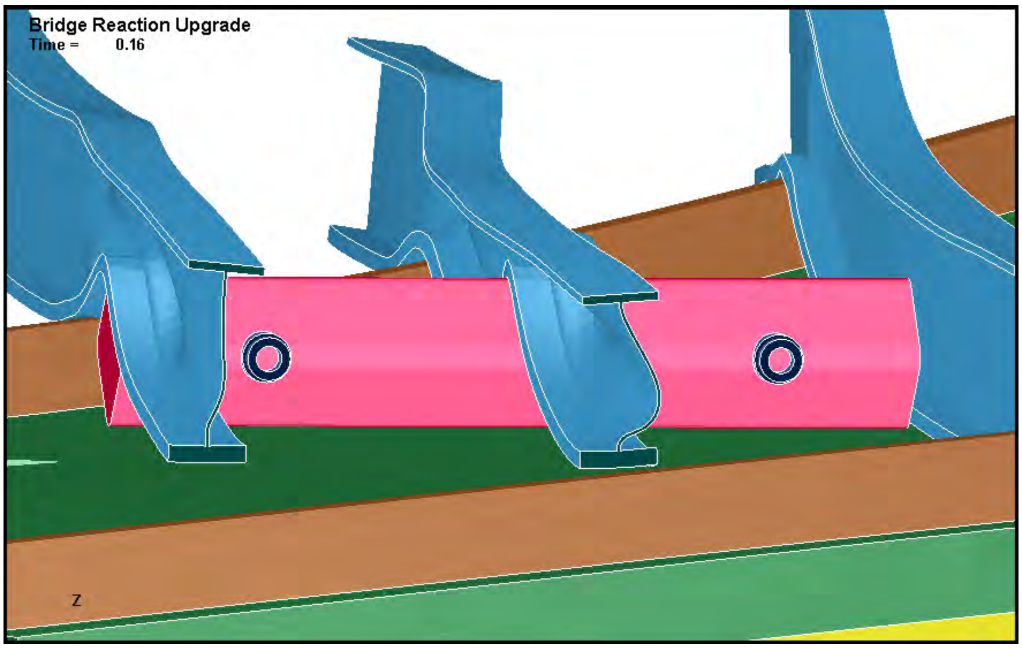


Figure 13. Predicted Deformation of I-580 Span after Impact (Package Perpendicular to Girders)

Of the scenarios evaluated, the most severe effects on the package were obtained with the package oriented parallel to the axis of the girders. Figure 14 shows contours of effective plastic strain on the package body after the collapse and impact of the I-580 span (local mesh and girder deformation images are added to the LS-DYNA contour plot, as supplemental information). One location at the bottom end of the package experienced localized plastic strains of about 10%. At this combination of temperature and strain rate, the expected plastic strain limit is beyond 30%. This result suggests that the plastic strains that could be experienced by the package in this drop scenario would not exceed the plastic strain limit of the package material.

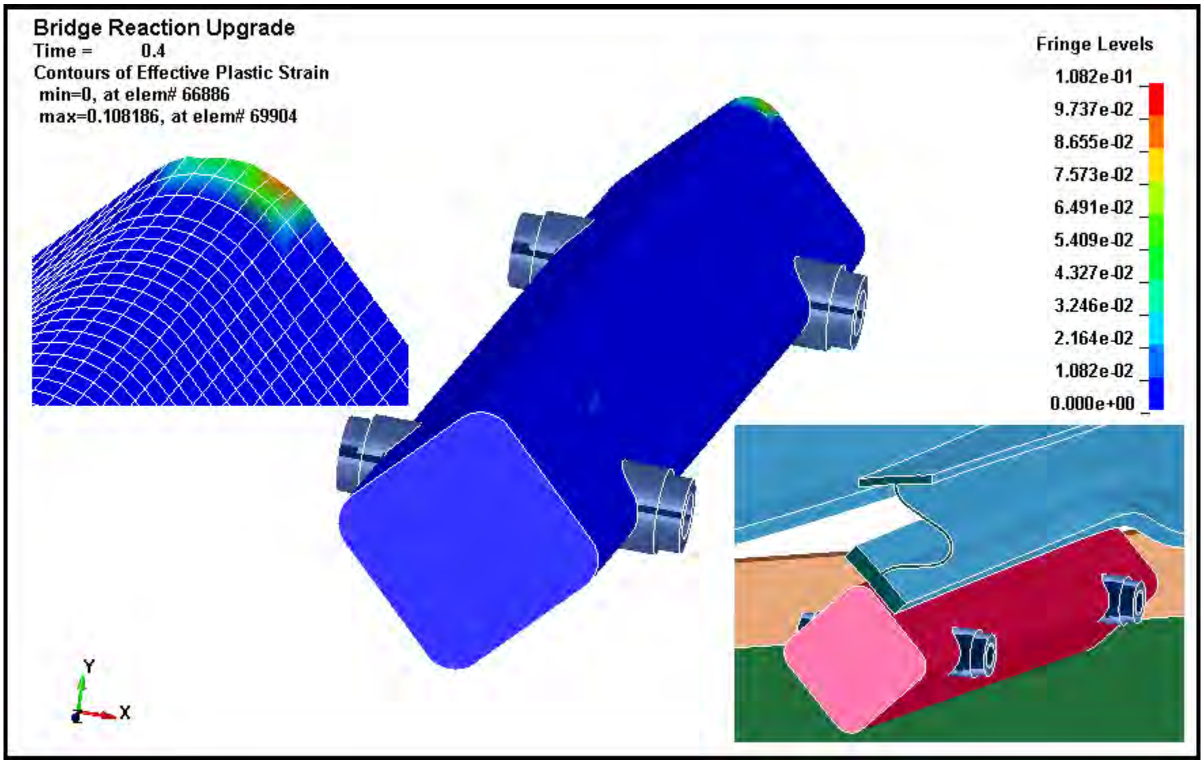


Figure 14. Plastic Strain in SNF Package Body after I-580 Span Impact Due to Collapse in Parallel Orientation. (Local mesh and girder deformation superimposed on contour plot.)

The MacArthur Maze Fire: Thermal and Structural Analyses Preliminary Conclusions

The detailed thermal models of the MacArthur Maze fire scenario with ANSYS and COBRA-SFS have produced preliminary results indicating that in a fire of this severity, the peak fuel cladding temperature would almost certainly exceed the short-term limit of 570ºC (1,058ºF), and would likely exceed the Zircaloy burst temperature for the design-bases spent fuel payload of the package. While additional work to refine and verify the results will be completed, the overall results of these analyses are consistent with the results obtained for the HAC fire evaluations with these models, and with previous fire analyses using similar models [15, 16]. These results, as well as future results produced by these models, can therefore be considered as reliable estimates of the temperatures that would be experienced in fire conditions as severe as the MacArthur Maze fire.

The preliminary results of the structural analyses show that the GA-4 package may be robust enough to withstand the impact of the overhead span without suffering major damage or deformation. However, development of a detailed model of the package lid and closure bolts, to further assess the potential consequences of this scenario, is being considered.

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