The MacArthur Maze Fire and Roadway Collapse:

Consequences for SNF Transportation - 12476

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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 tractor trailer carrying gasoline which impacted an overpass support column and burst into flames. The subsequent fire caused the collapse of portions of the Interstate 580 overpass onto the remains of the tractor-trailer in less than 20 minutes, due to a reduction of strength in the structural steel exposed to the fire. The US Nuclear Regulatory Commission is in the process of examining the impacts of this accident on the performance of a spent nuclear fuel transportation package, using detailed analysis models, in order to determine the potential regulatory implications related to the safe transport of spent nuclear fuel in the United States. This paper will provide a summary of this effort and present results and conclusions.

NOMENCLATURE

Caltrans – California Department of Transportation
CHP – California Highway Patrol
FDS – Fire Dynamics Simulator
HAC – Hypothetical Accident Condition
LWT SNF – Legal Weight Truck Spent Nuclear Fuel (package)
NIST – National Institute of Standards and Technology
NRC – United States Nuclear Regulatory Commission
SwRI® – Southwest Research Institute®

BACKGROUND

The primary objective of the work described in this paper was to assess the potential impact of this type of accident on a spent nuclear fuel transportation package, and, secondarily, to evaluate the accident in comparison to the hypothetical accident condition (HAC) fire exposure defined in Title 10 of the Code of Federal Regulations, Part 71, “Packaging and Transportation of Radioactive Material.” [1]

The MacArthur Maze Accident and Fire

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 that eventually led to collapses of the overpass started at about 3:38 a.m. when a gasoline tanker truck carrying 32,500 liters [8,600 gallons] of gasoline crashed and caught fire. The tanker truck was heading south along I-880 at the time of the accident. While nearing the I-580 overpass, the vehicle rolled onto its side and slid to a stop on the 21-foot-high ramp connecting westbound I-80 to southbound I-880.

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) completely collapsed onto 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. 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. The fire was determined to have burned intensely for about 40 minutes, but for the remaining 60 minutes of the fire, it was significantly reduced in size, due to the collapse of the two I-580 spans. 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[1] [2].

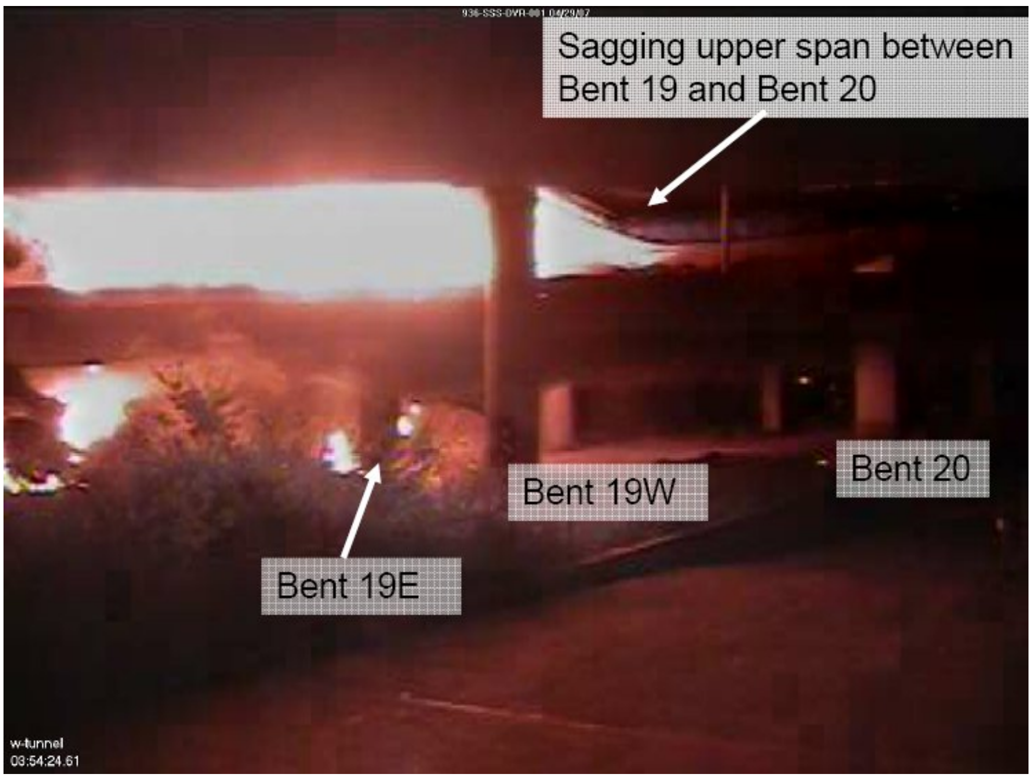


Fig. 1. MacArthur Maze fire at +16.7 minutes (video image at 03:54:24.61 PDT)

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

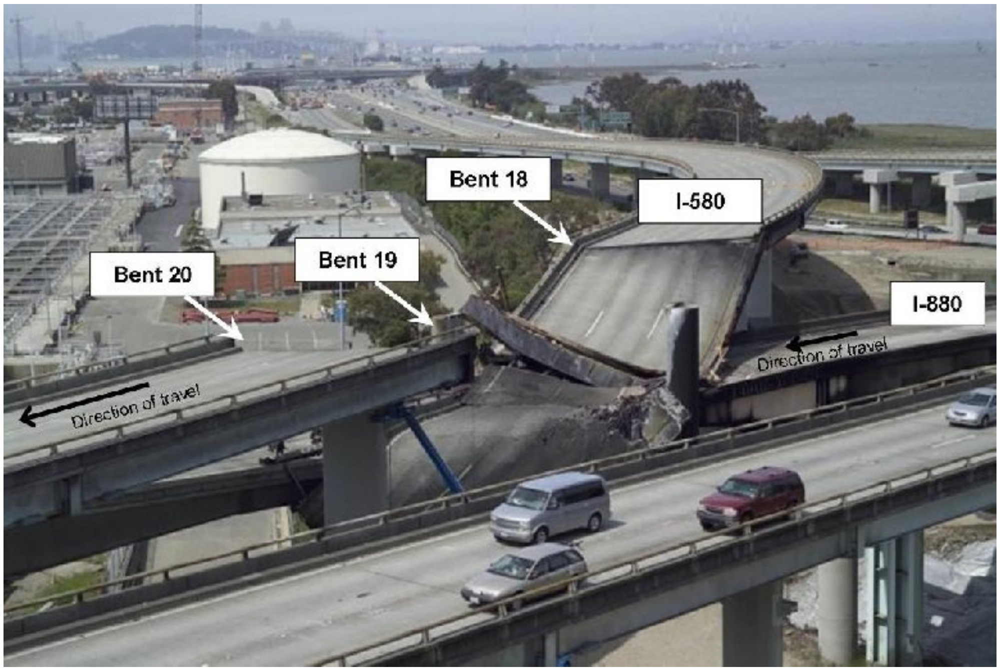


Fig. 2. Post-fire aerial view of the collapsed section of I-580 looking west. Picture from Caltrans http://www.dot.ca.gov/dist4/photography/images/070429.

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, and this estimate fails to take into account two crucial factors; the maximum temperatures achievable in an open hydrocarbon fueled pool fire, and 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 1000ºC (1832ºF). 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 1350ºC (2462ºF), 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 melting of alloys used on the tanker truck, spalling of concrete, damage to paint, and solid-state phase transformations in the steel girders. Spalling of the concrete was observed on the 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 temperature especially with the extensive photographic documentation available from Caltrans. NRC and SwRI® staff collected and analyzed material samples from the steel girders and the tanker truck to estimate exposure temperatures.

The MacArthur Maze Fire: Materials Analysis Conclusions

Based on the samples collected and the results of thermal exposures, the temperature of the fire below the I-580 overpass is 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 is estimated to be at least 720°C [1,328°F] and less than 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 a NRC NUREG/CR series report [7].

The insights gained from the materials analyses from the MacArthur Maze fire have been used to verify computer models of the fire and roadway collapse. This has allowed for further investigation of the potential effects that a fire of this magnitude and duration, followed by a roadway collapse, could have had on an NRC certified over-the-road radioactive material 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 using the FDS code [8, 9] for NRC at the Center for Nuclear Waste Regulatory Analyses, SwRI®, San Antonio, Texas under contract NRC-02-07-006, and provided an initial scoping analysis of the fire. The model was then refined and final calculations were performed at NIST. A diagram of the structural elements and roadways as represented in the FDS model is shown in Figure 5.

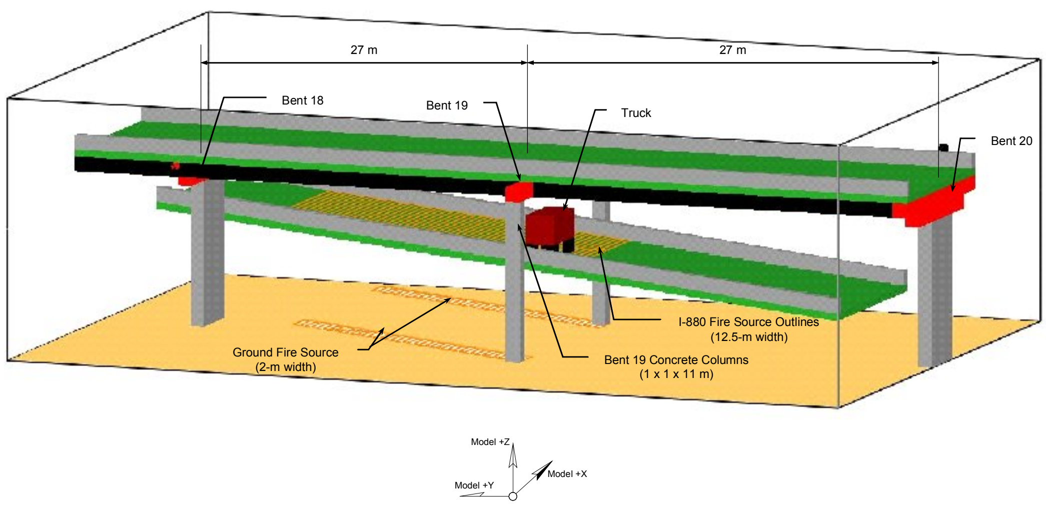
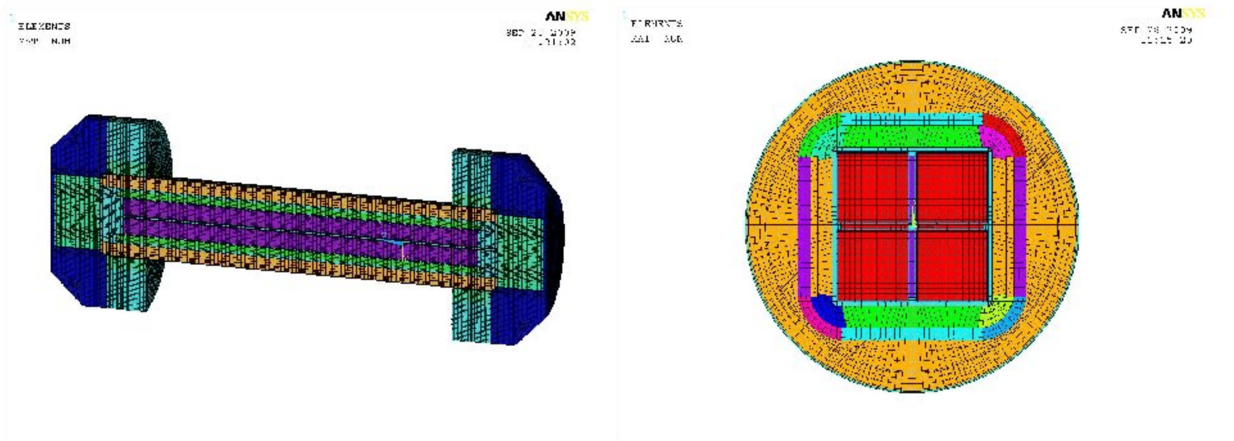


Fig. 5. Diagram of FDS model of MacArthur Maze Geometry for Fire Simulation

The FDS analysis was limited to the pre-collapse phase of the fire (17 minutes). The upper bound on the peak fire temperature during this first phase of the fire is 1100ºC (2012ºF), 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 above the roadway and 1 m 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 legal weight truck (LWT) SNF package, and the structural effects of the lower roadway dropping onto the package. For these analyses, the GA-4 LWT SNF package 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 in sequence a series of three sets of boundary conditions representing a large (pre-collapse) fully engulfing fire at 1100ºC (2012ºF), a smaller (post-collapse) fully engulfing fire at 900ºC (1652ºF), and the post-fire cooldown with the package beneath the fallen upper roadway. Two independent models were developed for this analysis, one using the ANSYS finite element code [10] and one using the COBRA-SFS thermal-hydraulics finite difference code [11]. 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

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

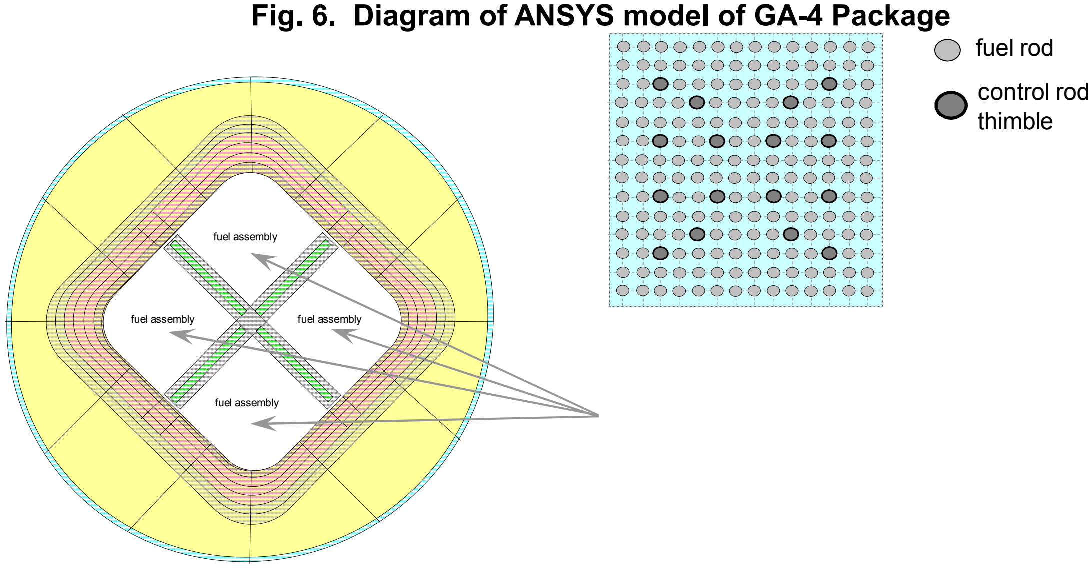


Fig. 7. Diagram of COBRA-SFS model of GA-4 Package

To simulate the pre-collapse fire, the package model was subjected to an ambient boundary temperature of 1100ºC (2012ºF) for 37 minutes, to conservatively represent the fire conditions before and during the collapse of the two overhead spans. To simulate the smaller post-collapse fire, the fire boundary temperature was reduced to 900ºC (1652ºF) 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 10CFR71. The figure clearly illustrates that the MacArthur Maze fire is larger in intensity and duration than the HAC fire in 10CFR71, therefore, it is considered an extra-regulatory fire.

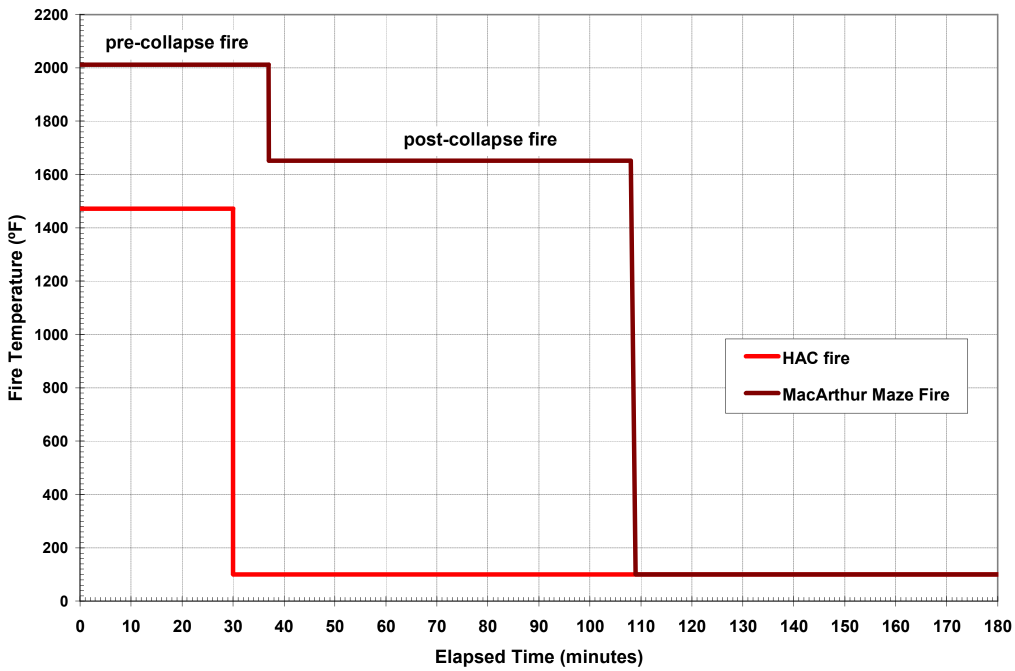


Fig. 8. Diagram of COBRA-SFS model of GA-4 Package

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 1100ºC (2012ºF) 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 (1652ºF).

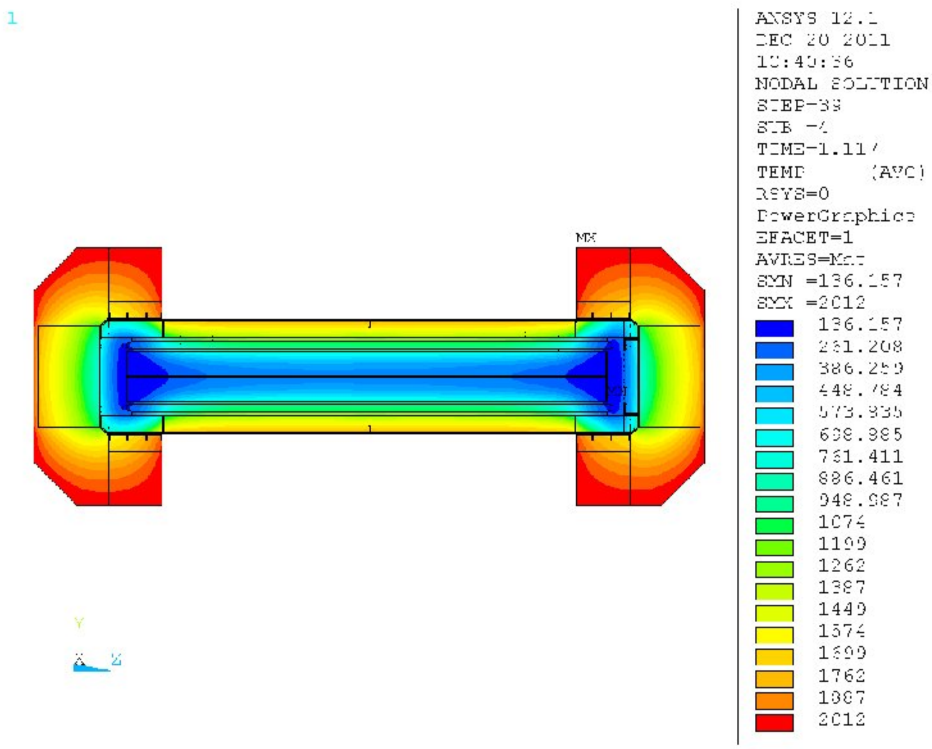


Fig. 9. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of Pre-collapse 1100ºC (2012ºF) Fully Engulfing Fire (37 minutes)

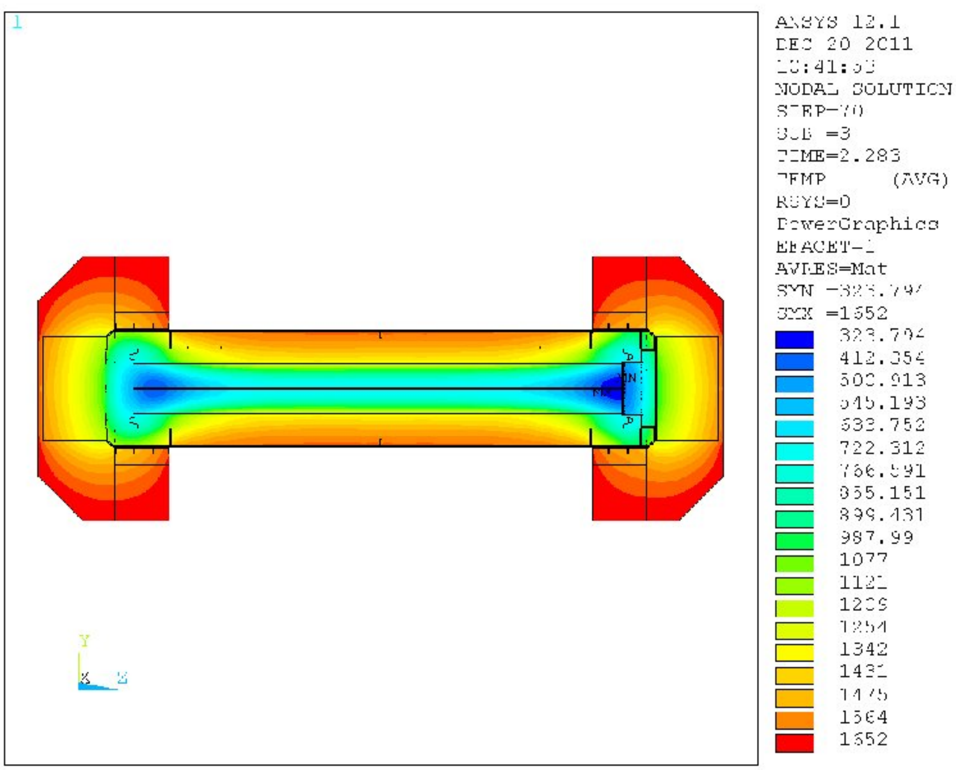


Fig. 10. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of fire (108 minutes), after Post-collapse 900ºC (1652ºF) Fully Engulfing Fire

The peak clad temperature predictions obtained with the COBRA-SFS model in the MacArthur Maze fire are shown in Figure 11. The peak cladding temperature predicted with the ANSYS model slightly exceeds the maximum temperature curve predicted with the COBRA-SFS model, due to the more conservative homogeneous k-effective model for the fuel region used in the ANSYS model. The maximum peak cladding temperature predicted with the COBRA-SFS model occurs at the end of the rod, where the steel base 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 exceed the short-term limit of 570ºC (1058ºF) by about 58 minutes. By the end of the fire, the maximum peak fuel cladding temperature predicted with both models is approaching 750ºC (1382ºF), the assumed Zircaloy burst temperature in previous transportation studies [12]. The mid-plane peak fuel cladding temperature predicted with the COBRA-SFS model is not far behind, at 675ºC (1248ºF).

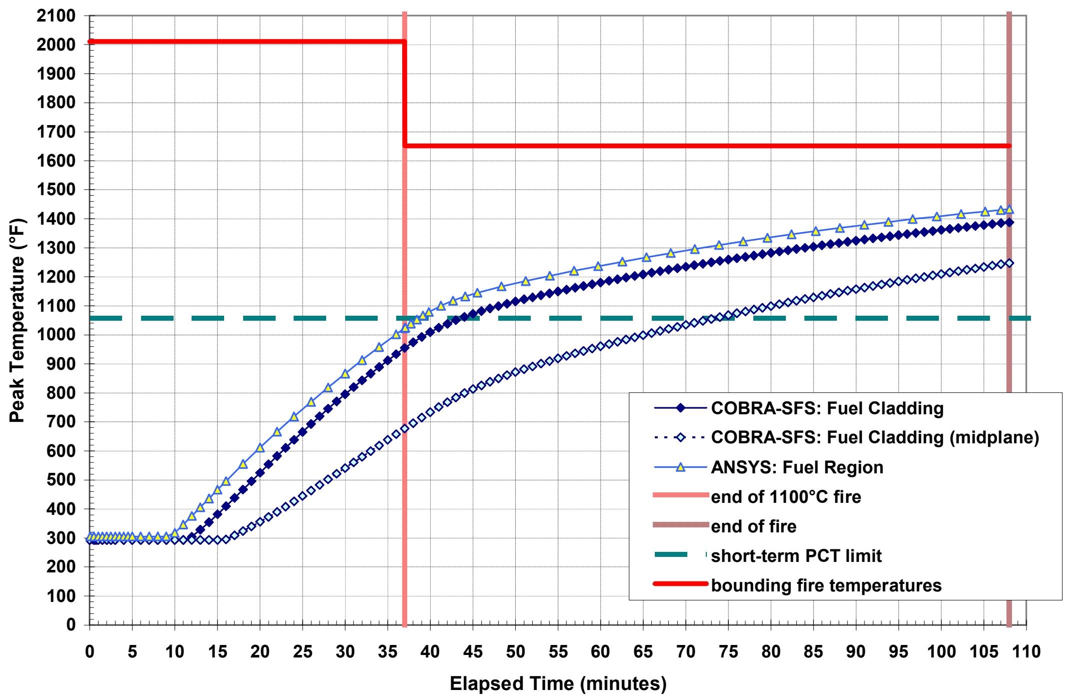


Fig. 11. Peak clad temperature predictions with ANSYS and COBRA-SFS models for the complete MacArthur Maze fire scenario

The effect of the impact limiters on the thermal response of the package is to restrict the most severe temperature rise in the fuel region to the middle section of the package. After the fire, the impact limiters insulate the ends of the package and the fuel rod ends continue to increase in temperature for several hours after the end of the fire. Preliminary results show that the peak fuel cladding temperatures predicted with both models continue 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 much below the required design rate during the post-fire cooldown. In the MacArthur Maze fire scenario, the cooldown rate is further slowed by the assumption that the SNF package is buried under the fallen span of the upper roadway. The peak clad temperature predictions for the cooldown portion of the transient are illustrated in Figure 12.

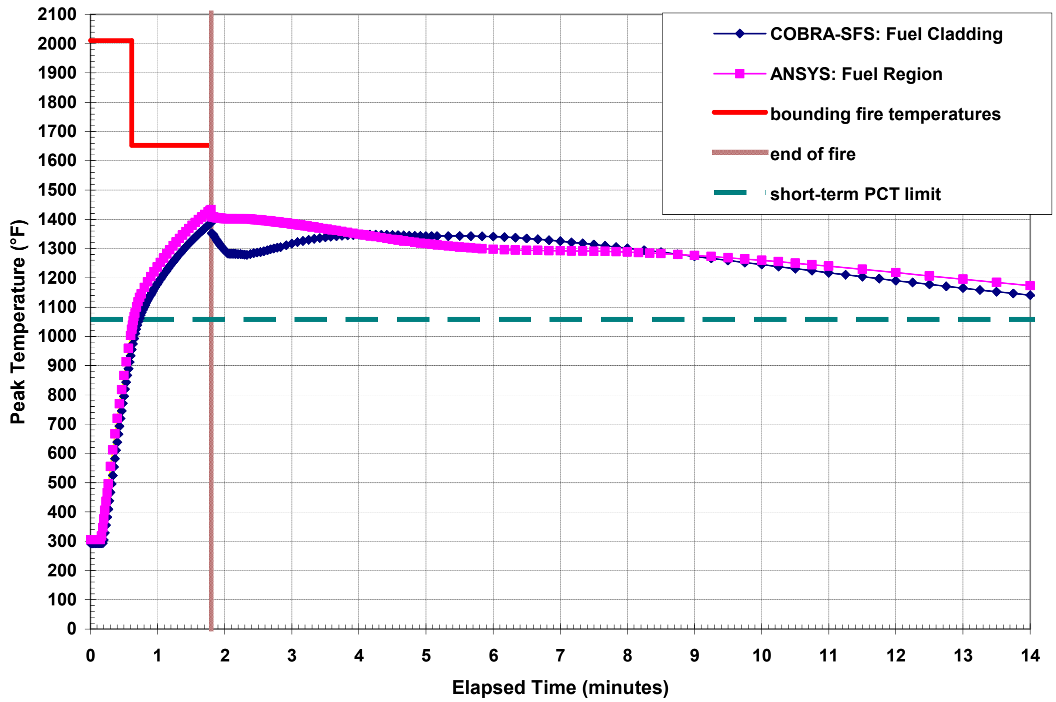


Fig. 12. Peak clad temperature predictions with ANSYS and COBRA-SFS models for the MacArthur Maze fire scenario to 14 hours

To evaluate the potential for fuel rod failure at the temperatures predicted in this fire scenario, a detailed analysis was performed with FRAPTRAN1.4 [13], a fuel performance code for calculating LWR fuel rod behavior in severe transient conditions. FRAPTRAN evaluates burst rupture using a burst stress/strain model developed from test data obtained for LOCA analyses. Spent fuel rods can fail by burst rupture, but creep rupture is considered a possible alternative mechanism of failure. To evaluate this possibility, an additional analysis was performed using the FRAPCON code [14] in conjunction with the DATING code [15], to apply a creep rupture model using the temperatures predicted for the MacArthur Maze fire scenario.

Based on the burst strain model, the fuel rods are expected to rupture before the end of the fire. The FRAPTRAN1.4 model predicts that rod ballooning initiates at 558ºC (1037ºF), with rod burst rupture at 592ºC (1097ºF). The creep rupture model also predicts that the fuel rods would begin rupturing before the end of the fire, when the clad temperature reaches 665ºC (1229ºF). Furthermore, the thermal models predict that the peak cladding temperature remains significantly above these rupture temperatures for more than ten hours, due to thermal inertia and build-up of decay heat that is not removed from the package during and immediately following the fire. By 4.2 hours (2.37 hours after the end of the fire), the peak temperature on every rod in the package exceeds the highest temperature predicted for cladding rupture (665ºC (1229ºF)).

Evaluation of the potential consequences of the hypothetical involvement of the GA-4 package in this severe accident scenario is in progress. This work involves evaluation of package integrity during the fire, and the potential for release of radioactive material from the package.

Preliminary Results of Structural Analysis with LS-Dyna

The I-580 roadway is modeled in LS-Dyna [16] as a deformable impact object for the analyses of the potential effects of the upper roadway dropping onto the GA-4 package. The model of the span between Bent 19 and Bent 20 was constructed using the original 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 they 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 acceleration and an initial velocity based on the maximum vertical clearance between the cask body and the underside of the overpass girders at a given location. A number of cask locations and orientations were analyzed in an effort to cover the worst-case drop scenario, so each case had a slightly different impact velocity. The cask was always placed at a point on the I-880 road surface and the I-580 overpass section always fell straight down.

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 10CFR71 (see Ref. 1). In contrast to the prescribed package drop scenario, 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 with 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 (1800ºF) was obtained for the girder temperatures in the drop scenario, based on the material data analyses discussed above, 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 into the fire. This value was applied uniformly along the axial length of the steel girders for the drop calculation.

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 was investigated. These included (1) orienting the package perpendicular to the axis of the girders so that the main impact was across the center of the package, (2) orienting the package parallel to the axis of the girders so that one girder would strike the cask along its full axial length, (3) orienting the package such that the main impact would be localized on the package closure, and (4) orienting the package such that the girder impact is localized on one of the trunnions. 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 containment boundary. The bolted lid and flange end was represented as continuous material instead of modeling the lid and bolts as separate components. After the preliminary set of impact evaluations, it was determined that a more realistic representation of the bolted flange area was not necessary for the purposes of this study.

The results of these analyses showed 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, and the deformation of the girders is clearly visible in the graphic (the overpass concrete has been removed from this image, for clarity).

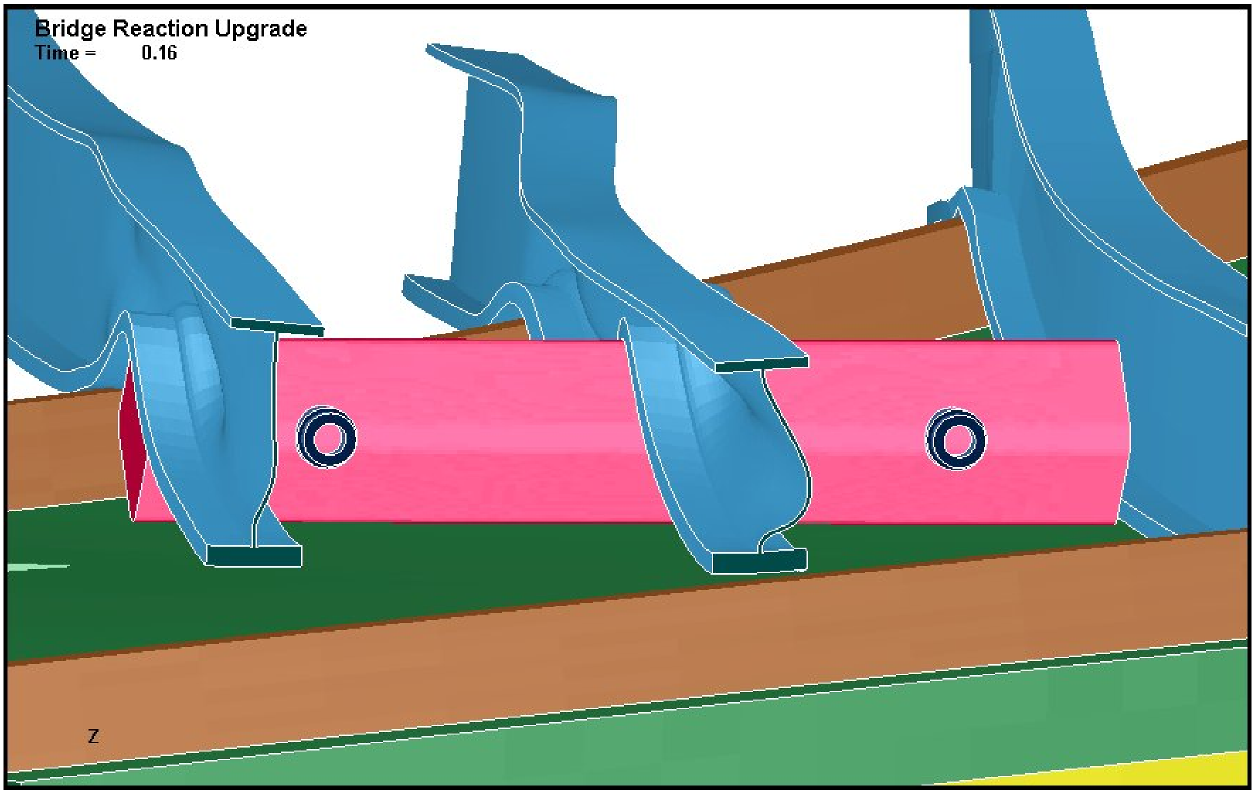


Fig. 13. Predicted Deformation of I-580 Span after Impact; Package Oriented Perpendicular to Girders

Of the cases 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 (local mesh and girder deformation images added to the standard LS-DYNA contour plot, as supplemental information.) One location at the bottom end of the cask experiences localized plastic strains of about 10%. At this combination of temperature and strain rate, the expected plastic strain limit is beyond 30%. This level of localized plastic strain is not expected to be a challenge to the structural integrity of the containment boundary, but the location of the plastic deformation near the bolted closure lid requires additional consideration. The closure end is represented as solid material which envelopes a region that includes a lid, bolts, and two O-ring seals. The impact model results suggest that, when actual cask geometry is considered, local deformation of the flange lip could potentially contact the side of the lid and transfer a transverse mechanical shock load to the lid. This shock load is not expected to cause structural damage, but is considered in the ongoing assessment of the potential consequences of this accident scenario.

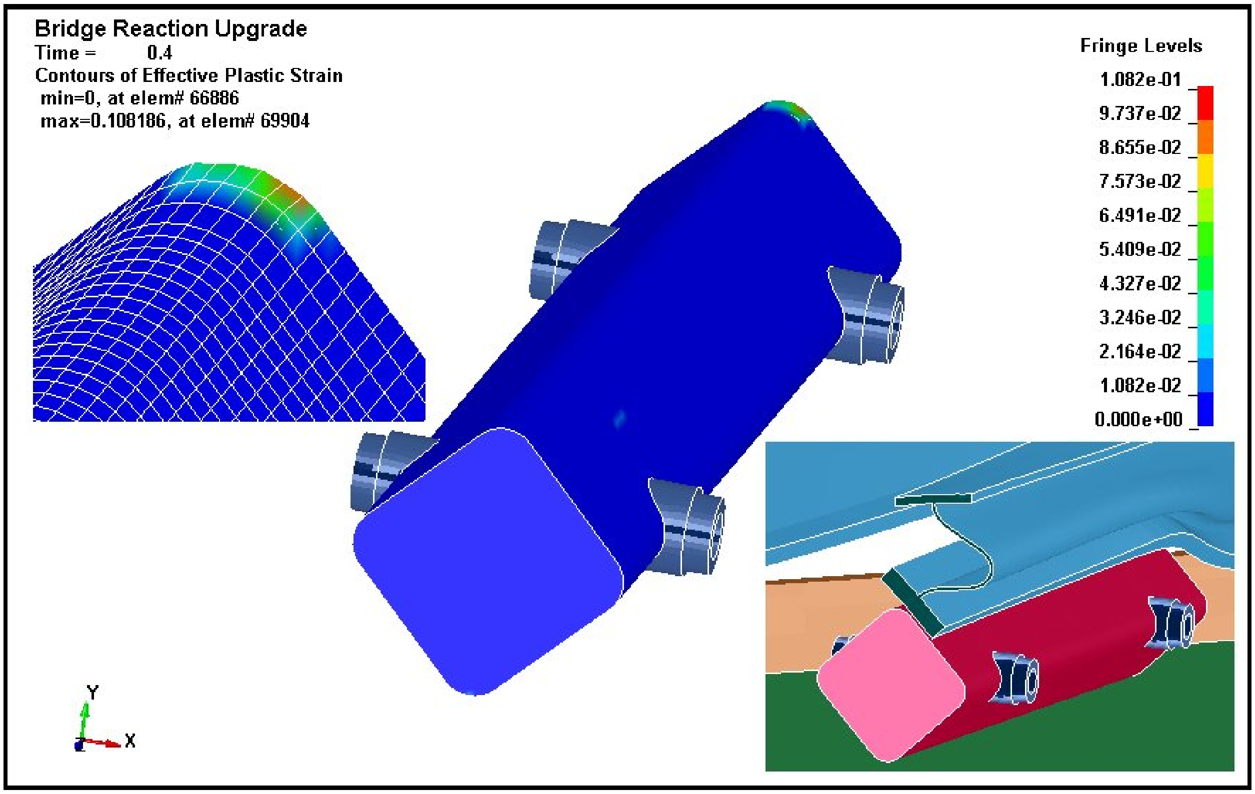


Fig. 14. Plastic Strain in SNF Package Body after I-580 Span Impact in Parallel Orientation. (Local mesh and girder deformation superimposed on contour plot.)

Preliminary Results of Bolt Evaluation

Thermal expansion stresses in the closure bolts and impact limiter bolts were both evaluated at the predicted extra-regulatory temperatures. The GA-4 design uses stainless steel threaded inserts in both bolt types to protect against thread galling. At these predicted extra-regulatory fire temperatures, the threaded inserts tended to be the weakest link in the connection between the nickel alloy bolts and the XM-19 stainless steel of the cask. It was determined that the thermal expansion in the impact limiter bolts is expected to cause yielding in the threaded inserts, but the bolt shank would begin to yield and release tension before failure of the insert could occur. At worst, this would allow some release of bolt tension and loosen the connection of the impact limiter to the cask, but it is not credible to assume that the impact limiter attachment could be lost. This finding is critical to the closure bolts, which are expected to maintain their attachment throughout the fire when the impact limiters are present, but could reach compromising temperatures in the closure region if the thermal protection of the impact limiters was lost. With impact limiters attached, the closure bolt threaded inserts are expected to remain in the elastic shear stress region throughout the collapse of the overpass until the end of the 108 minute fire, by which time they are expected to exceed the insert yield strength and release some amount of the increased bolt tension. This response at the closure is being considered in the ongoing assessment of the potential consequences of this hypothetical accident scenario.

The MacArthur Maze Fire: Thermal and Structural Analysis 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 (1058ºF), and would likely exceed the Zircaloy burst temperature limit of 750ºC (1382ºF) assumed in previous transportation studies [12]. Additional work is needed to refine and verify some of the details of these complex models, but the overall results are consistent with previous fire analyses with similar models, and with the results obtained for the HAC fire evaluations with these models. 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 of the severity of the MacArthur Maze fire scenario.

The structural analyses show that the GA-4 package is robust enough to withstand the impact of the overhead span without suffering major damage or deformation to the containment boundary. The greatest potential for local package damage in this scenario appears to be at the bolted closure end. The thermal expansion response of the closure bolts and impact limiter attachment bolts were evaluated in a separate analysis, and it was determined that both the lid and impact limiters are expected to remain in place. The response of the closure seal is currently being evaluated separately in the context of the accident's overall potential to release radioactive material in the environment.

ACKNOWLEDGEMENTS

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