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THE MACARTHUR MAZE FIRE AND ROADWAY COLLAPSE: A "WORST CASE SCENARIO" FOR SPENT NUCLEAR FUEL TRANSPORTATION?

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ABSTRACT

In 2007, a severe transportation accident occurred near Oakland, California, at the interchange known as the "MacArthur Maze." The accident involved a double tanker truck of gasoline overturning and bursting into flames. The subsequent fire reduced the strength of the supporting steel structure of an overhead interstate roadway causing the collapse of portions of that overpass onto the lower roadway in less than 20 minutes. The US Nuclear Regulatory Commission has analyzed what might have happened had a spent nuclear fuel transportation package been involved in this accident, to determine if there are any potential regulatory implications of this accident to the safe transport of spent nuclear fuel in the United States. This paper provides a summary of this effort, presents preliminary results and conclusions, and discusses future work related to the NRC's analysis of the consequences of this type of severe accident.

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 is 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 drains 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 37 minutes after the fire began. The fire was observed to have burned intensely for about 37 minutes, but was significantly reduced in size, due to the collapse of the two I-580 spans, for the remaining 71 minutes of the fire. 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].

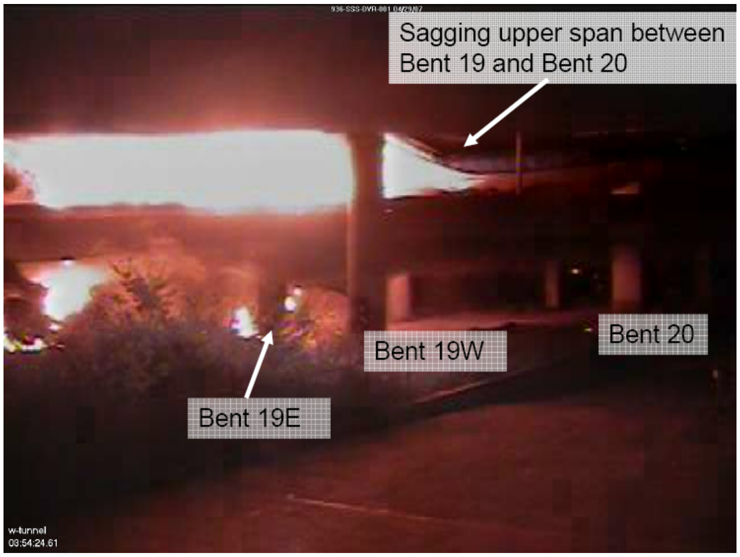

Fig. 1. MacArthur Maze fire at +16.7 minutes (video image at 03:54:24.61 PDT)

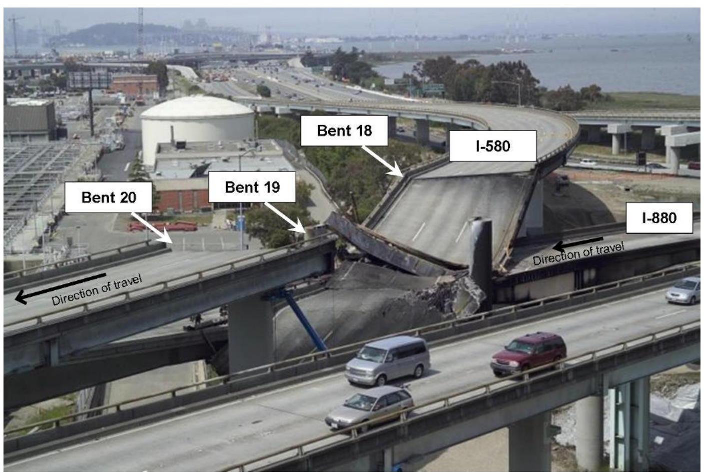

Fig. 2. Post-fire aerial view of the collapsed section of I-580 looking west. Picture from Caltrans http://www.dot.ca.gov/dist4/photography/images/070429.

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 of the fire were taken, 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 on the steel girders of the I-580 overpass also served as useful indicators 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 exposure tests, 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] but 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 is provided in previous papers [6], as well as a NRC NUREG/CR series report [7].

The insights gained from the materials analyses of samples 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.

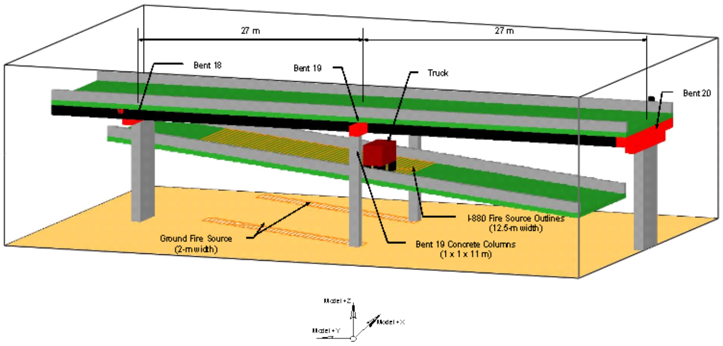

Fig. 5. Diagram of FDS model of MacArthur Maze Geometry for Fire Simulation

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 upper 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 THE 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 including: 1) a large (pre-collapse) fully engulfing fire at 1100ºC (2012ºF), 2) a smaller (post-collapse) fully engulfing fire at 900ºC (1652ºF), and 3) 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 allow for cross-checking and verification between the codes. Figure 6 shows cross-sections 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.

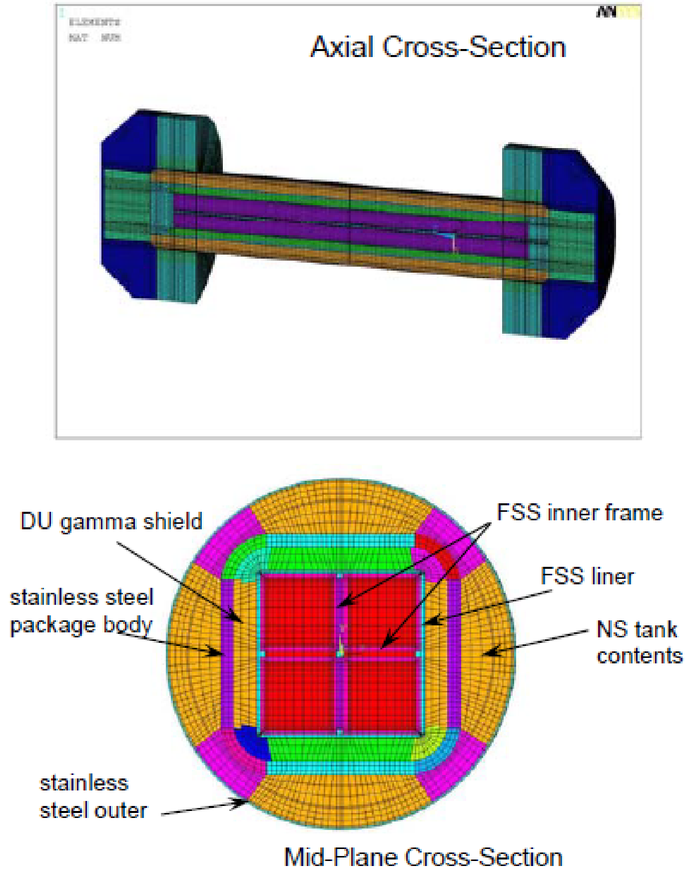

Fig. 6. ANSYS model of GA-4 Package

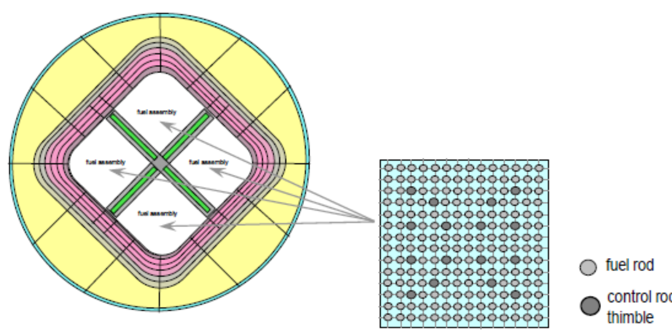

Fig. 7. Diagram of COBRA-SFS model of GA-4 Package

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 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.

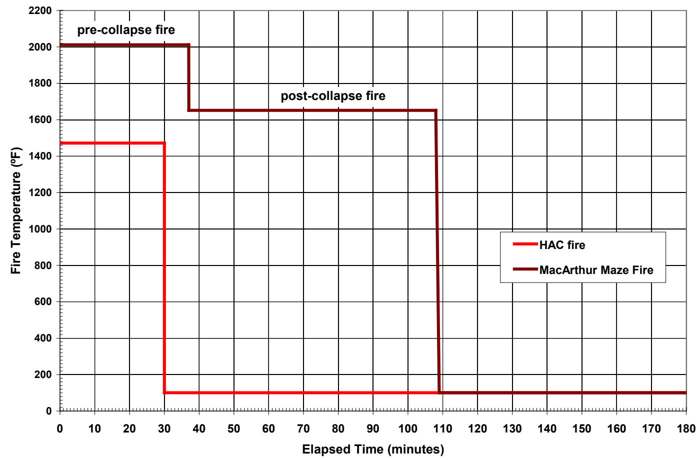

Fig. 8. Diagram of COBRA-SFS model of GA-4 Package

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).

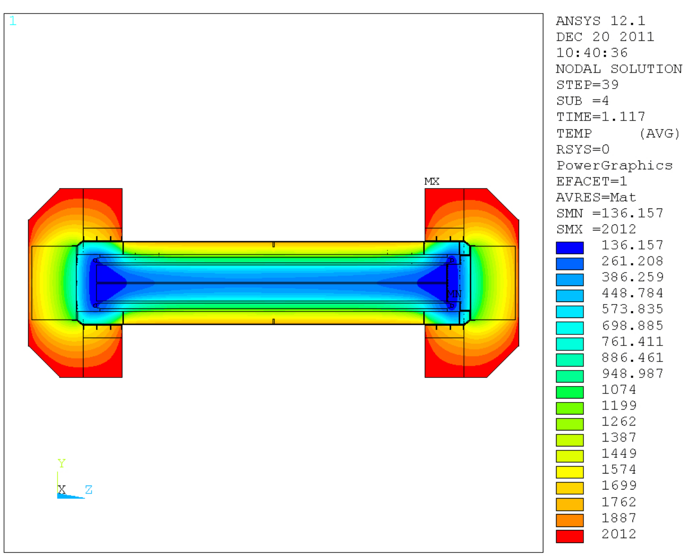

Fig. 9. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of Pre-collapse 1100ºC (2012ºF) Fully Engulfing Fire (37 minutes)

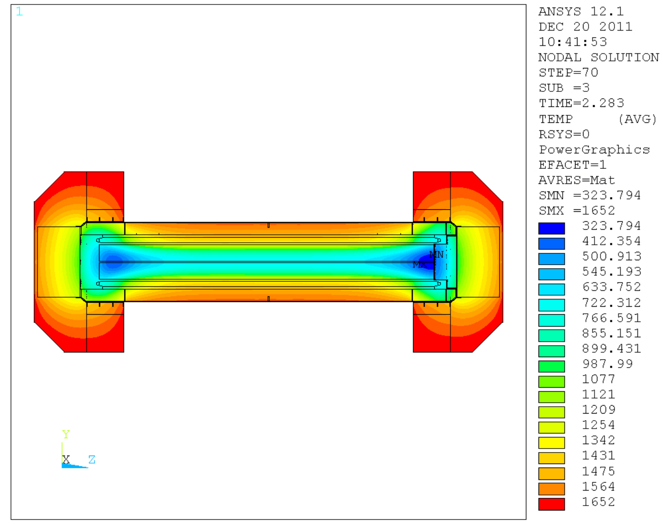

Fig. 10. Temperature distribution Predicted with ANSYS model for the GA-4 Package at end of fire (108 minutes), after Post-collapse 900ºC (1652ºF) Fully Engulfing Fire

The peak clad temperature predictions obtained with the COBRA-SFS model in the MacArthur Maze fire are shown in Figure 11.

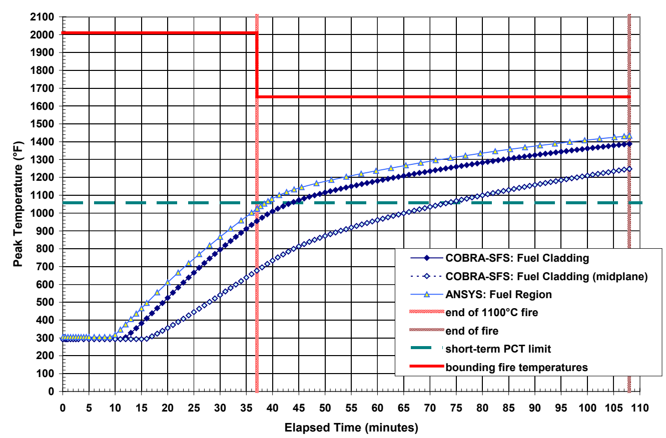

Fig. 11. Peak clad temperature predictions with ANSYS and COBRA-SFS models for the complete MacArthur Maze fire scenario

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).

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.

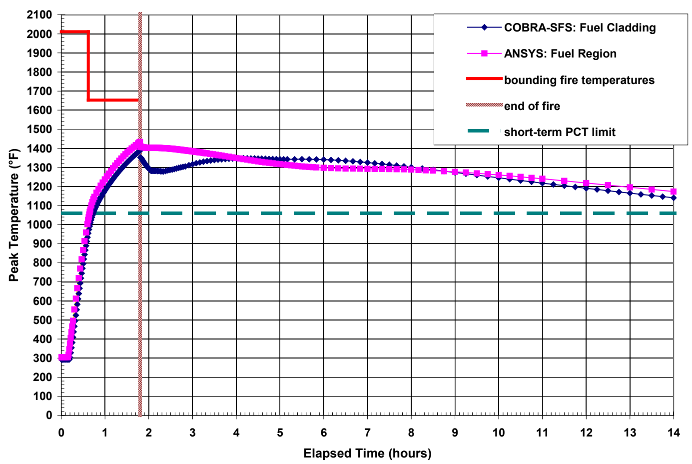

Fig. 12. Peak clad temperature predictions with ANSYS and COBRA-SFS models for the MacArthur Maze fire scenario to 14 hours

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 cannot be removed from the package during and immediately after 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 (See Figure 13).

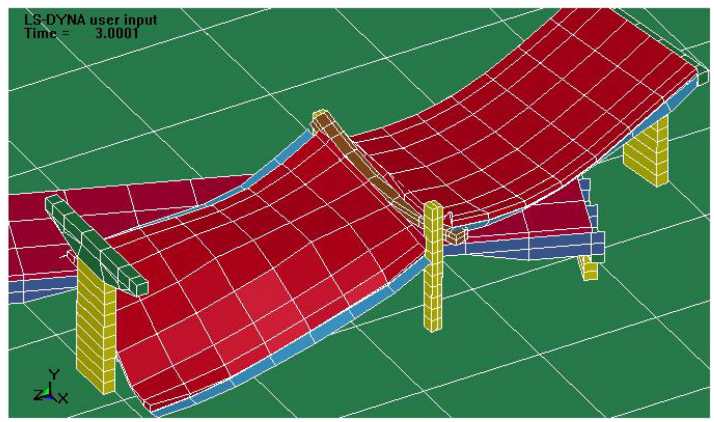

Fig. 13. Model of Collapsed I-580 Roadway

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 of 4 m (13.1 ft) 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 order to evaluate the worst-case drop scenario, so each case had a slightly different impact velocity. The cask was in each case placed at a point on the I-880 road surface such that the I-580 overpass section would fall straight down on it.

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 specified in 10CFR71 [1]. In contrast to the prescribed package drop scenario, which occurs at normal ambient temperatures, the drop scenarios in the MacArthur Maze fire scenario occur when the package is at an elevated temperature. Therefore, the temperature distribution on the I-580 overpass 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, as a conservative simplification.

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 as an initial simplification, but the preliminary impact results showed that the effects on the package structure were so minor that enhancing the model with detailed flange and closure geometry was not necessary. Instead, thermal effects on the seal, lid bolts and impact limiter bolts were determined to be more critical to package integrity, and these features were evaluated separately to determine their specific effects on the containment boundary during the accident. These separate evaluations are discussed in subsequent sections.

The results of the structural impact 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 14 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).

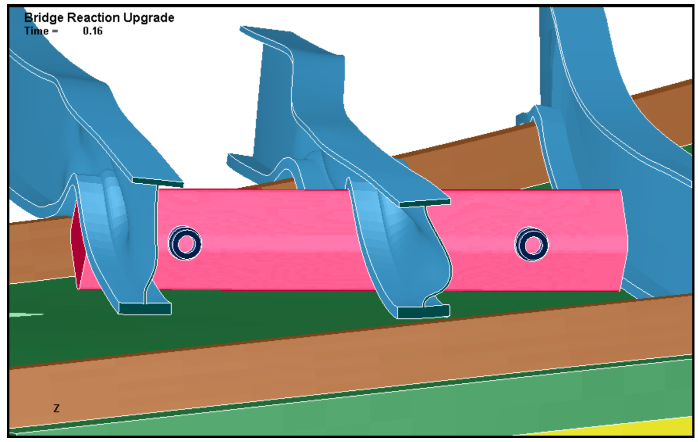

Fig. 14. Predicted Deformation of I-580 Span after Impact; Package Oriented Perpendicular to Girders

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 15 shows contours of effective plastic strain on the package body. (Local mesh and girder deformation images have been added to the standard LS-DYNA contour plot, as supplemental information.)

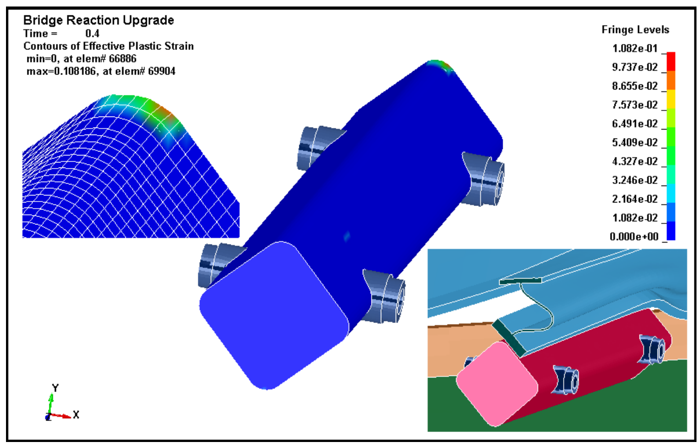

Fig. 15. Plastic Strain in Package Body after Girder Impact in Parallel Orientation.

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 the lid, closure 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 this is being evaluated in the ongoing assessment of the potential consequences of this accident scenario.

Preliminary Results of Bolt Evaluation

Thermal expansion stresses in the closure bolts and impact limiter attachment bolts were evaluated at the predicted temperatures. The GA-4 design uses stainless steel threaded inserts in both bolting locations to protect against thread galling. The threaded inserts act as the intermediary connective material between the bolt threads and the mating threads of the closure flange or impact limiter anchor point. Tension in the bolts is supported by shear loading in the threads, and at elevated temperatures thermal expansion tends to add tension beyond the initial bolt preload. At the predicted extra-regulatory fire temperatures, the strength of the threaded insert material tends to drop more than the nickel alloy bolts or temperature-resistant steel of the mating threads, so the strength of the threaded inserts can become the most limiting factor in the bolted connections. Tensile stresses in the bolt shanks, shear stresses in the bolt threads, and shear stress in the threaded inserts were evaluated with a combination of fundamental thread mechanics equations and finite element models.

The closure bolts were evaluated under two separate circumstances, using the temperatures predicted in the ANSYS thermal model, which included impact limiters, and the temperatures predicted by the COBRA-SFS thermal model, which neglects the impact limiters. The two situations lead to substantially different outcomes for the closure. When the impact limiters are present, they tend to insulate and protect the closure region from potentially damaging temperatures. Figures 9 and 10 (above) show that the closure region remains relatively cool, at the end of the large fully engulfing pool fire and the end of the fire. Considering the temperature-dependent material properties (including thermal expansion coefficients) and the geometry of the bolt closure region, the plots in Figure 16 show the total expected bolt tension (assuming uniform bolt temperature) compared to the yield and ultimate shear strength of the insert and the yield strength of the bolt.

If the impact limiters remain attached to the package, the closure bolt temperature does not exceed 427°C (800°F). The predicted temperatures are below insert yield, until just before the 108 minute end of the fire scenario. The inserts are expected to yield somewhat and reduce the tension in the bolt, but because the shear force remains below the ultimate shear strength limit, the connection of the closure to the flange would not be lost. However, without the protection of the impact limiters, the temperature in the closure bolts could exceed 954ºC (1750ºF) before the end of the 37-minute fire, which is long before the end of the total 108-minute fire duration. Following the bolt tension curve in Figure 16, the threaded inserts would yield and potentially fail before the bolt could start to yield.

The bolt tension curve in Figure 16 does not account for the reduction in tension due to yielding in the insert, and it is not clear what its actual post-yield behavior would be. For the purposes of this study, it is concluded that if the impact limiters remain attached, the bolted closure will remain closed. If the impact limiters do not remain attached, additional evaluation to better understand the mechanical impact response of the closure region would be required. Without the thermal insulation provided by the impact limiters, there is a potential for threaded insert failure and detachment of the closure plate from the package.

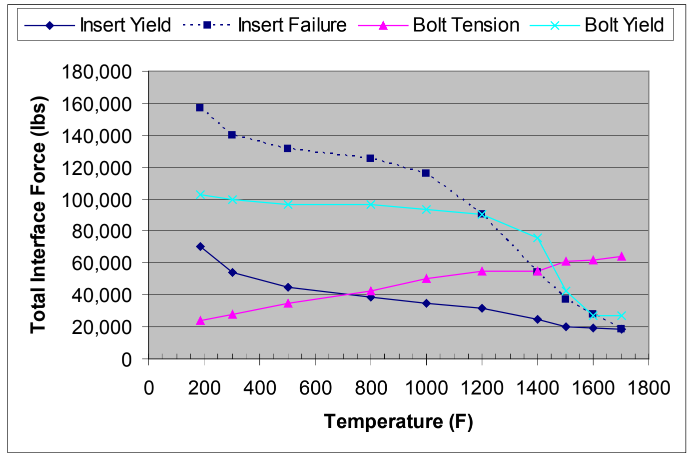

Fig. 16. Closure Bolt Thermal Expansion

The closure bolt evaluation makes the presence of impact limiters a much more critical topic than it is in the thermal evaluation. As Figures 11 and 12 demonstrate, the two thermal models agree well when peak cladding temperature is the parameter of interest. Under normal HAC conditions, impact limiters are expected to remain attached during all transportation accident scenarios. Since the fire temperatures in the MacArthur Maze fire scenario exceed HAC fire conditions, the possibility that the impact limiter attachment bolts or inserts could fail due to thermal expansion effects must be evaluated. The impact limiter bolts and inserts were first evaluated with uniform temperature assumptions in a similar manner to the closure bolts, as a scoping calculation. However, the temperature distribution in the bolts, as calculated in the detailed ANSYS thermal model, is distinctly non-uniform. The average bolt temperature tends to be significantly lower than the surrounding material, which makes the tension increase more than would be the case with a uniform bolt temperature.

An ANSYS model of one impact limiter bolt and its surrounding material, as shown in Figure 17, was developed to study the thermal expansion effects on the bolt.

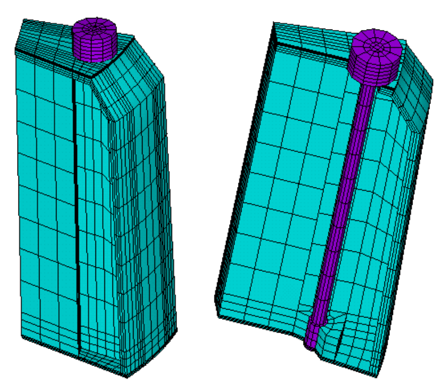

Fig. 17. Impact Limiter Bolt Thermal Expansion Model. Full model (left) and cutaway (right)

Bolt temperatures were available at many points along its length from the ANSYS package model. The temperature distribution of the surrounding material was estimated from the package nodal temperature results and the interface force was calculated at a number of time steps, up to 108 minutes. The Best Estimate case in Figure 18 uses averaging to determine the temperature distribution parallel to the bolt axis. The Conservative case in Figure 18 uses local maximum temperatures to determine the distribution, as a check on the effect of averaging.

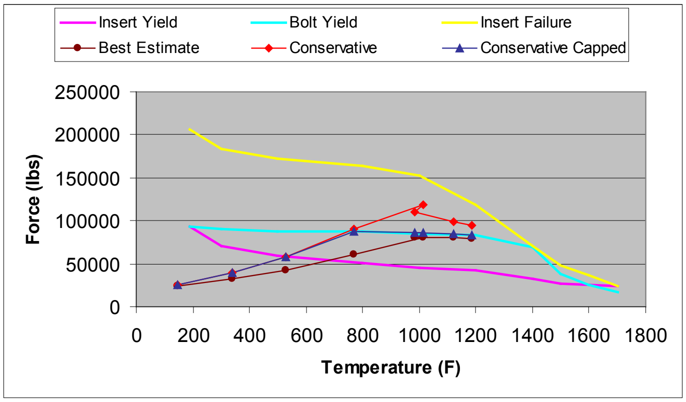

Fig. 18. Impact Limiter Bolt Thermal Expansion

The Conservative case has much higher forces, but it crosses the Bolt Yield threshold. Material yield in the threaded insert might relieve some of the buildup of tension, but if it does not the bolts are expected to yield before the threaded inserts reach their failure limit. The Capped Conservative curve in Figure 18 estimates the maximum bolt tension when it is limited by the yielding of the bolt. It is worth noting that the Bolt Yield curve is below the Insert Failure curve for all temperatures in the range of interest. For all such cases, the bolt is expected to yield before the threaded insert has the opportunity to reach its failure limit. While the yield behavior of the threaded insert may be difficult to predict, yielding in the bolt is expected to behave like a typical tensile test. The ductility limit of the nickel alloy bolts is near or above 20% elongation, so failure is unlikely in this scenario. This provides reasonable assurance that the impact limiter bolts would maintain their attachment during the extra-regulatory MacArthur Maze fire scenario. The closure bolt evaluation that assumes a missing impact limiter does not represent a credible condition.

It can be concluded from this bolt evaluation that the impact limiters will remain attached in this scenario and provide thermal protection to the closure region. At the time of the overpass collapse, the closure bolts remain relatively cool and the connection maintains most of its strength. Near the end of the 108 minute fire the closure bolt inserts are expect to yield, which would reduce the bolt tension and clamping force, but would remain far from a tension that might cause the insert to fail. The potential for a release from the package is currently being evaluated and will consider the bolt response as appropriate.

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. It was determined that both the lid and impact limiters are expected to remain in place, with some potential for material yield and bolt tension relief. 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.

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