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# The MacArthur Maze Fire and Roadway Collapse: A "Worst Case Scenario" for Spent Nuclear Fuel Transportation?

Christopher S. Bajwa, Earl P. Easton
*U.S. Nuclear Regulatory Commission, Washington, DC*
Harold Adkins, Nicholas Klymyshyn, Judith Cuta, Sarah Suffield
*Pacific Northwest National Laboratory, Richland, WA*

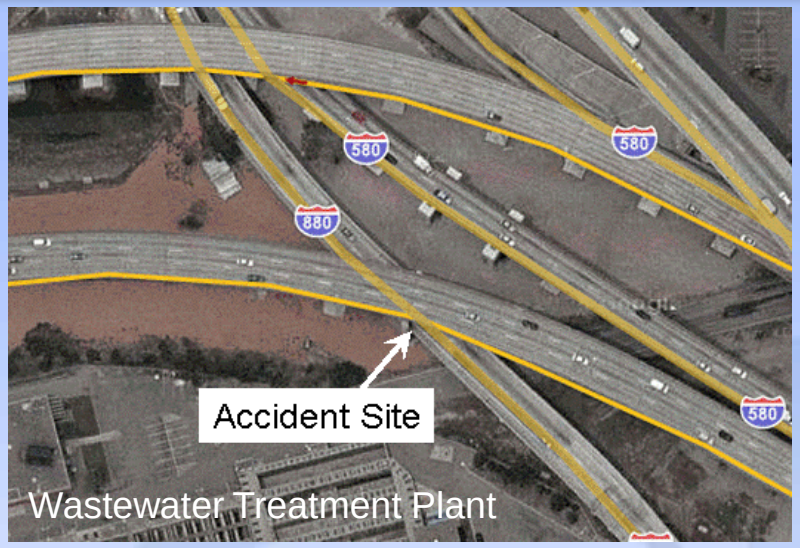
# Outline

- Introduction
- MacArthur Maze Accident Description and Post Accident Analysis
- Characterization of Fire Scenario for Thermal and Structural Analysis
- FEA and CFD Models of Legal Weight Truck Package (GA-4)
- Preliminary Evaluation of Thermal and Structural Response of GA-4 Exposure to MacArthur Maze Fire Scenario

# Introduction

- 10 CFR Part 71 – Packaging and Transportation of Radioactive Materials
  - Section 73: Hypothetical Accident Conditions (HAC)
    - 30 Minute fire: Average Flame Temp. 800°C (1475°F)
- Evaluate real world accidents against this standard
  - Do the regulations cover recent severe accidents such as the MacArthur Maze fire?

# MacArthur Maze Fire





- Occurred April 29, 2007 at about 3:38AM in the MacArthur Maze, an interchange connecting I-80, I-580, and I-880 in Oakland, California
- Double tanker gasoline truck traveling south along Interstate 880
  - 32,500 liters [8,600 gallons] of gasoline
- Driver lost control at ~60 mph, tanker and trailer rolled over, eventually came to rest on I-880 ramp directly beneath I-580 overpass
- Spilled fuel from damaged tanker ignited, resulting in fire on I-880, leading to collapse of I-580 overhead span approximately 17 minutes after the fire started; slower partial collapse of second span of I-580 over subsequent ~20 minutes
- Entire fire lasted approximately 108 minutes

# Collapse of I-580 Overhead Spans--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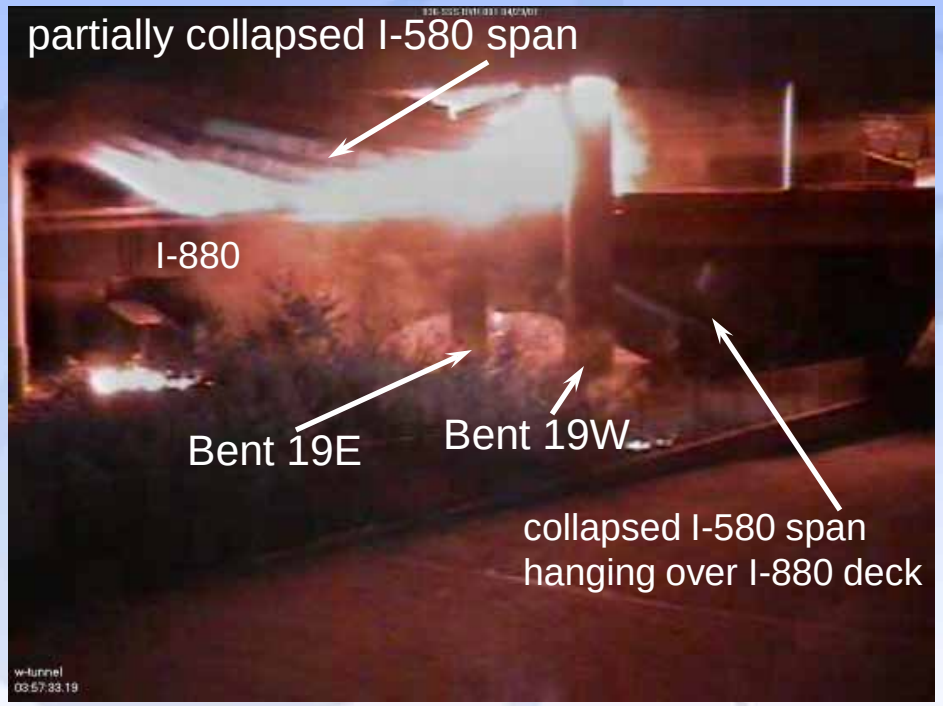


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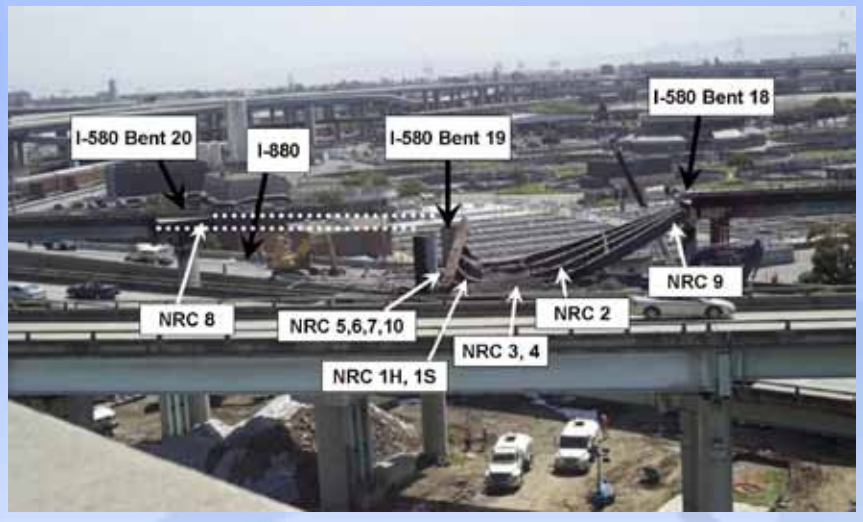
# Estimates of Material Temperatures in MacArthur Maze Fire

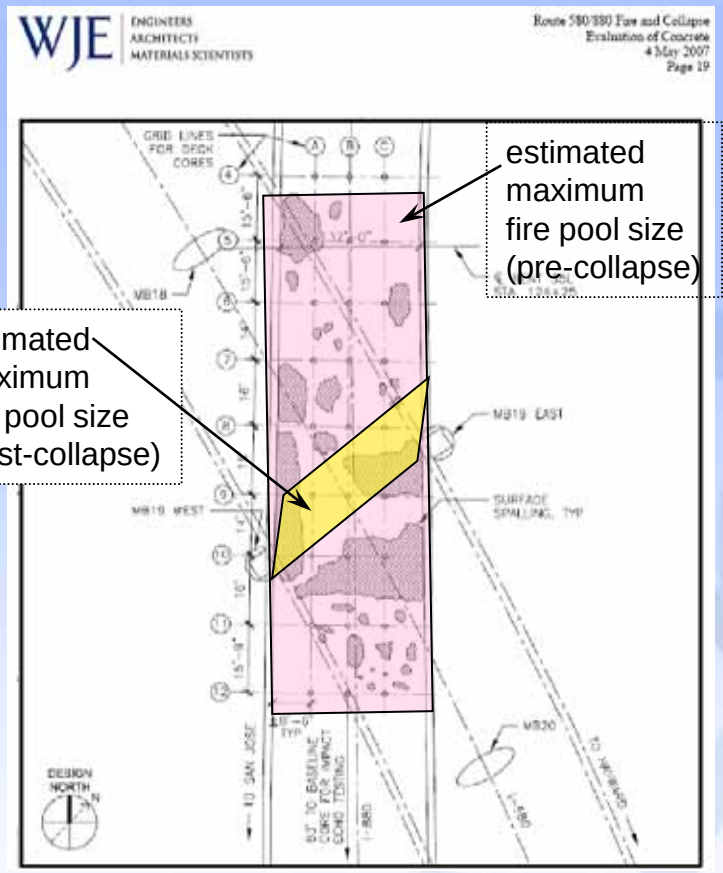



- NRC and SwRI staff collected samples to determine temperatures experienced by girders and truck during the fire
- Performed isothermal exposures of unaltered specimen (Sample NRC 9) to 900°C (1652°F) to determine weld transformation temperatures
- Performed metallurgical analysis of girders and truck materials, including microstructure evaluation of weld regions

# MacArthur Maze Fire: Materials Analyses Conclusions

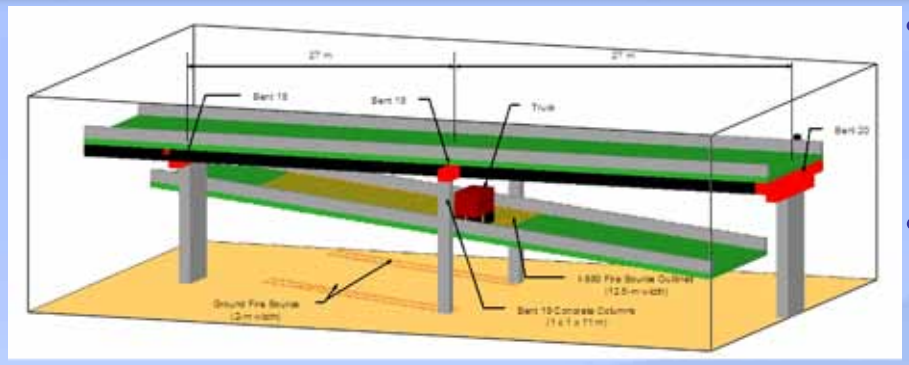
- Based on the samples collected and the results of thermal exposure tests, the temperature of the I-580 overpass is estimated to have ranged from 850°C [1,562°F] to approximately 1,000°C [1,832°F].
- Near the truck, the maximum exposure temperature is estimated to be at least 720°C [1,328°F] but less than 930°C [1,706°F].
- The hottest gas temperatures during the fire were located above the I-880 roadway near the steel girders of the I-580 overpass.

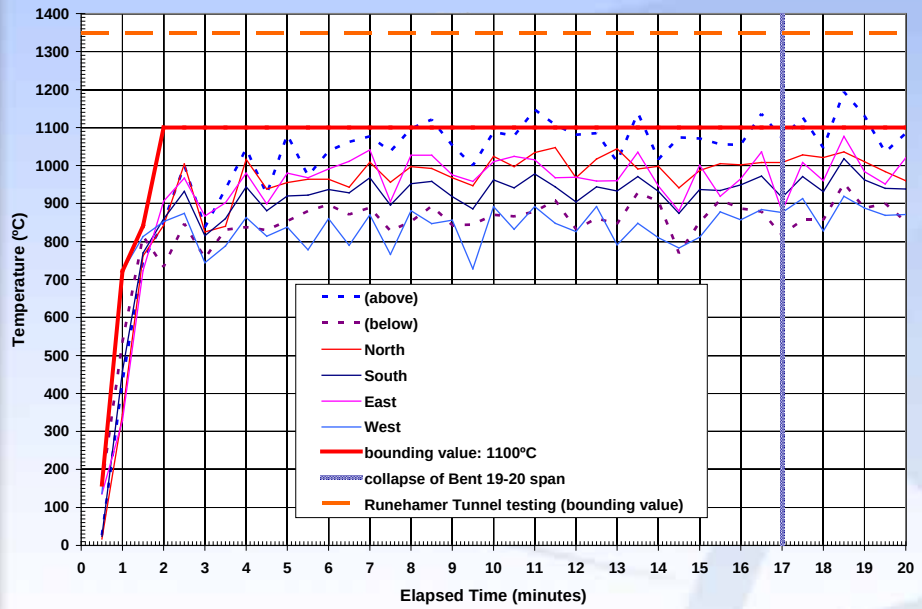
# MacArthur Maze Fire Model




- The MacArthur Maze fire went through three distinct phases:
  - a large open pool fire for ~17 minutes, until complete collapse of Bent 19-20 overhead span
  - a gradual decrease in size over ~20 minutes, due to intrusion of partially collapsing Bent 18-19 overhead span
  - a smaller open pool fire in the gap between the collapsed spans for ~71 minutes, to end of fire at 108 minutes
- Fire Modeling with the Fire Dynamics Simulator (FDS) code encompassed only the large open pool portion of the fire, to obtain bounding fire temperatures

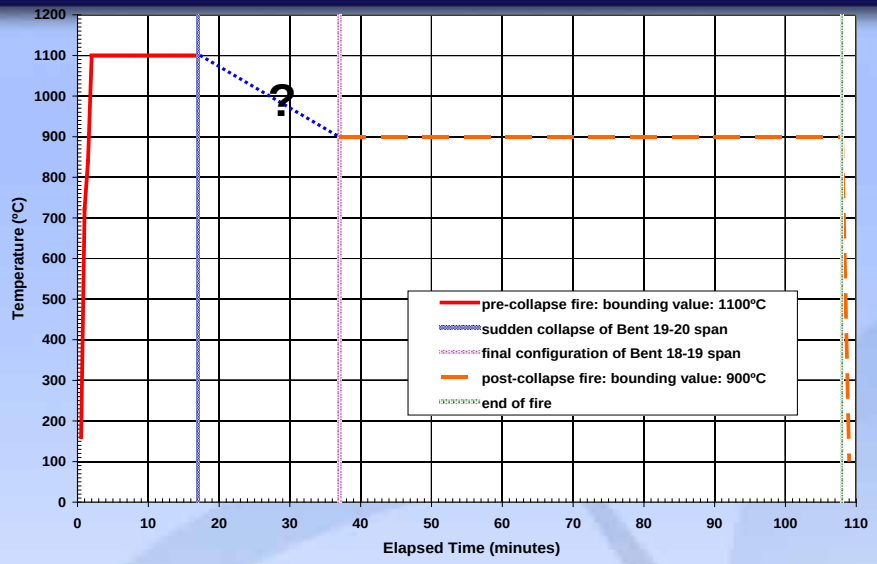
# Estimate of Maximum Flame Temperature: Fire Modeling Results

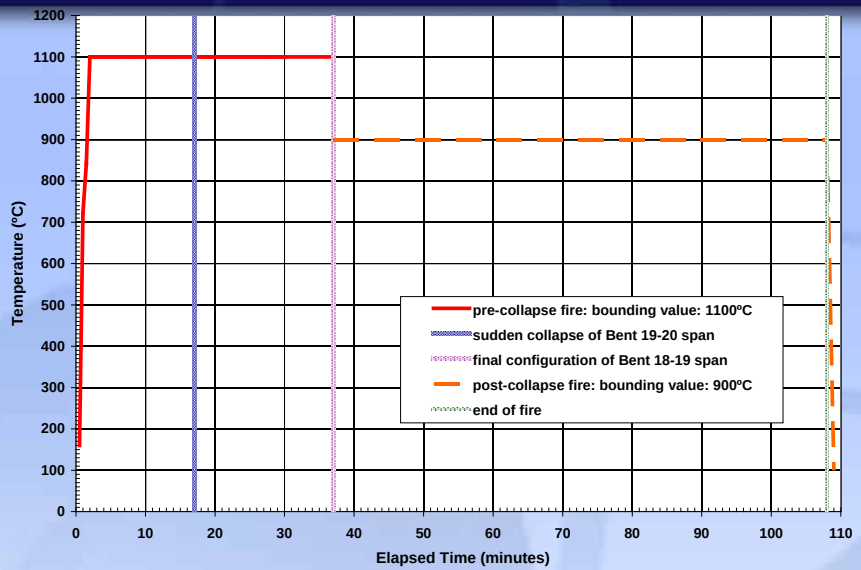





- Large open-pool hydrocarbon fires can be characterized with a uniform flame temperature of approximately 1000°C (1832°F)
- Upper temperature limit for confined but fully oxygenated fires is about 1350°C (2462°F), based on Runehamar Tunnel tests, and NFPA 502
- Preliminary analysis with the Fire Dynamics Simulator (FDS) code predicted conservative estimates of 1320°C (2408°F) for maximum temperature in the pool fire
- Refinement of the model to account more precisely for specific features of the MacArthur Maze fire yielded results conservatively bounded by a uniform temperature of 1100°C (2012°F)

# Temperature Boundary Conditions for MacArthur Maze Fire Scenario



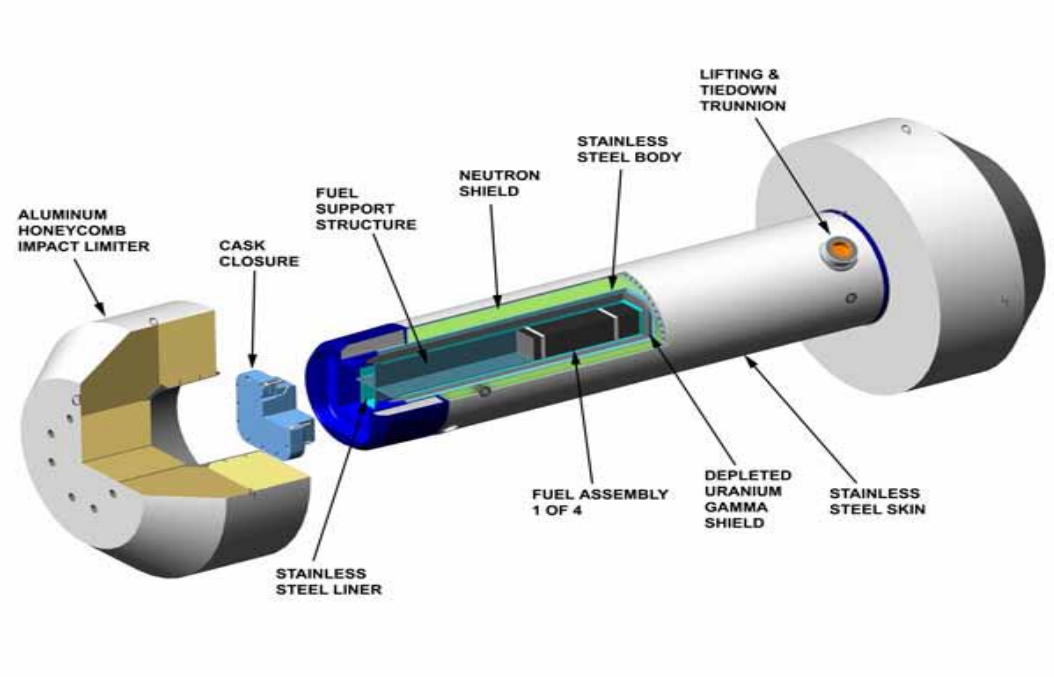

- Pre-collapse fire (0-17 minutes) modeled as fully engulfing fire with uniform temperature 1100°C (2012°F), 0.9 emissivity
- Fire gas temperatures during collapse of Bent 18-19 span cannot be as high as attainable in an unconstrained open pool fire
  - Transition from large pool to smaller pool fire conservatively bounded by extending fully engulfing fire at 1100°C (2012°F) to 37 minutes
- Post-collapse fire (37-108 minutes) modeled as fully engulfing fire with uniform temperature 900°C (1652°F), 0.9 emissivity

# Modeling Effects of MacArthur Maze Fire on an SNF Truck Transportation Package

- GA-4 package selected for analysis
  - Relatively high capacity Legal Weight Truck package
- LS-DYNA model of bridge structure created to simulate collapse of I-580 overhead span between Bent 19 and Bent 20
- ANSYS model of GA-4 package (including impact limiters) developed to simulate structural and thermal response of cask to fire conditions and post-fire cooldown under fallen roadway
- COBRA-SFS model of GA-4 package (with & without impact limiters) developed to simulate thermal response to fire conditions, and effect of concrete over package in post-fire cooldown

# GA-4 Legal Weight Truck Transportation Package

- GA-4 package is designed to transport
  - up to 4 intact PWR 14x14 or 15x15 spent fuel assemblies




Ømaximum decay heat load of 2.468 kW, with maximum of 0.617 kW/assembly

Ømaximum average burnup of 35 GWd/MTU (10-yr cooled) or 45 GWd/MTU (15-yr cooled)

- Stainless steel cask body, with
  - depleted uranium gamma shield
  - propylene glycol/water mixture for neutron shield
  - gross wt. 55,000 lb (25,000 kg)

# 'Most Limiting' Fire Scenario for Thermal Response of GA-4 SNF Package to MacArthur Maze Fire

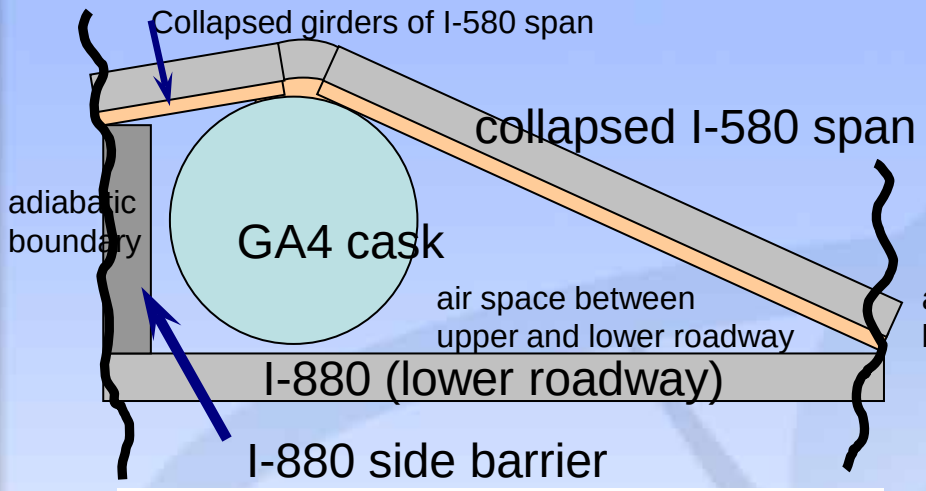
- 37 minutes of exposure to a fully engulfing fire at 1100ºC (2012ºF) to simulate the pre-collapse portion of the fire
  - Assume concrete surfaces of roadway also exposed to fully engulfing fire temperature
- From 37 minutes to end of fire at 108 minutes, assume
  - Fully engulfing fire, temperature reduced to uniform bounding value of 1652ºF (900ºC)
  - Assume concrete surfaces of roadway also exposed to fully engulfing fire temperature
- after 108 minutes, assume package 'blanketed' by fallen roadway;
  - free convection to still air (including thermal radiation exchange with enclosing roadway surfaces)
  - free convection and radiation from exposed roadway surfaces

# 'Most Limiting' Scenario for Structural Response of GA-4 SNF Package to MacArthur Maze Fire

- Impact analysis evaluating effect of section of I-580 roadway falling onto the SNF package
  - Free-fall drop of Bent 19-20 span onto package
  - Upper roadway girders assumed at lowest possible temperature, to conservatively maximize stiffness at time of impact with package
  - Package temperatures assumed conservatively high for time of impact, to bound vulnerability to structural damage
- Evaluation of SNF package structural response to extraordinary thermal load imposed by the fire scenario and post-fire cooldown, including
  - effects of temperature exposure and thermal expansion on package lid closure bolts
  - effects of temperature exposure and thermal expansion on impact limiter attachment bolts

# Diagrams of Thermal Models of SNF Package Beneath Collapsed I-580 Span

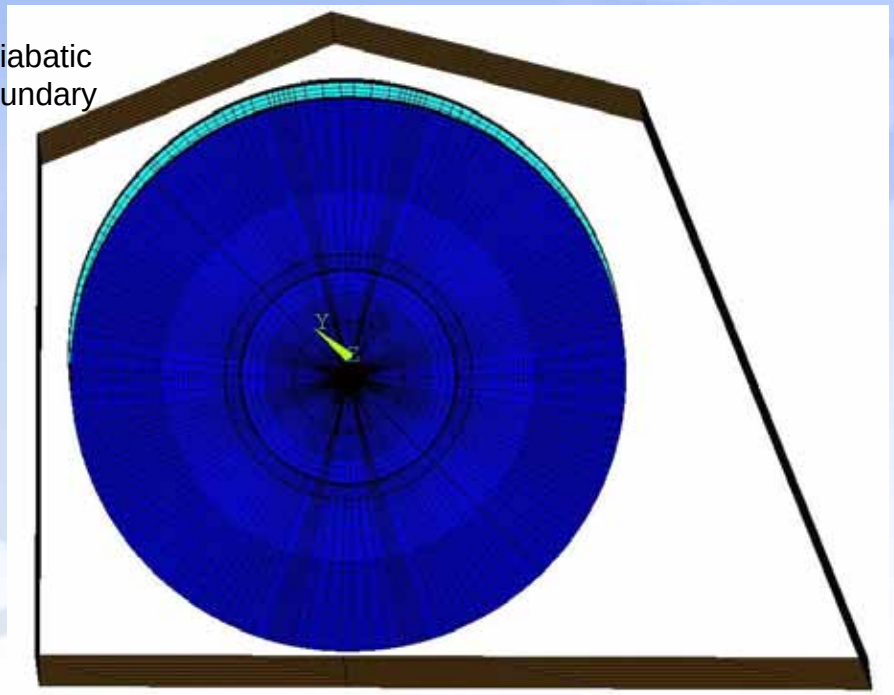
## *COBRA-SFS model*



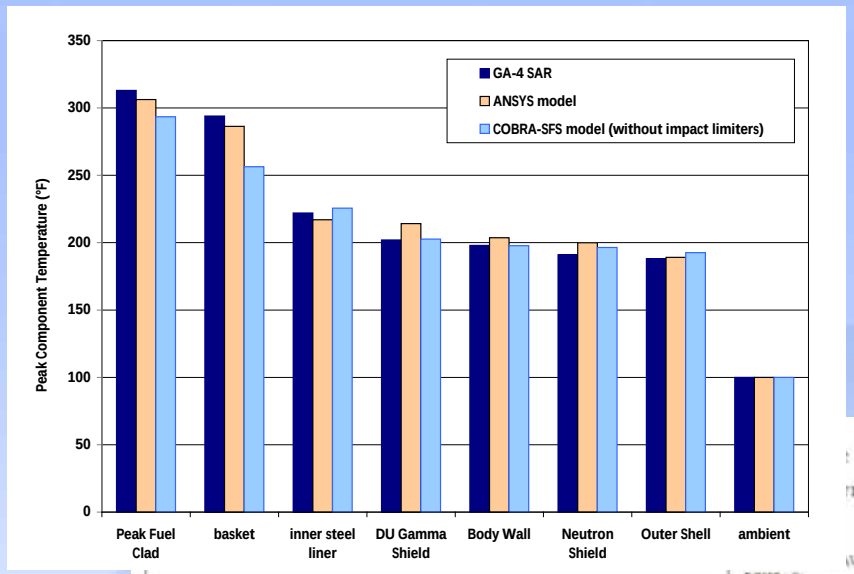


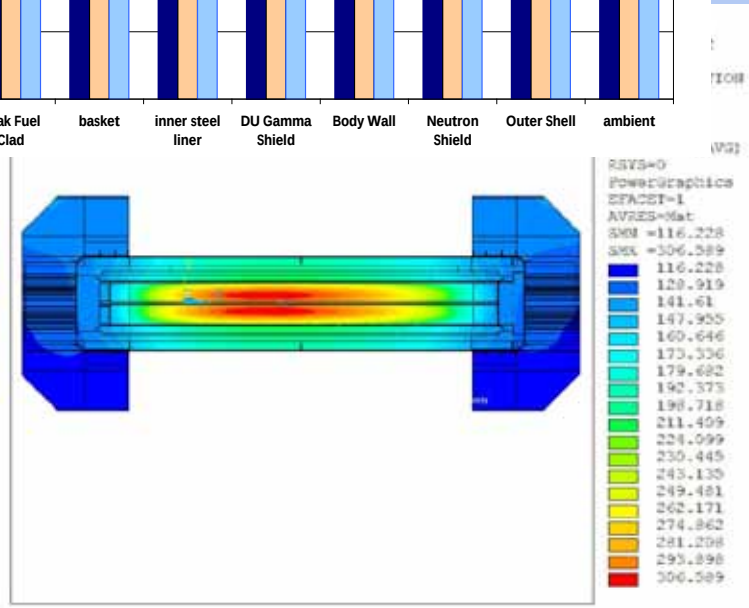
NOTE: model diagrams are not to scale

## *ANSYS model*



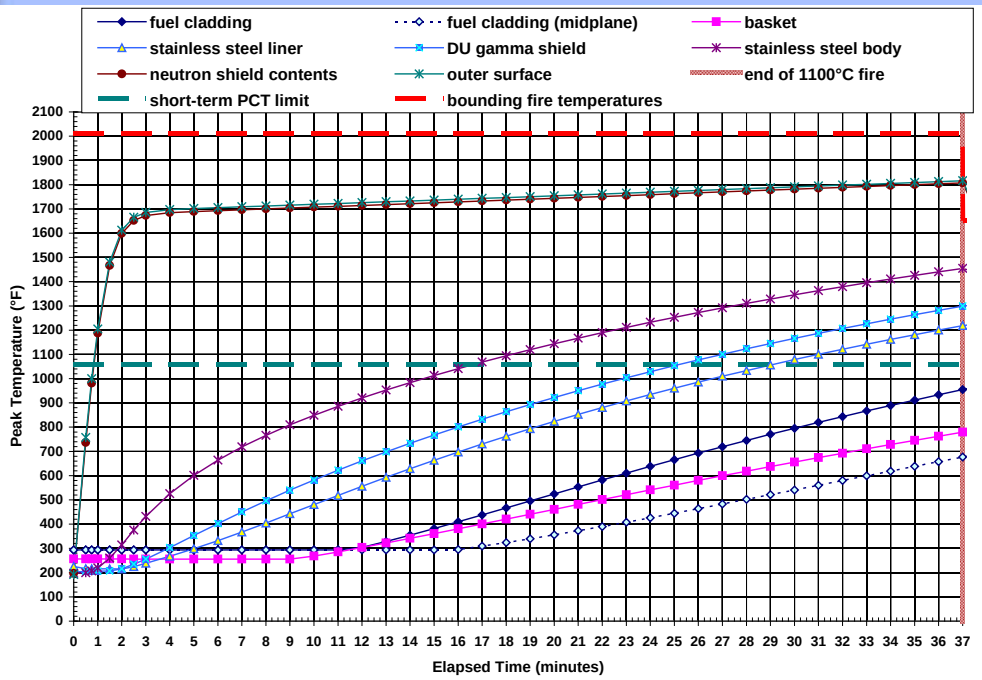
# Modeling Results: GA4 Package for Normal Conditions of Transport (NCT)— 38ºC (100ºF), with insolation



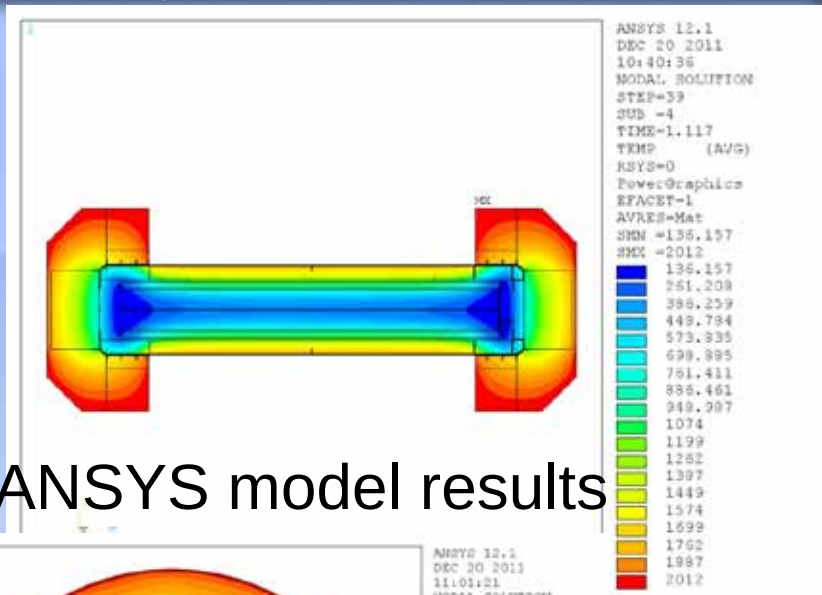



- Peak clad temperature predictions are
  - 156ºC (313ºF) from SAR
  - 152ºC (306ºF) from ANSYS model (with impact limiters)
  - 146ºC (293ºF) from COBRA-SFS model (without impact limiters)
- Differences in results are small, and consistent with known differences in modeling approaches

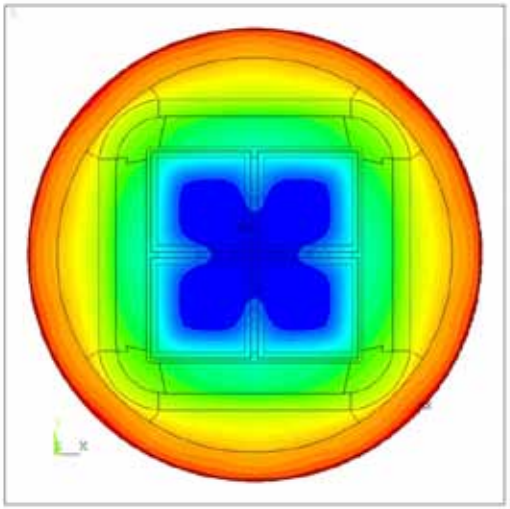
# MacArthur Maze Fire Modeling – Preliminary Results for 1100°C Fully Engulfing Fire (37 minutes)




COBRA-SFS model results

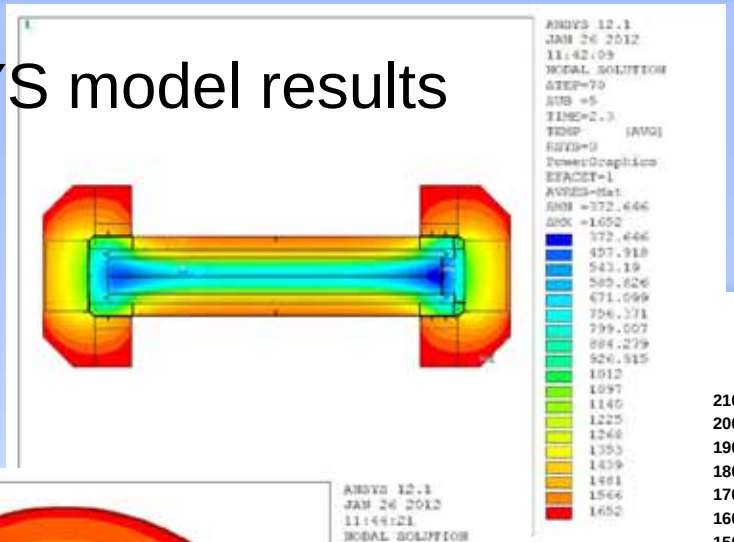


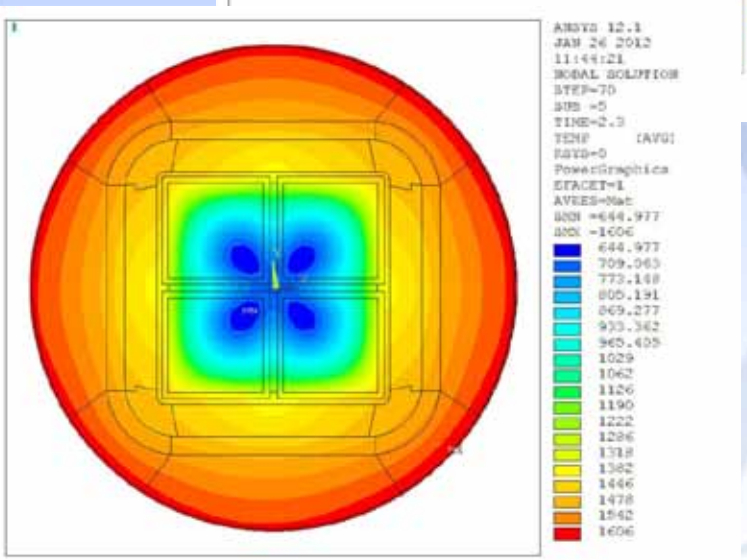

ANSYS model results



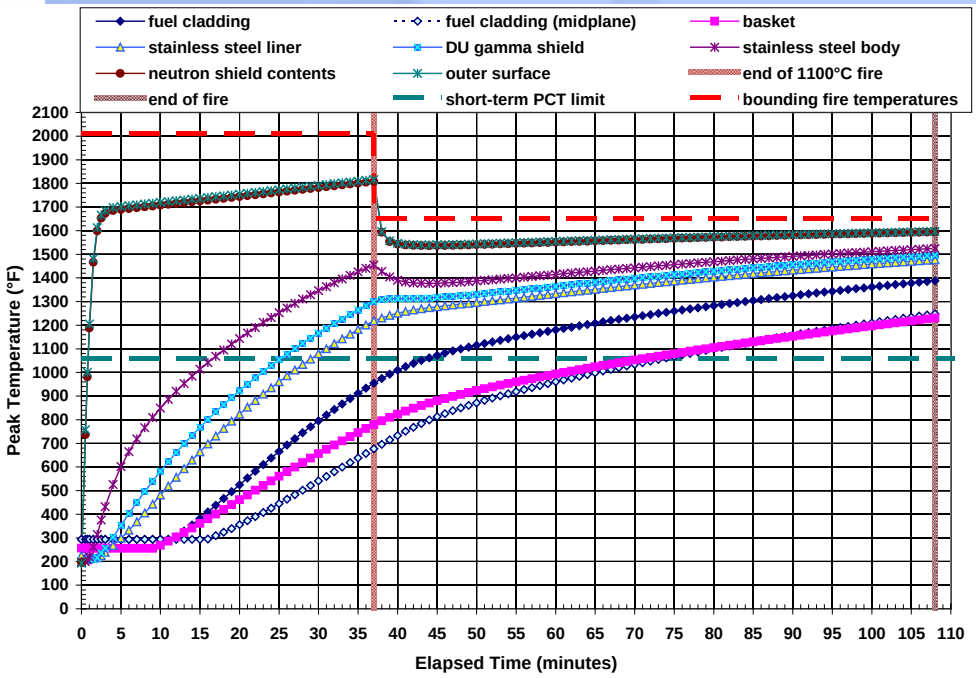
# MacArthur Maze Fire Modeling – Preliminary Results for 1100ºC/900ºC Fully Engulfing Fire (108 minutes)

## ANSYS model results

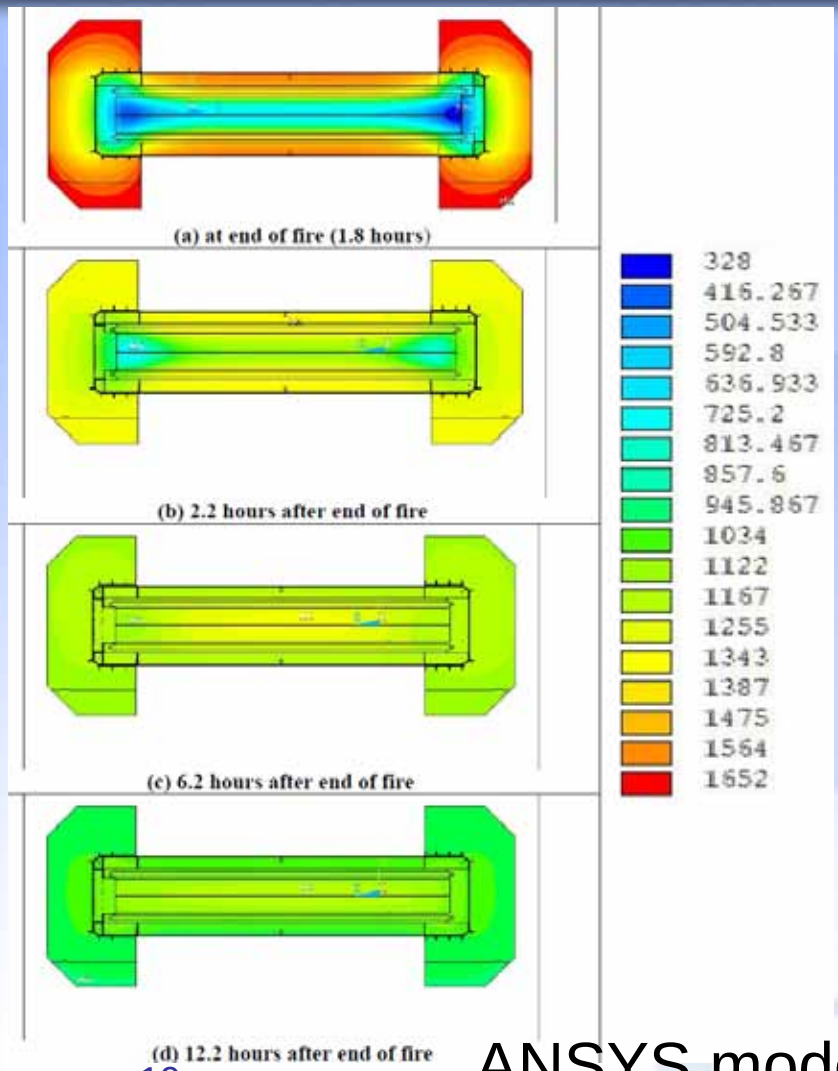




## COBRA-SFS model results

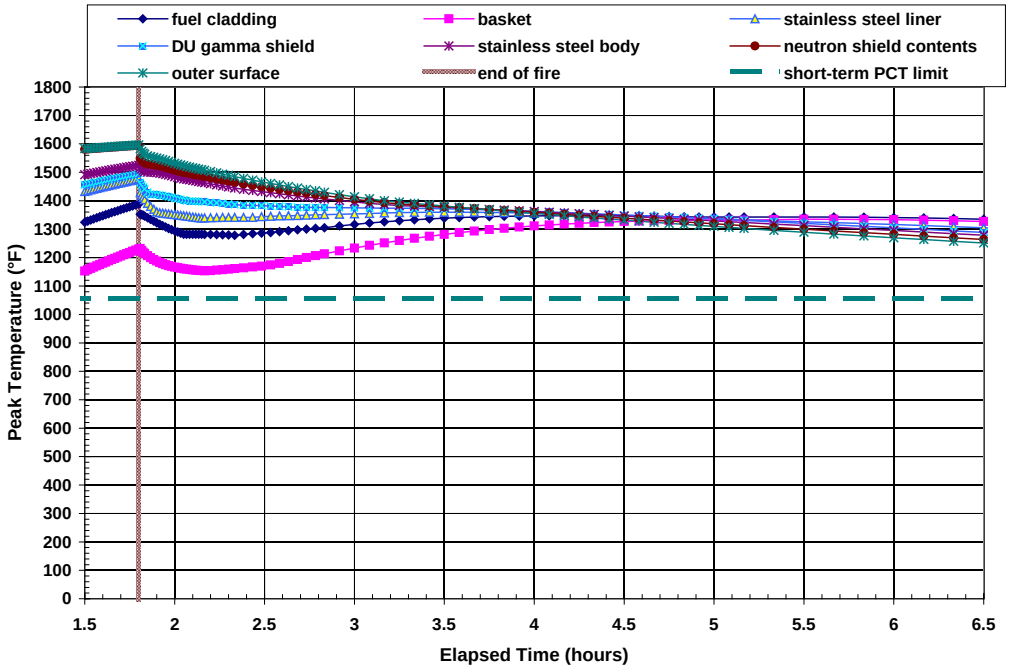


# MacArthur Maze Fire Modeling – Preliminary Results for Post-Fire Cooldown Under Concrete Blanket (>12 hours)




ANSYS model results

## COBRA-SFS model results



# MacArthur Maze Fire Modeling – Preliminary Results: Thermal Response Summary

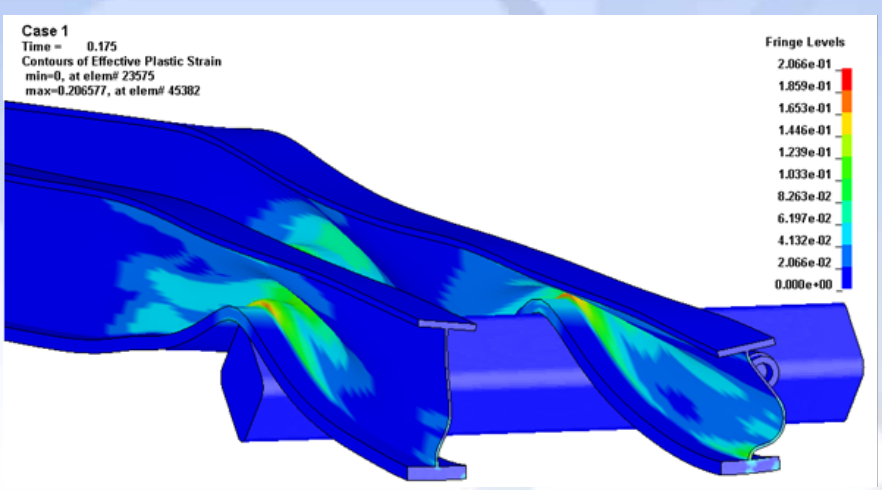
- Predicted maximum peak clad temperatures significantly exceed calculated burst rupture and creep rupture temperatures (1097ºF (592ºC) to 1229ºF (665ºC)) before the end of the fire
  - all fuel rods in this package are predicted to exceed the burst rupture temperatures for at least ~6 hours in the fire scenario and cooldown
  - peak clad temperatures remain above short term limit (1058ºF (570ºC)) for more than 15 hours during fire scenario and post-fire cooldown
  - for GA-4 thermal design-basis fuel, cladding is predicted to experience burst rupture in this fire scenario
- In post-fire 'cooldown', peak temperatures on package ends (beneath impact limiters) continue to increase for approximately 4 more hours, due to
  - Insulating effect of impact limiters on package ends
  - Insulating effect of concrete 'blanket' on entire package
  - thermal inertia of the fuel
- Seal region temperatures are predicted to exceed seal material long term temperature limit within first hour of fire transient
  - Seal region temperatures remain above the long-term temperature limit for >14 hours

# Structural Models for Analysis of GA-4 Response to MacArthur Maze Fire Scenario

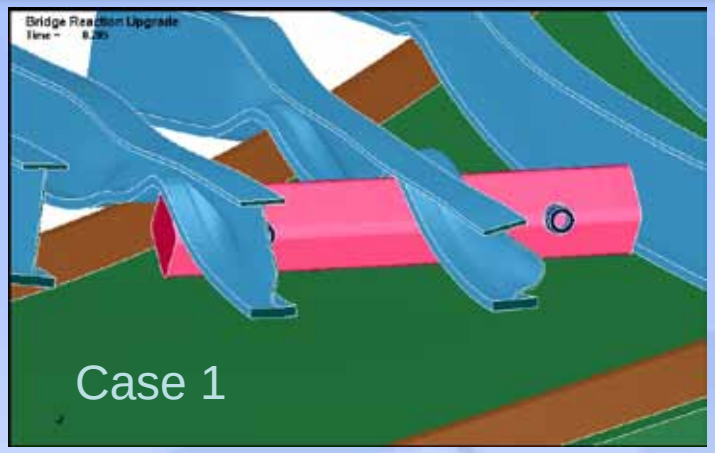
- Structural impact model constructed with LS-Dyna, representing GA-4 package and
  - one span of lower (I-880) roadway (ends fixed in space)
  - one span of upper (I-580) roadway
- Roadway spans modeled as elastic-plastic plate girders and linear-elastic concrete slabs
  - Lower roadway properties at 80ºF (27ºC) to conservatively represent stiffness of platform beneath package
  - Upper roadway steel girder properties at 1800ºF (982ºC) to conservatively represent strength of girders at elevated temperature
  - Analysis initiated with upper span in freefall; pre-collapse sagging and air drag neglected
- GA-4 package represented with steel body, DU gamma shield, and steel trunnions for impact analyses
  - Impact limiters and fragile steel shell of neutron shield neglected
- Detailed ANSYS model of impact limiter attachment bolts for thermal expansion effects study

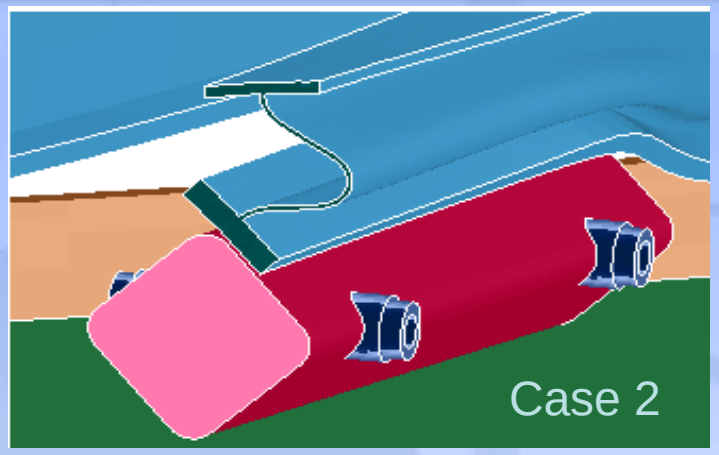
# Potential Effects of Roadway Collapse on GA4 Package in MacArthur Maze Fire Scenario

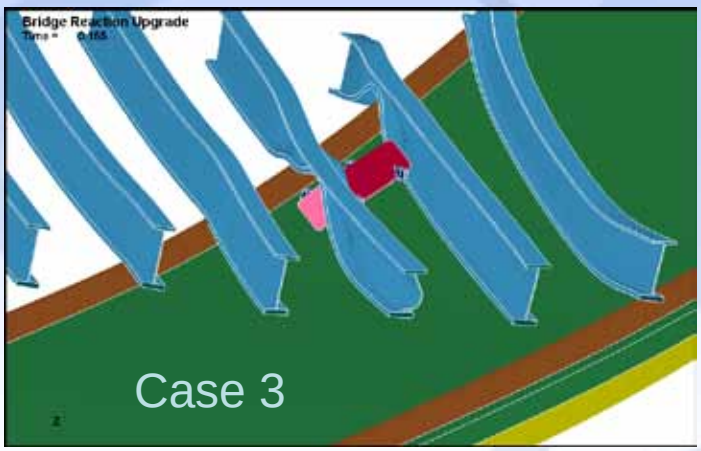
- Analyses performed with GA4 package positioned on lower roadway, in 4 postulated orientations:
  - Case #1: perpendicular to upper roadway girders: main impact on package center
  - Case #2: parallel to upper roadway girders: main impact along axial length of package
  - Case #3: oriented for main impact on package lid
  - Case #4: oriented for direct impact on lifting trunnion
- Results show that steel plate girders of overhead roadway are more severely affected by the drop impact than the GA4 package

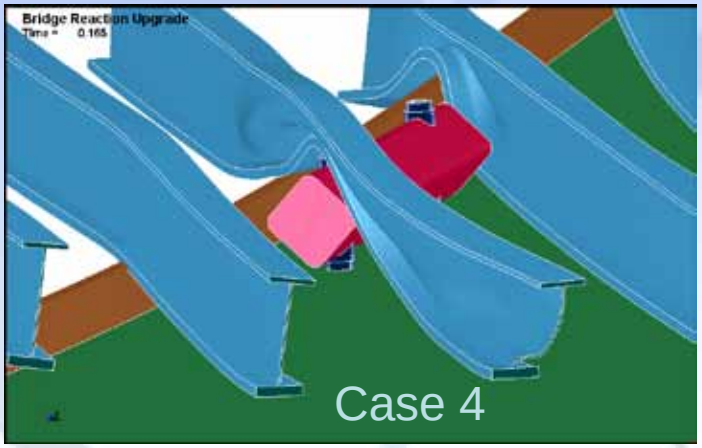



# LS-Dyna Results: Girder Behavior in I-580 Roadway Collapse onto GA-4 Package

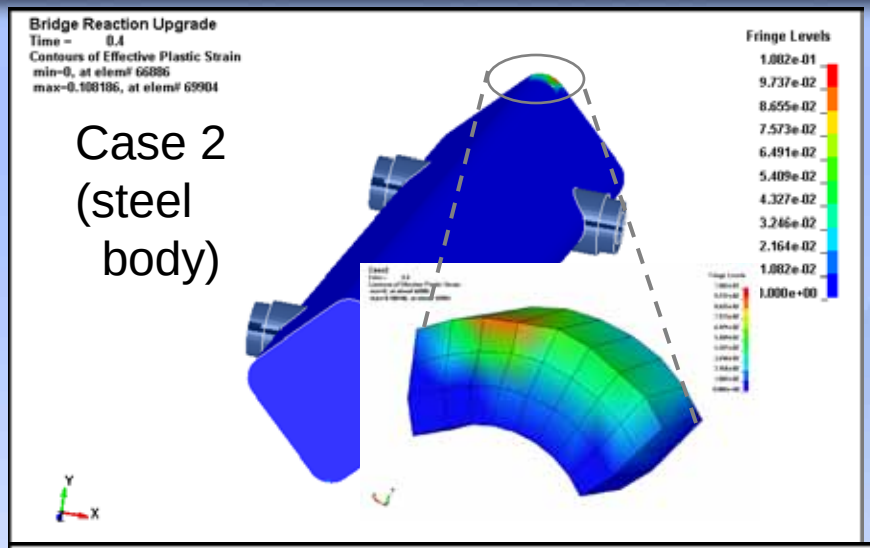


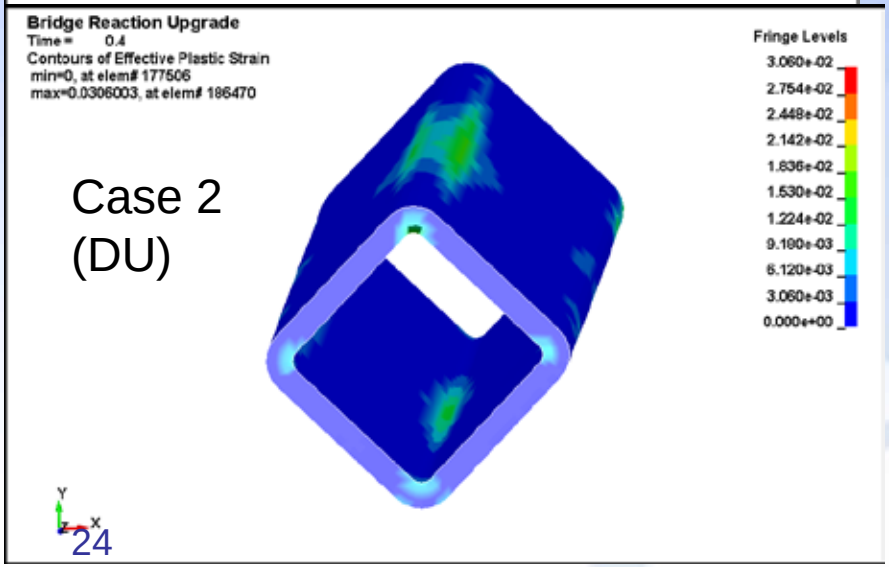



# Summary of LS-Dyna Results: GA-4 Package Response to I-580 Roadway Collapse




- Case #1: maximum plastic strain of 2.4%, localized on upper edge of package
- Case #2: highest plastic strains of the four cases considered
  - Maximum strain of 11% in steel body
  - strains are not severe enough to compromise structural integrity of package
- Case #3, assuming localized impact of only one girder on package end
  - Case #2 causes greater plastic deformation near the closure region
- Case #4, assuming localized impact on trunnion
  - evaluates special case of potential for localized impact directly on package wall
  - Least severe impact effects of all cases considered

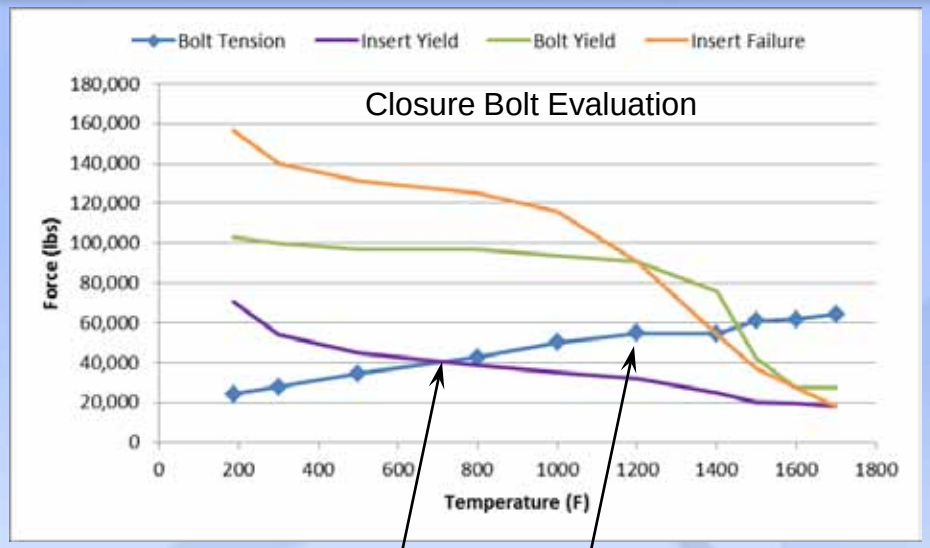
# Summary of Results of Structural Analysis of Impact Modeling in MacArthur Maze Fire Scenario

- Steel structure of the GA-4 package wall remains largely undamaged in the impact scenarios
  - plastic strains in the steel wall are well within expected ductility limit of the material, even at elevated temperatures
  - Some permanent deformation of the steel wall is predicted, but not a gross failure or rupture
- Plastic strain predicted in the DU gamma shield is also within expected ductility limits of the material
  - DU gamma shield is not part of the containment boundary and is not treated as a structural member in the GA-4 design
  - Included in modeling only to provide minimal realistic support for package wall
- Preliminary models investigated the effects of
  - increased overpass mass
  - alternative girder geometries
  - wide range of assumed temperatures for package and roadway
- In all cases investigated, analysis has shown that the GA-4 package would remain largely intact for the impacts postulated in the MacArthur Maze fire scenario

# Potential Thermal Effects on Performance of Bolts of the GA4 Package in MacArthur Maze Fire Scenario

- Thermal expansion of dissimilar materials cause bolt tension to increase with increasing temperature
  - Inconel closure bolts fasten package lid to flange (both XM19 stainless steel)
  - Inconel impact limiter bolts fasten impact limiters to XM19 anchor plates on package body
  - All Inconel bolts interface with XM19 steel components with Type 304 stainless steel threaded inserts
- Thermal expansion evaluation shows that the bolted connection response to this fire scenario is more challenging to the containment boundary than the roadway impact
  - threaded inserts are expected to yield due to reduced strength at elevated temperature, and relieve tension in both the closure bolts and impact limiter bolts
  - Inconel closure bolts are thermally shielded by top impact limiter, and are expected to remain below yield
  - Inconel impact limiter bolt heads are directly exposed to fire temperatures, and could potentially yield

# Preliminary Results – Closure Bolt Evaluations in MacArthur Maze Fire Scenario

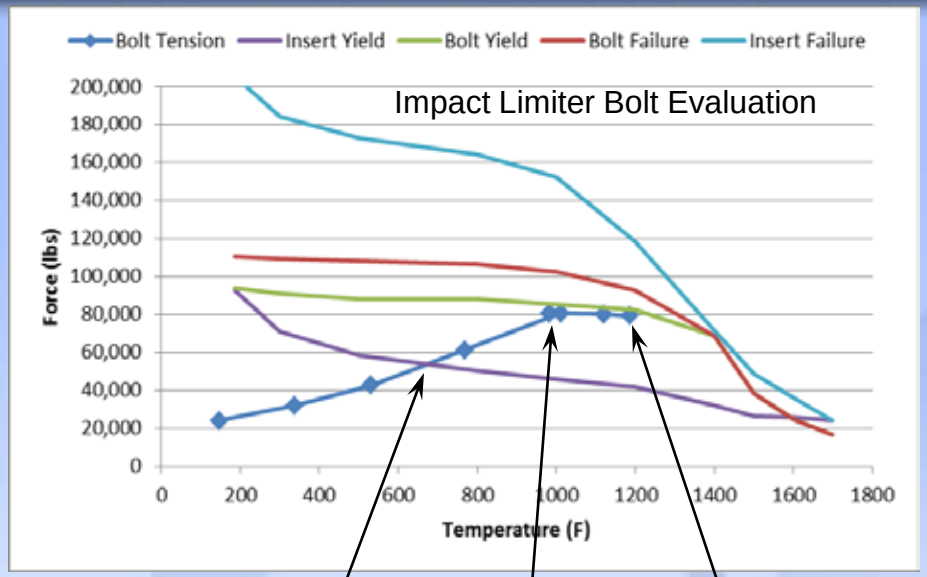



Threaded inserts yield

Maximum bolt tension

- Closure bolt threaded inserts exceed 750ºF (~400ºC) and are predicted to yield before end of fire
  - Reduction of tension due to yield of inserts is conservatively neglected in this analysis
  - Insert failure limit is not reached, even with conservative assumptions
- Maximum bolt temperature predicted during cooldown is ~1200ºF (~650ºC) at ~7 hours
- Maximum bolt tension at ~1200ºF (~650ºC) is predicted to be significantly below bolt yield
- Closure bolts are expected to experience some loss of tension, but will maintain connection of lid to package

# Preliminary Results – Impact Limiter Bolt Evaluations in MacArthur Maze Fire Scenario




Threaded inserts yield

Inconel bolts yield

Bolt tension at maximum temperature

**Note: Bolt yield curve represents maximum credible force and provides a conservative ceiling for failure evaluation. In this scenario,**

**--Bolt failure is not predicted until at least ~1400ºF (~760ºC)**

**--Insert failure is not predicted until at least ~1600ºF (~870ºC)**

- Impact limiter bolt threaded inserts exceed 750ºF (~400ºC) and are predicted to yield by ~20 minutes
- Impact limiter bolts exceed 1000ºF (~540ºC) and are predicted to yield by ~37 minutes
  - Results in a self-limiting yield of bolt shank
  - Bolt has enough elongation capacity to reduce tension to zero without failing
- Maximum bolt temperature occurs during cooldown, reaching ~1200ºF (~650ºC) at ~6 hours
- Tensile failure in bolt or shear failure of insert would not occur due to self-limiting load
- Impact limiters would remain attached to the package throughout the fire scenario

# Summary

- Preliminary results of this multi-faceted investigation of the MacArthur Maze fire scenario indicate that
  - Structural consequences for an SNF transportation package are likely to be less severe than HAC drop scenario in 10 CFR Part 71
  - Thermal consequences are likely to be significantly more severe than HAC fire in 10 CFR Part 71
- Ongoing work:
  - Evaluation of potential releases from package, due to failure of seals and rupture of fuel rods due to extreme thermal environment of the fire scenario

# Acknowledgements


- California Department of Transportation
- California Highway Patrol
- Pacific Northwest National Laboratory
- Center for Nuclear Waste Regulatory Analysis
- National Institute of Standards and Technology

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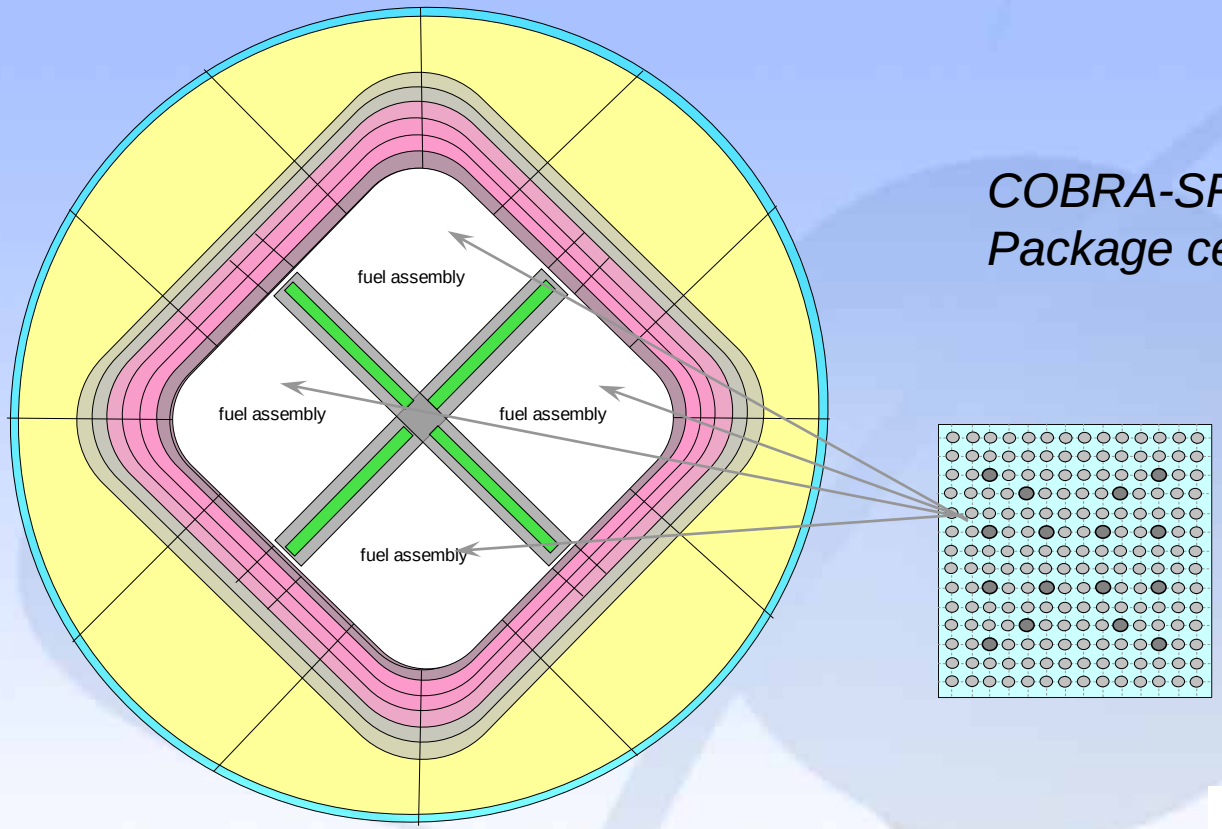
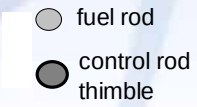
# Backup Slides

# COBRA-SFS Model of GA-4 Package

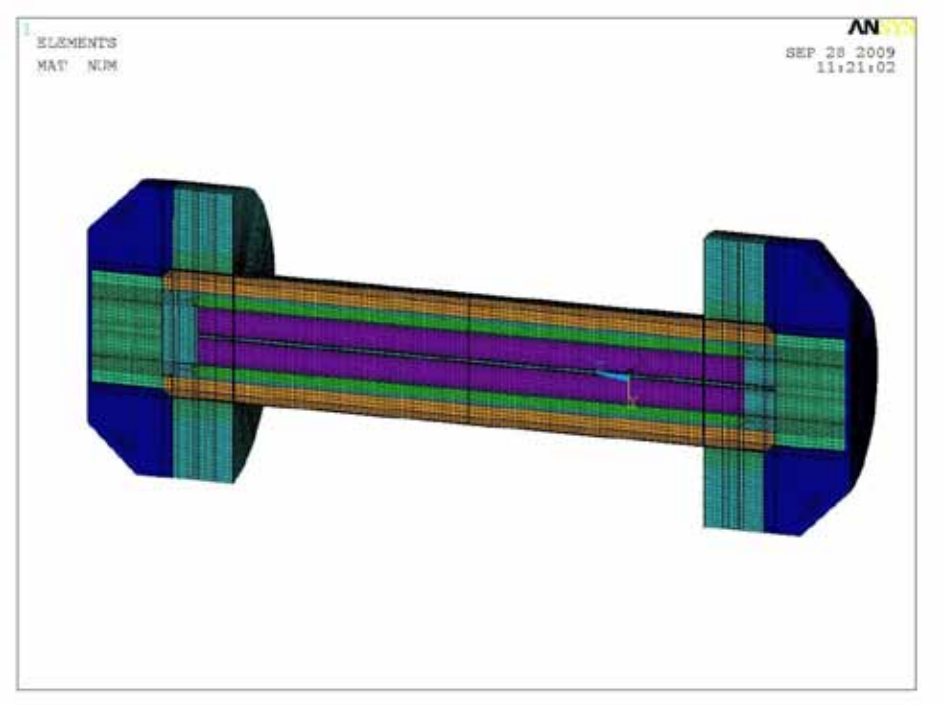



*COBRA-SFS model:*
*Package center cross-section*

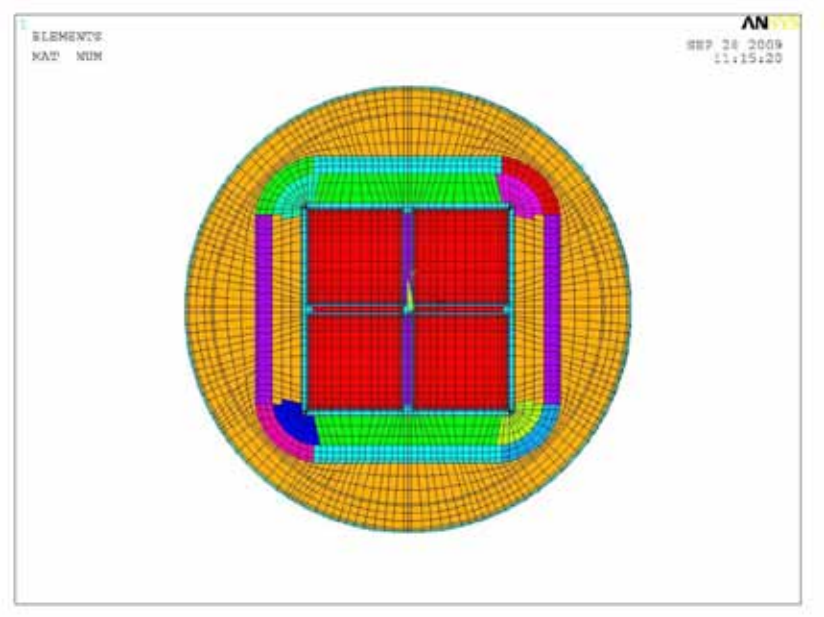




# ANSYS Model of GA-4 Package

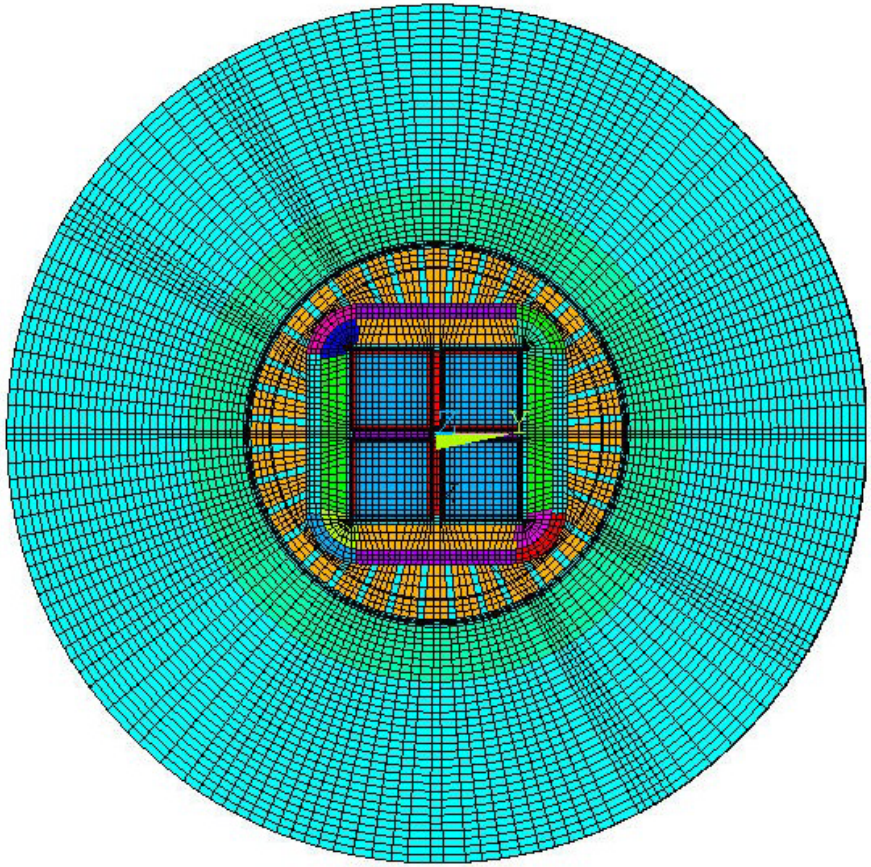



Package axial cross-section

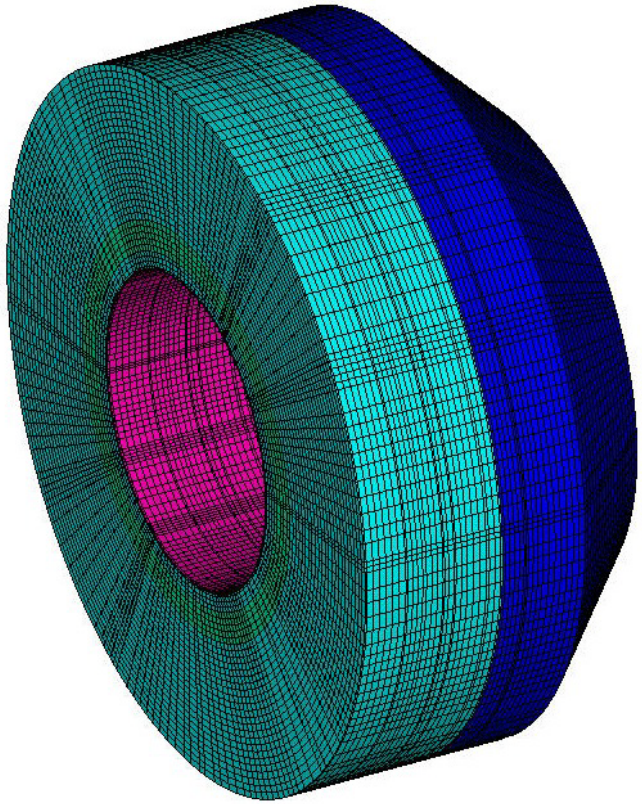



Package center cross-section

# ANSYS Model of GA-4 Cask: Basic Geometry



Package cross-section through impact limiter



Impact Limiter Structural Details