Fuel Reconfiguration - Implications to Criticality and Radiation Safety

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U.S.NRC
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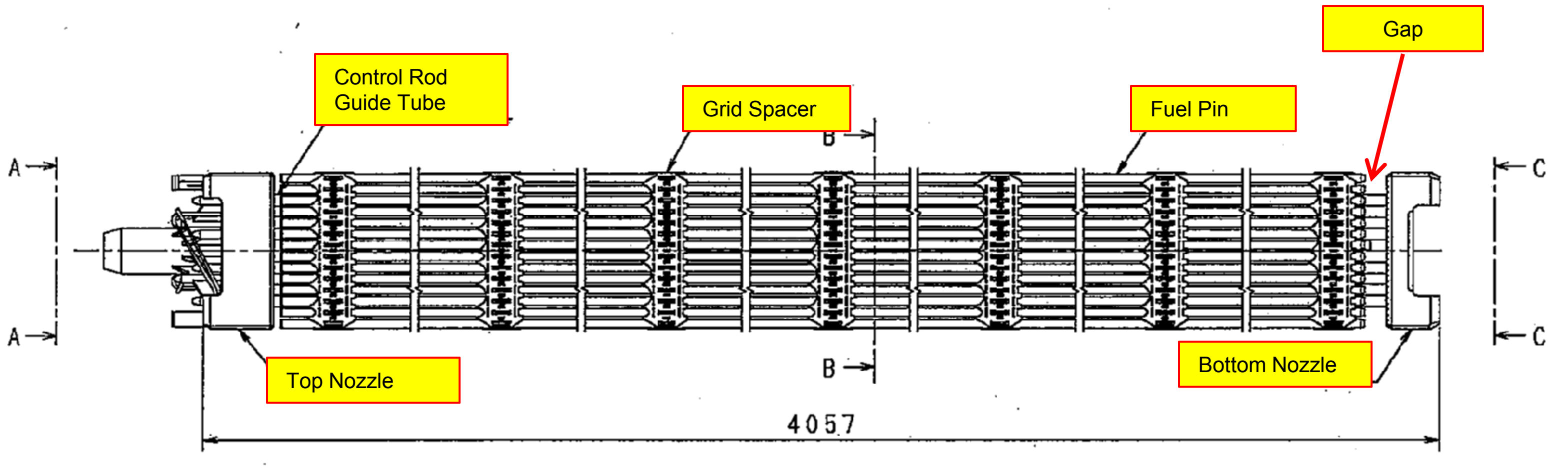
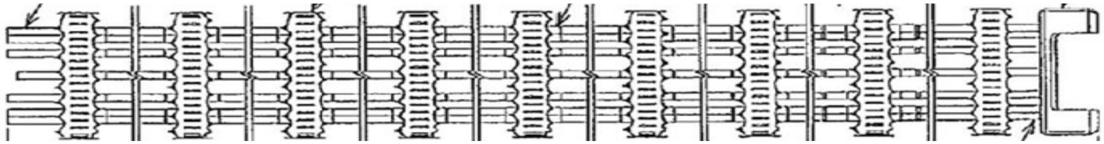
Protecting People and the Environment

Overview

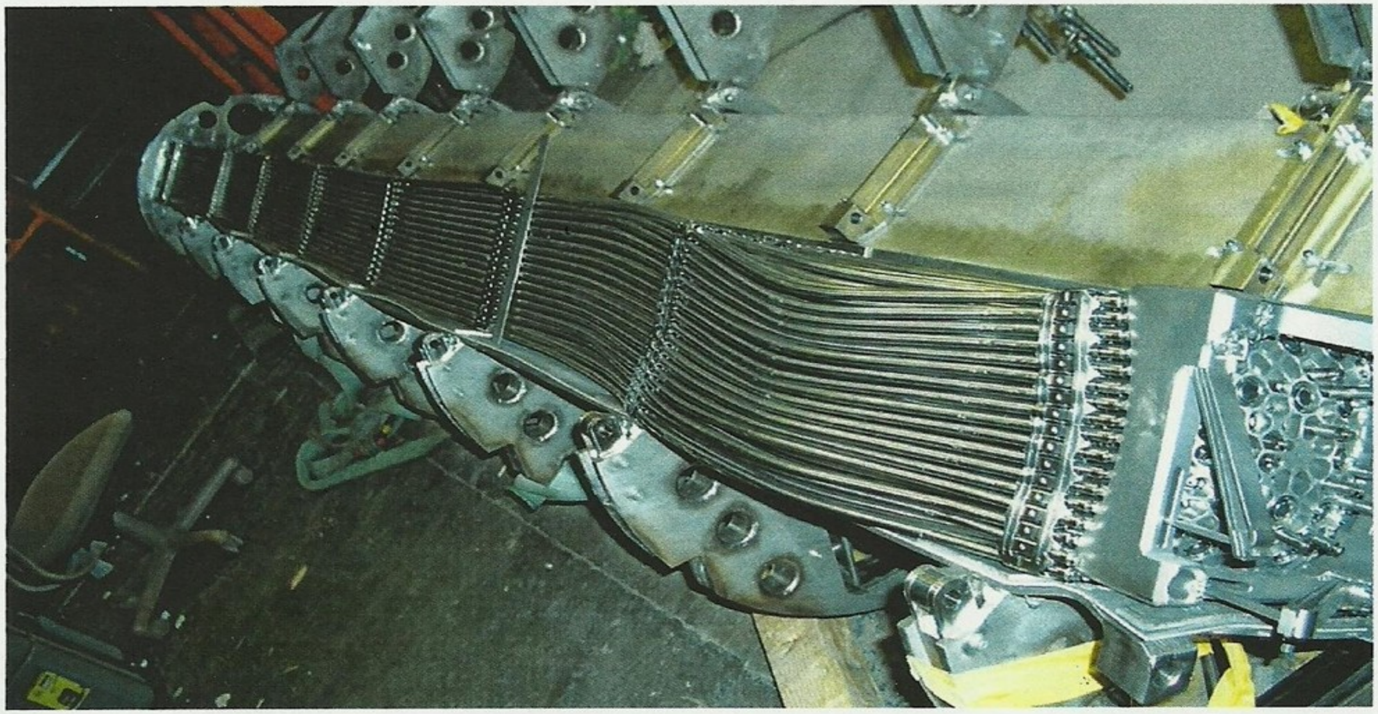
- Cask end-drop fuel rod performance
  - Fuel assembly structural attributes
  - Cask-content interaction and delayed strike
  - Single-pin model representation
  - Results and evaluation for potential fuel reconfiguration
- Implication to criticality safety
  - Lattice expansion in low burnup/enrichment ratio region
  - Lattice compression in high burnup/enrichment ratio region
  - Fuel relocation due to cladding fracture
- Implication to radiation safety
  - Source term concentration vs. materials densitification

Fuel Assembly Structural Attributes





Lattice Expansion and Compression
(fresh fuel; limited lateral restraint; high g-load)



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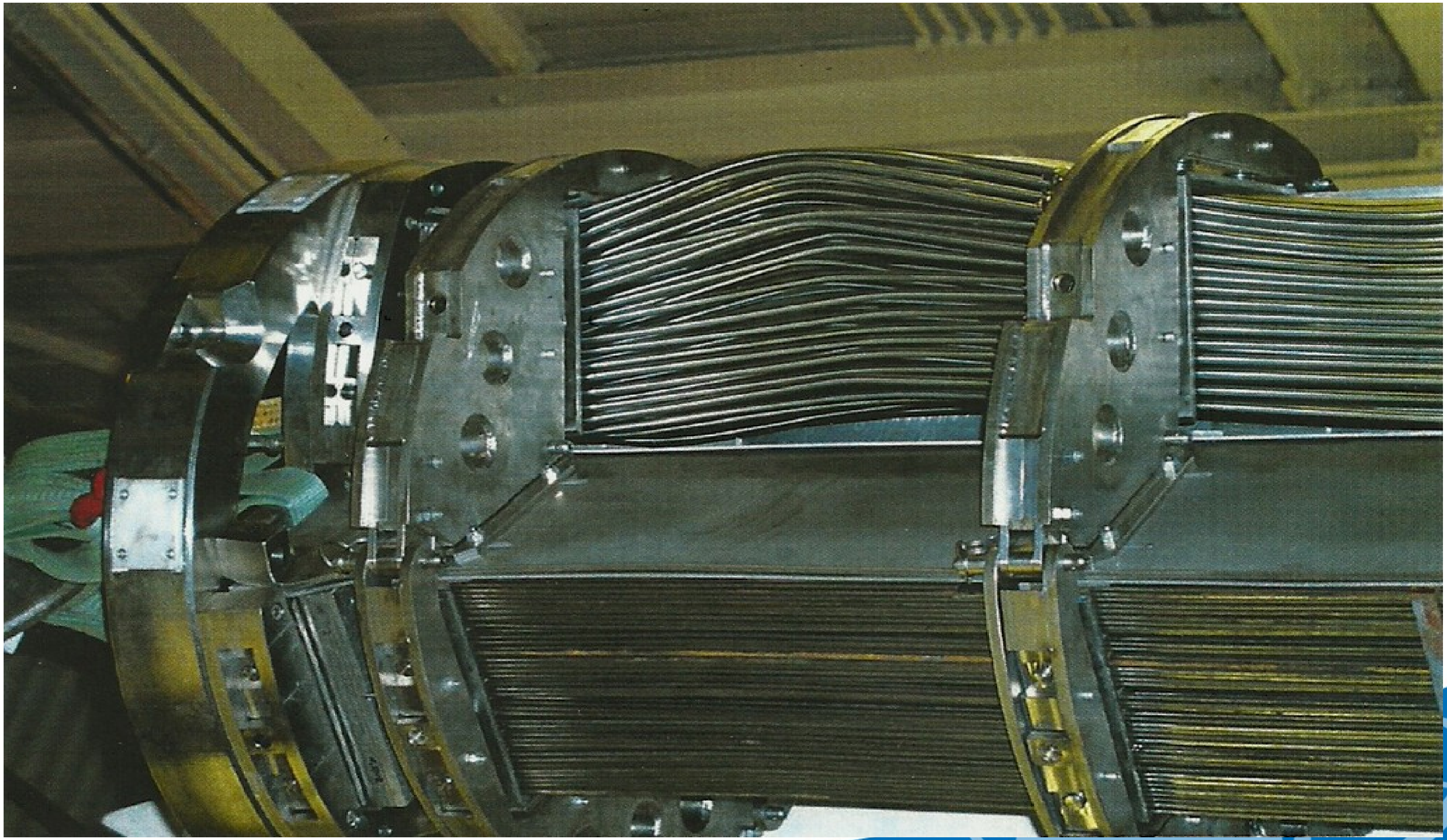
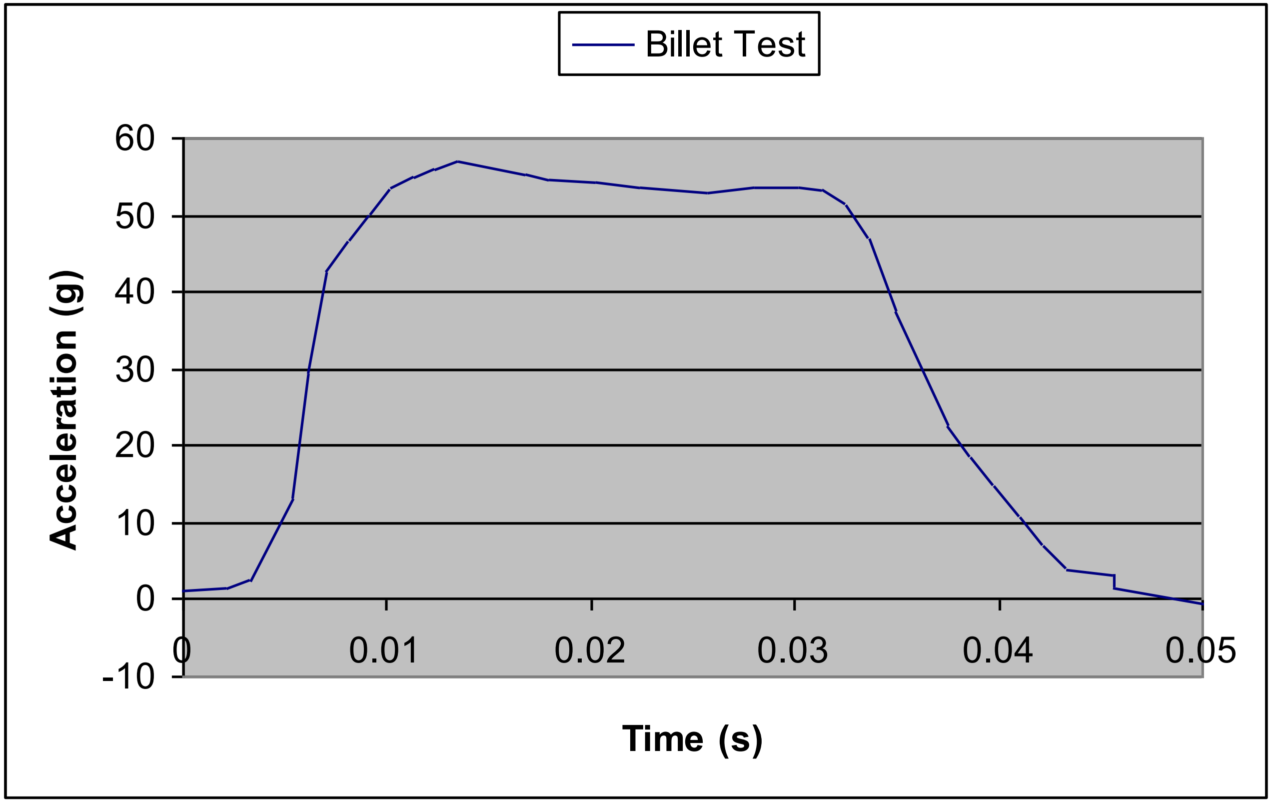
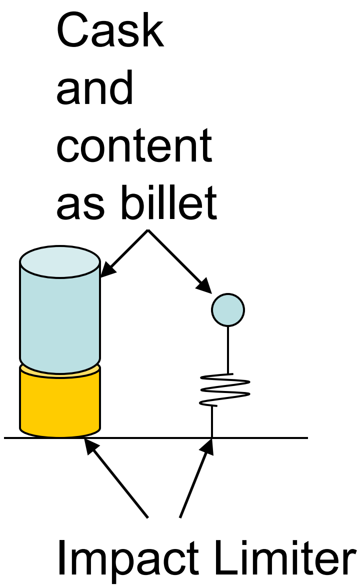


Impact Limiter Scale-Model Testing

(no cask-content interaction)

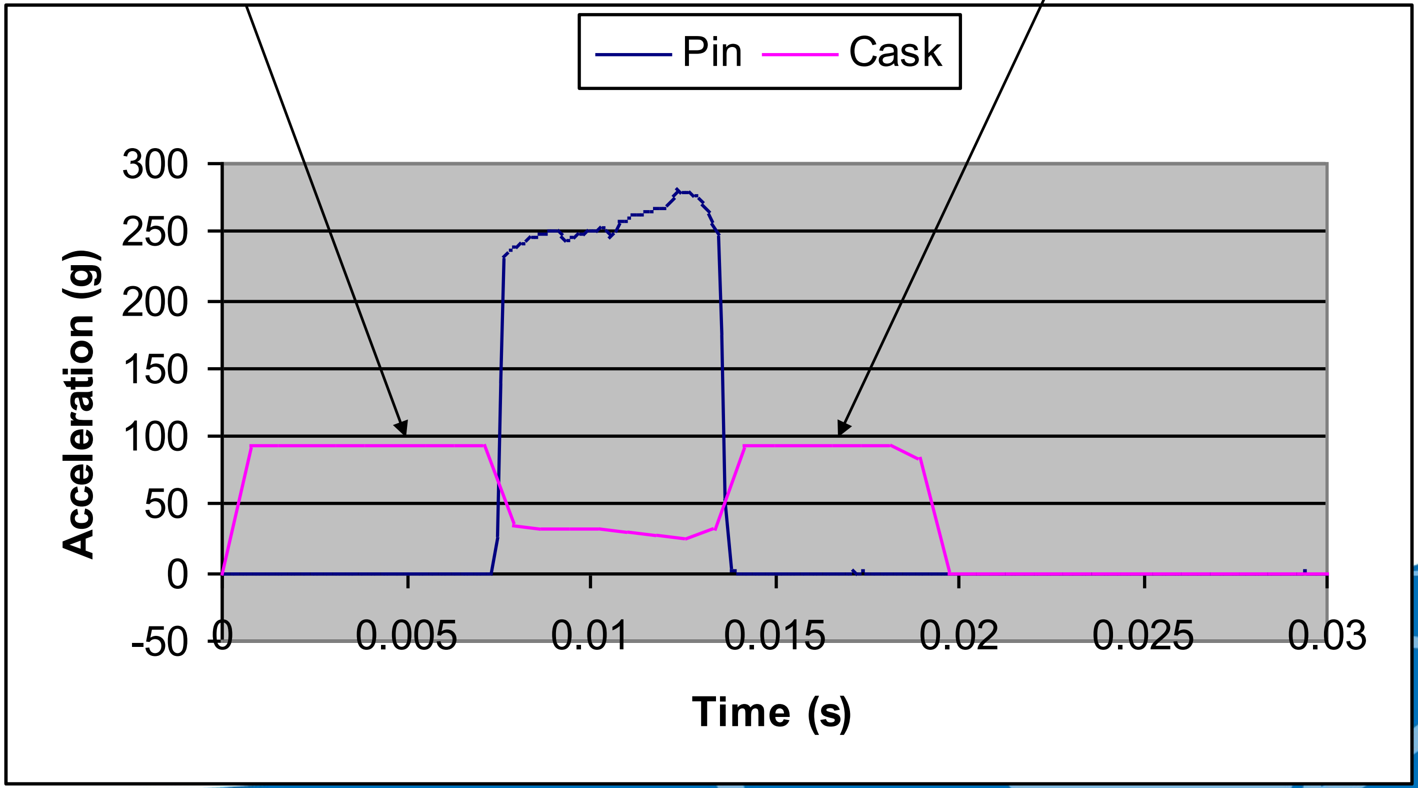




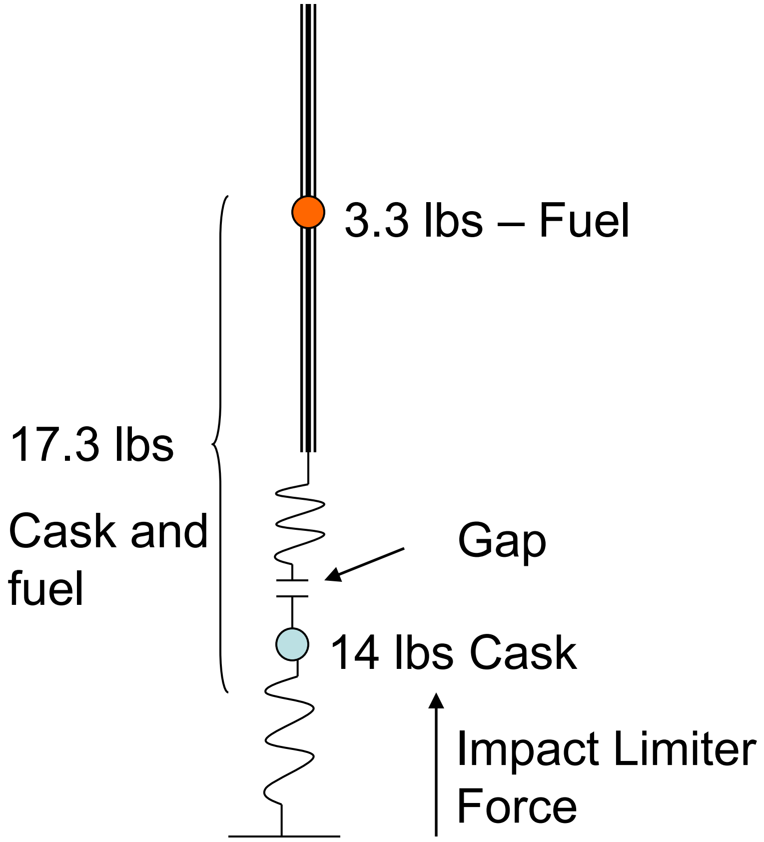
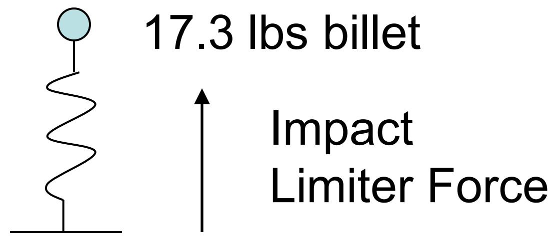
Cask-Content Interaction and Delayed Strike (1-inch gap)

Impact limiter force pushes on the cask mass.
At about 0.005 sec, the pin catches up.
Cask moving alone: 95 g
Cask/content moving together : 75 g

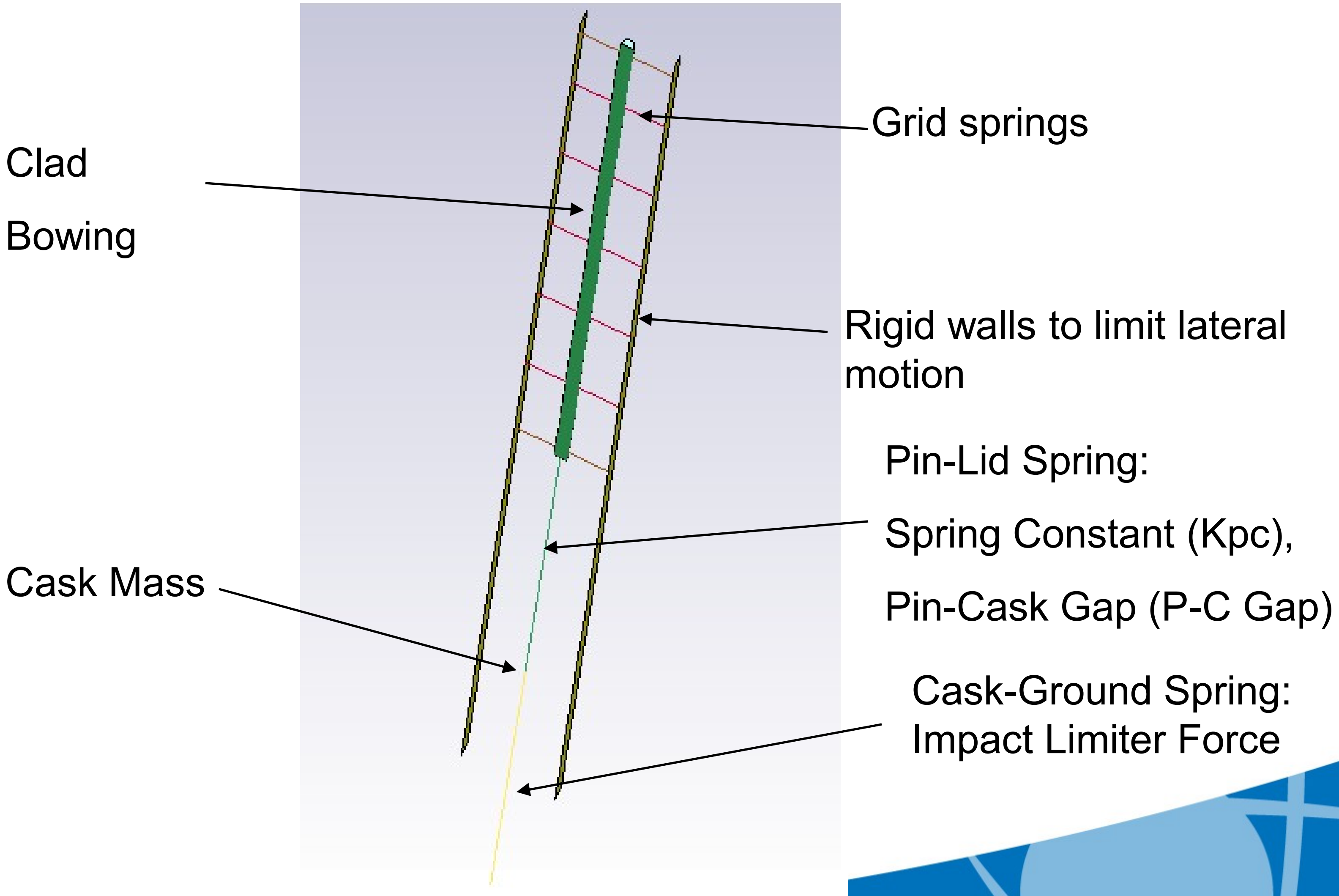
On this side, the pin is pushed back out of contact, reducing mass again.



Single-Pin Model

Single Pin Model	Scale Model Test
	The scale model drop test involves a single, solid mass. It determines the maximum impact limiter force, but not the true maximum deceleration of the cask or its fuel and internals. 

Single Pin Model

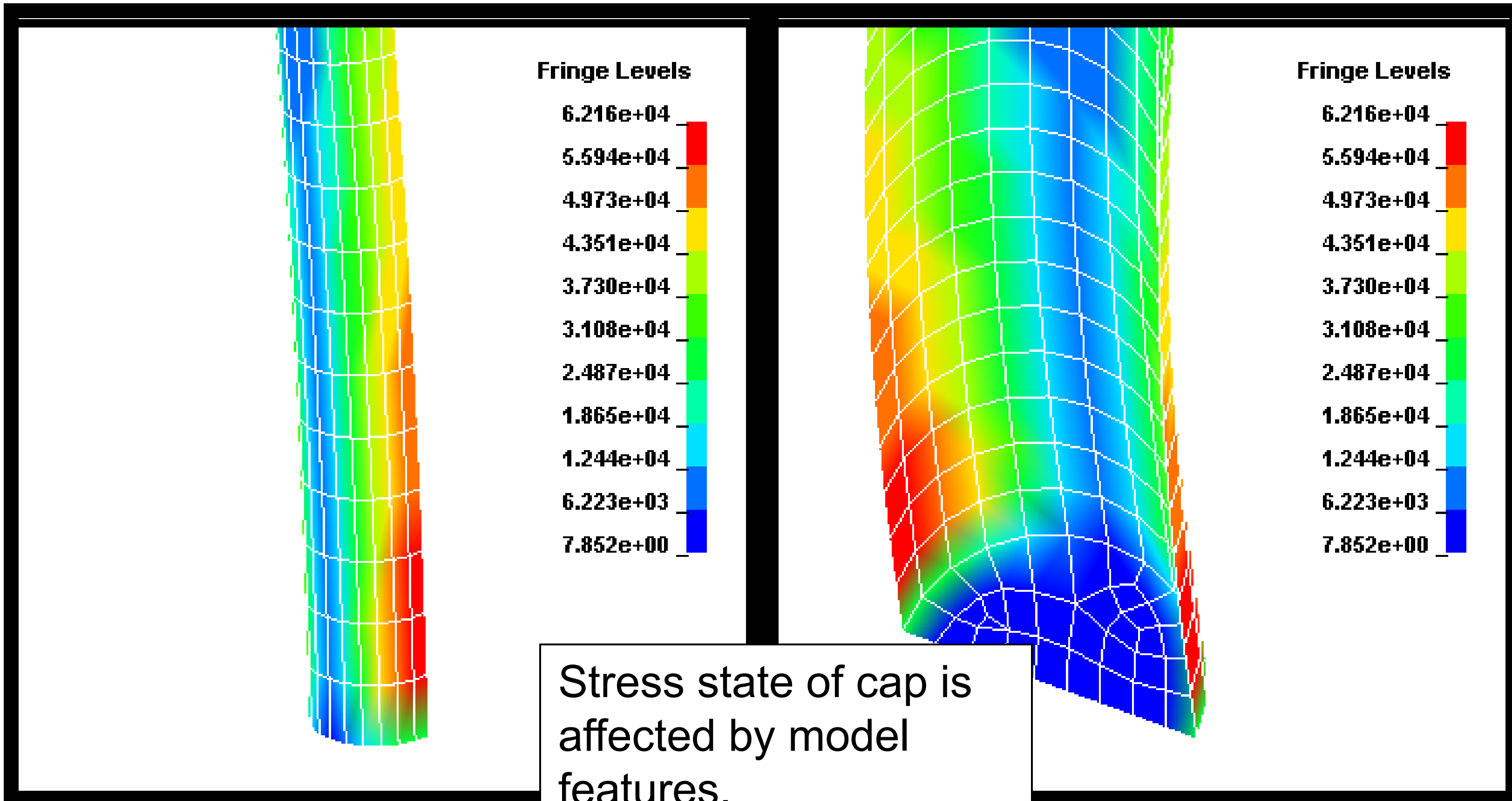


Model Parameters

- Realistic gap – “delayed strike” drives fuel performance
  - fuel/cavity thermal/radiation growths
  - end fitting compliance, if justifiable
- Impact limiter constant spring stiffness
  - reduced from test results
  - design dependent
- Clad thickness reduction - oxidation layer
- Rod bowing assumption, between grid spacers
- Fuel pin internal pressure – with and without
- Sensitivity analysis of model parameters

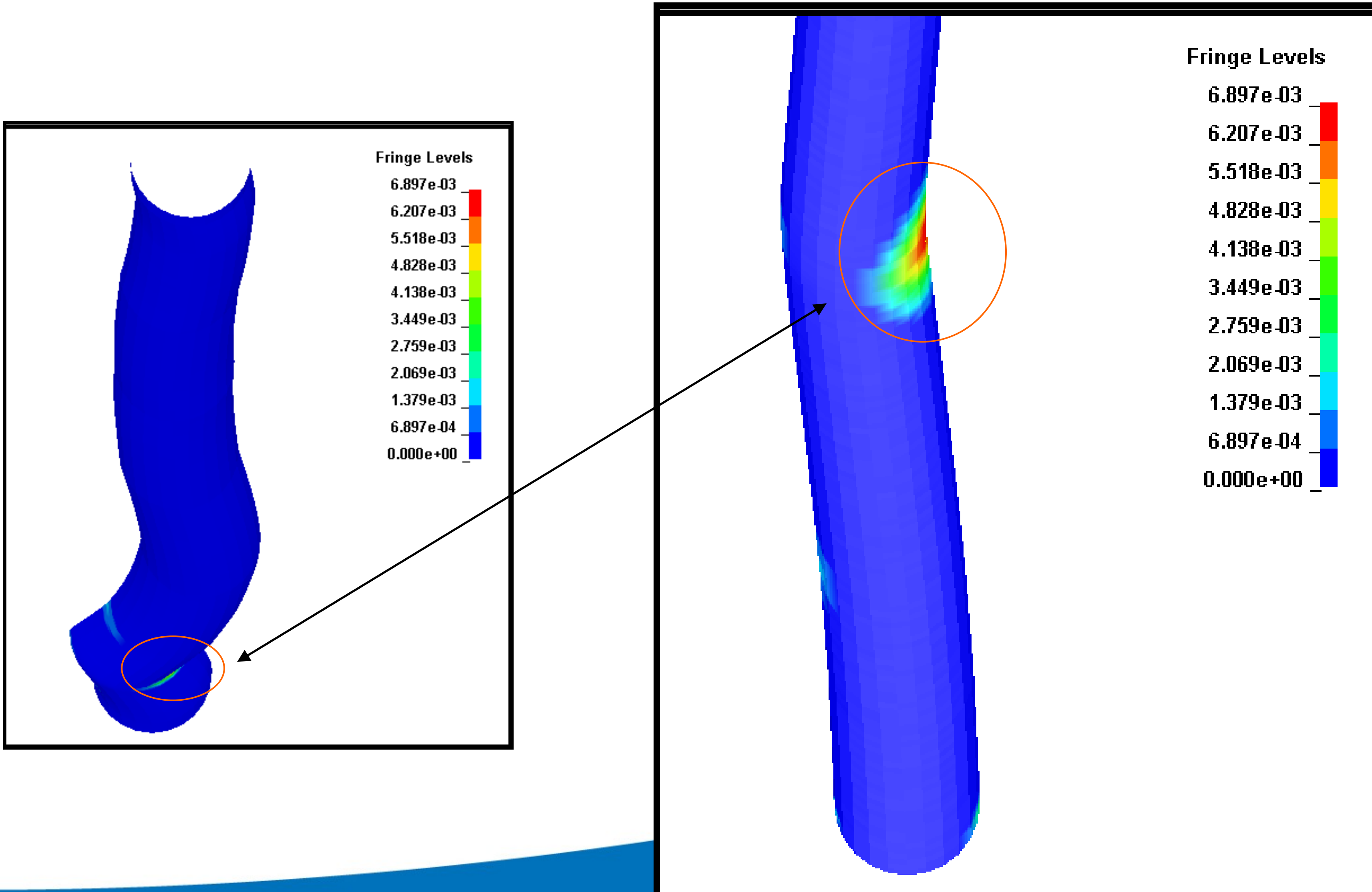
Fringe Plots - von Mises Stress

(Impact End of Pin)



Stress state of cap is affected by model features.

Fringe Plots - Plastic Strain

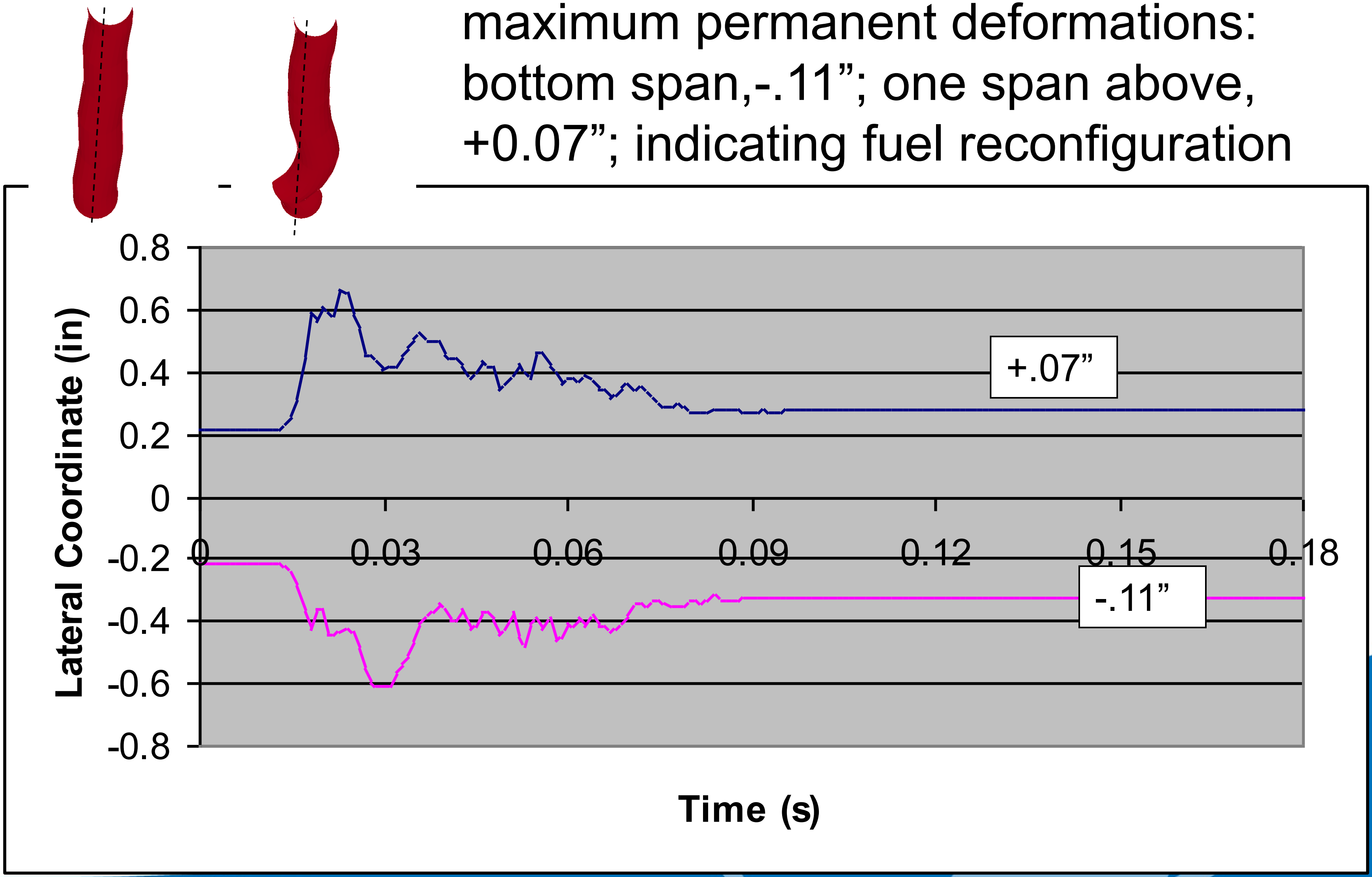


Results and Evaluation
(elasto-plastic analysis;1.45” gap; 54 g cask/content)

- Regular burnup fuel – ductile clad
- Clad stress and plastic strain
  - plastic strain: von Mises stress exceeds yield criterion
- No clad fracture – sufficient clad ductility supply
- Maximum permanent fuel pin lateral deformations
  - bottom span: -.11”
  - one span above: +0.07”
- Permanent deformations suggest fuel reconfiguration

Maximum Lateral Deformations

maximum permanent deformations: bottom span,-.11”; one span above, +0.07”; indicating fuel reconfiguration



Application to High Burnup Fuel

(elasto-plastic analysis;1.45" gap; 54 g cask/content)

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- High burnup fuel – brittle clad
- Clad fracture per maximum principal strain failure criterion
  - $\sigma_1 - \nu (\sigma_2 + \sigma_3) < \sigma_y$
  - $E = 10.98 \times 10^3$ ksi; $\sigma_y = 92.4$ ksi; $\varepsilon_y = 0.84\%$
- Clad fracture failure: $\varepsilon_1 = 0.92\% > \varepsilon_y = 0.84\%$
- Permanent fuel pin lateral deformations
  - Considered meaningful: if $\sigma_1 - \nu (\sigma_2 + \sigma_3) < \sigma_y$
- Clad fracture failure or permanent deformations suggest fuel reconfiguration

Concluding Remarks

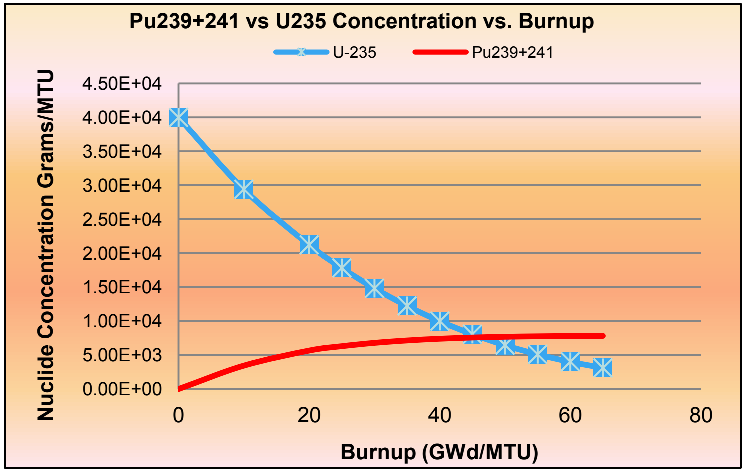
- Permanent deformations or clad fracture: fuel reconfiguration
- Application to high burnup fuel – brittle clad
  - clad fracture: maximum principal strain failure criterion
- Proper design of impact limiter and gap sizing may alleviate fuel reconfiguration potential
- Due to the complexity in analytical modeling, non-mechanistic lattice expansion/compression may need to be considered for criticality/shielding evaluation

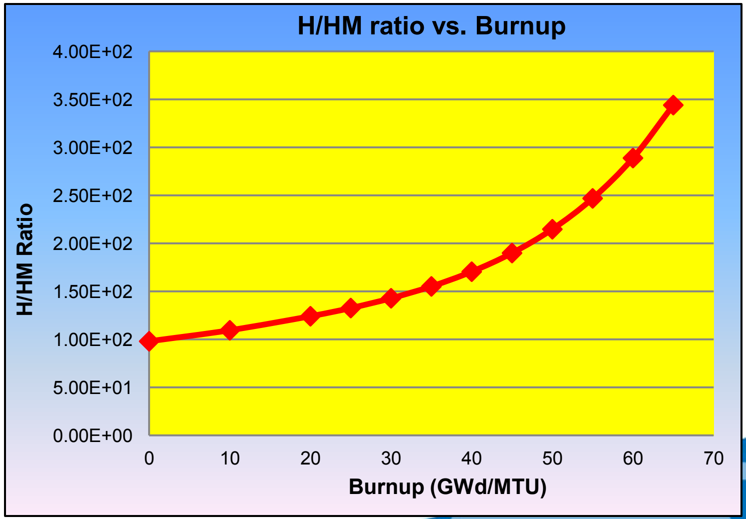
Fuel Reconfiguration – Implications to Criticality & Radiation Safety

- Fuel reconfiguration
  - Lattice mechanical deformation
  - Fuel rod fracture
  - Non-mechanistic failure
- Impact on package criticality safety
  - Lattice expansion in low burnup/enrichment ratio region
  - Lattice compression in high burnup/enrichment ratio region
  - Rods slide out of lattice
  - Assemblies slide out of cask poisoned region
- Impact on package radiation safety
  - Source term concentration vs. self-shielding due to materials relocation

The Criticality Effects of Fuel Reconfiguration

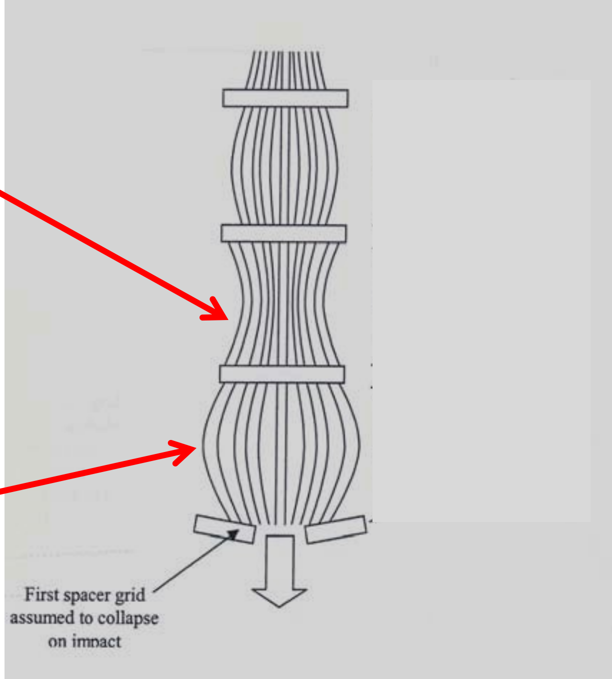
- The nuclear physics characteristics of the lattice change as burnup increases
  - Lattices are designed to be under-moderated
  - Lattices may become over-moderated as burnup increases
  - The performance of cladding of high burnup fuel is not clear





Impact to criticality safety

- Lattice compression in high burnup/enrichment region
  - Decrease in moderation
  - Compressed lattice become more reactive due to decrease in moderation if the region is over-moderated
- Lattice expansion in low burnup/enrichment region
  - Increase in moderation
  - Expanded lattice becomes more reactive due to increase in moderation in under-moderated region



Excerpt from: An Industry Initiative to Facilitate the Criticality Assessment and Subsequent Licensing of Transport Packages, Lyn M. Farrington, PATRAM 2007

Studies on the Impact of Fuel Reconfiguration on Criticality Safety

- NUREG/CR-6835, "Effects of Fuel Failure on Criticality Safety and Radiation Dose for Spent Fuel Casks," ORNL, 2002
- EPRI Report 1015050, "Fuel Relocation Effects for Transportation Packages," EPRI, June 2007

Impact of Fuel Reconfiguration on Criticality Safety

NUREG/CR-6835:

- Impact to criticality safety due to:
  - — Lattice expansion
  - — Individual rod slide out of fuel assembly
  - — Collapse of fuel rods
  - — Loss of cladding

Impacts are:

cask design dependent

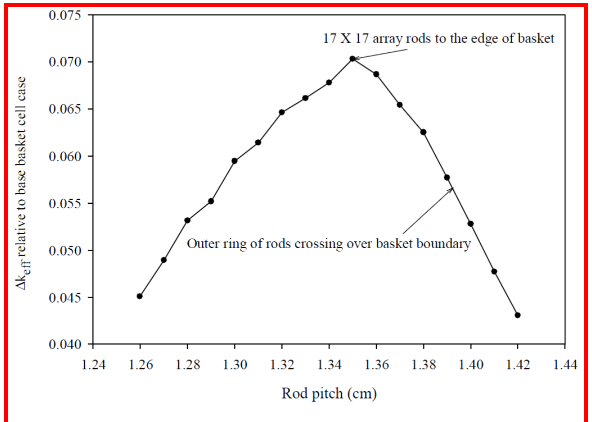
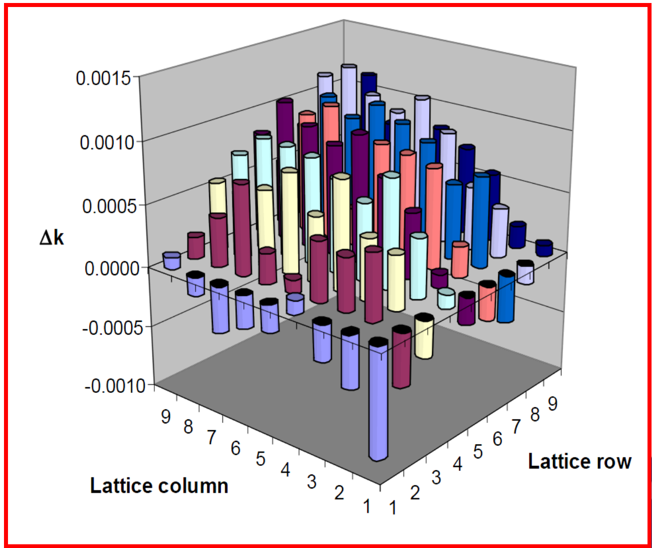
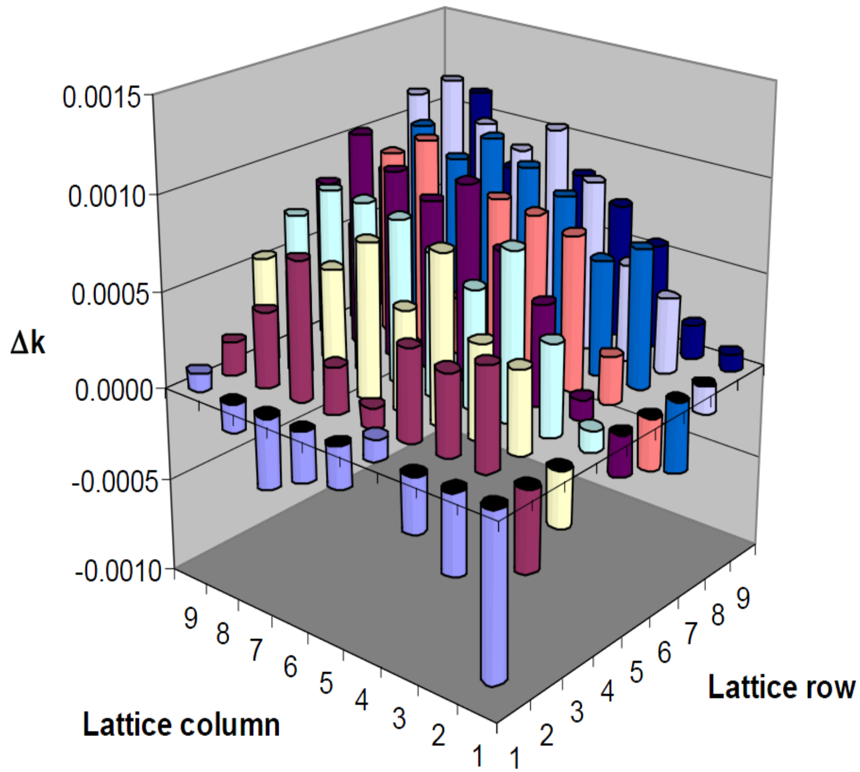


Figure 22 Optimum rod pitch in MPC-24 cask





Change in k_{eff} for single rod removal in the MPC-24 basket cell for one quadrant of the 17 × 17 fuel assembly

Change of K_{eff} of the MPC-24 vs. Lattice Pitch

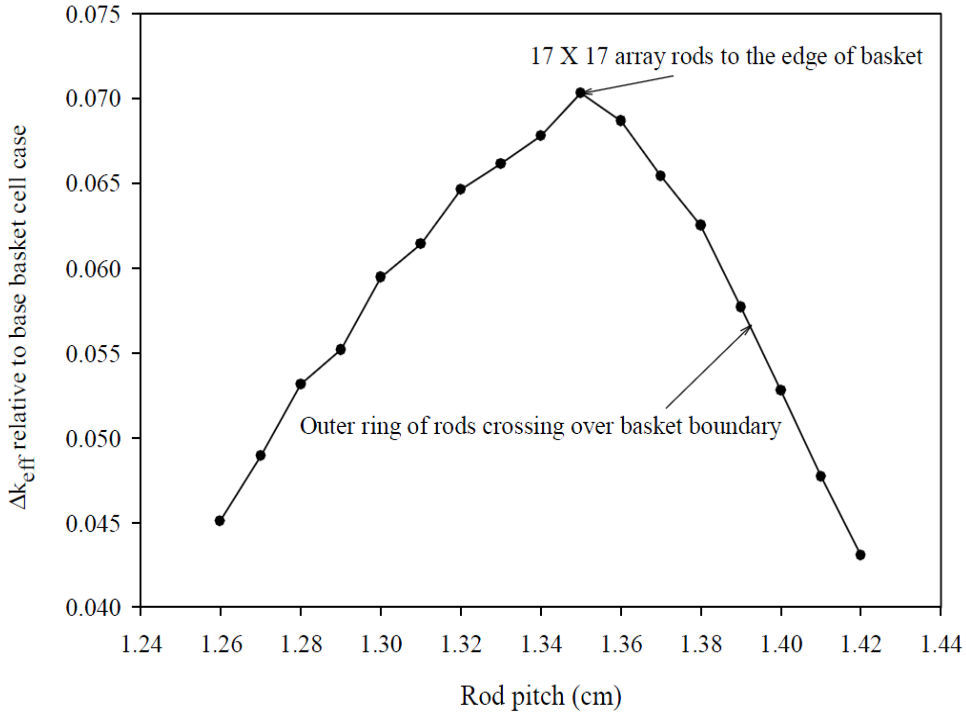
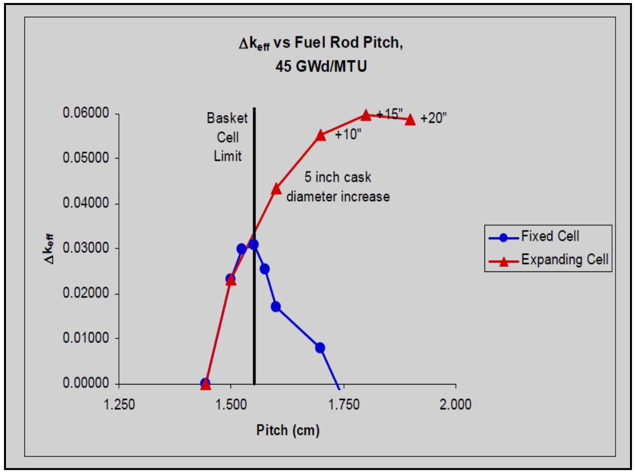


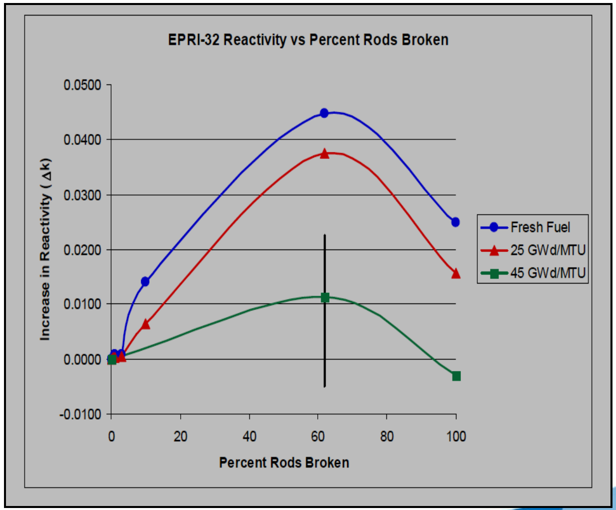
Figure 22 Optimum rod pitch in MPC-24 cask

The Criticality Effects of Fuel Reconfiguration

EPRI Report 1015050:

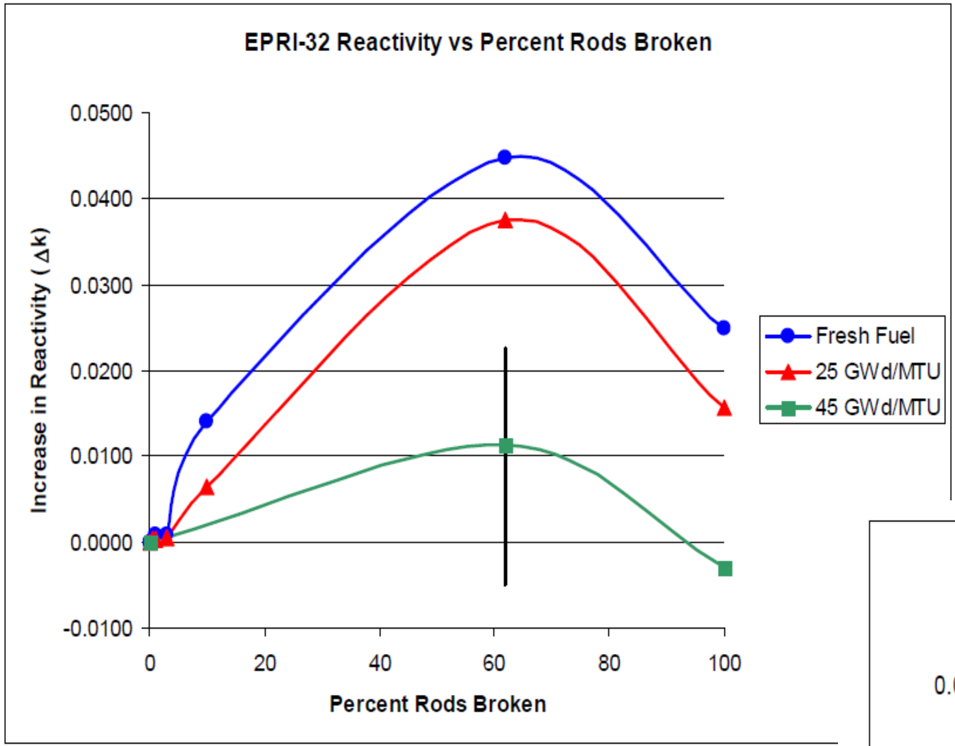
- Impact to criticality due to change of fuel rod pitch
- Impact to criticality due to change of fuel rod pitch

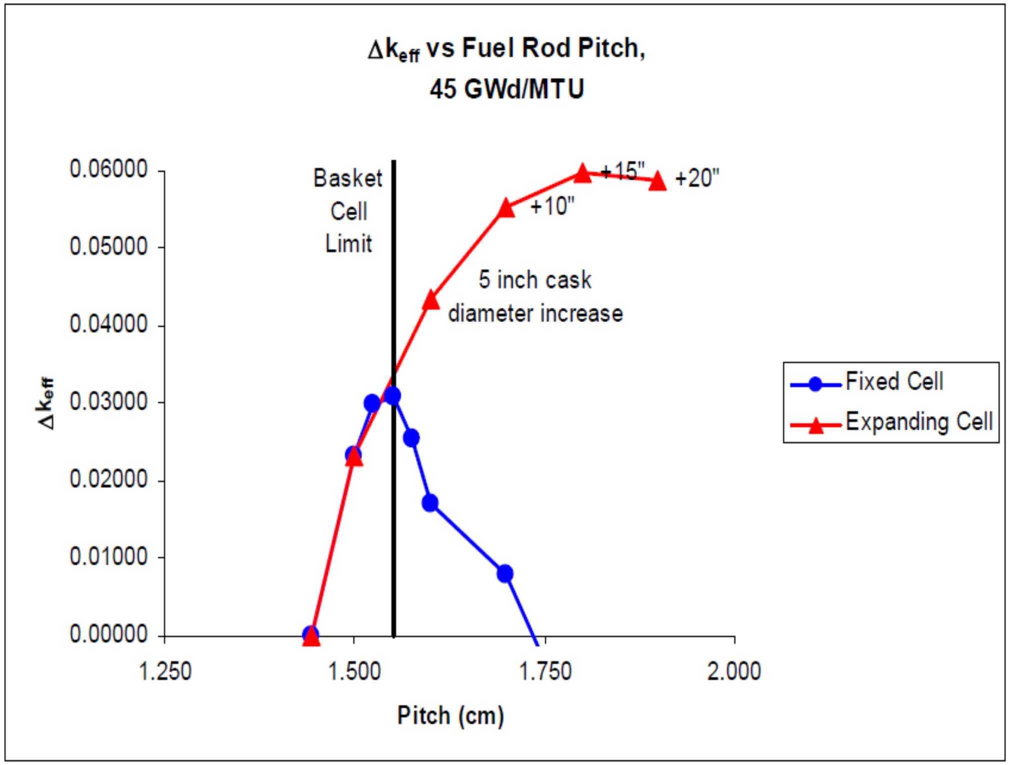




Impacts are:

- *Burnup Dependent*
- *Cask Design Dependent*


EPRI-32 Reactivity vs Percent Rods Broken
Increase in Reactivity (Δk)
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
-0.0100
0 20 40 60 80 100
Percent Rods Broken
Fresh Fuel
25 GWd/MTU
45 GWd/MTU


Δkeff vs Fuel Rod Pitch,
45 GWd/MTU
Δkeff
0.06000
0.05000
0.04000
0.03000
0.02000
0.01000
0.00000
1.250 1.500 1.750 2.000
Pitch (cm)
Basket
Cell
Limit
+10"
+15"
+20"
5 inch cask
diameter increase
Fixed Cell
Expanding Cell

Cask Dose Rate Impact

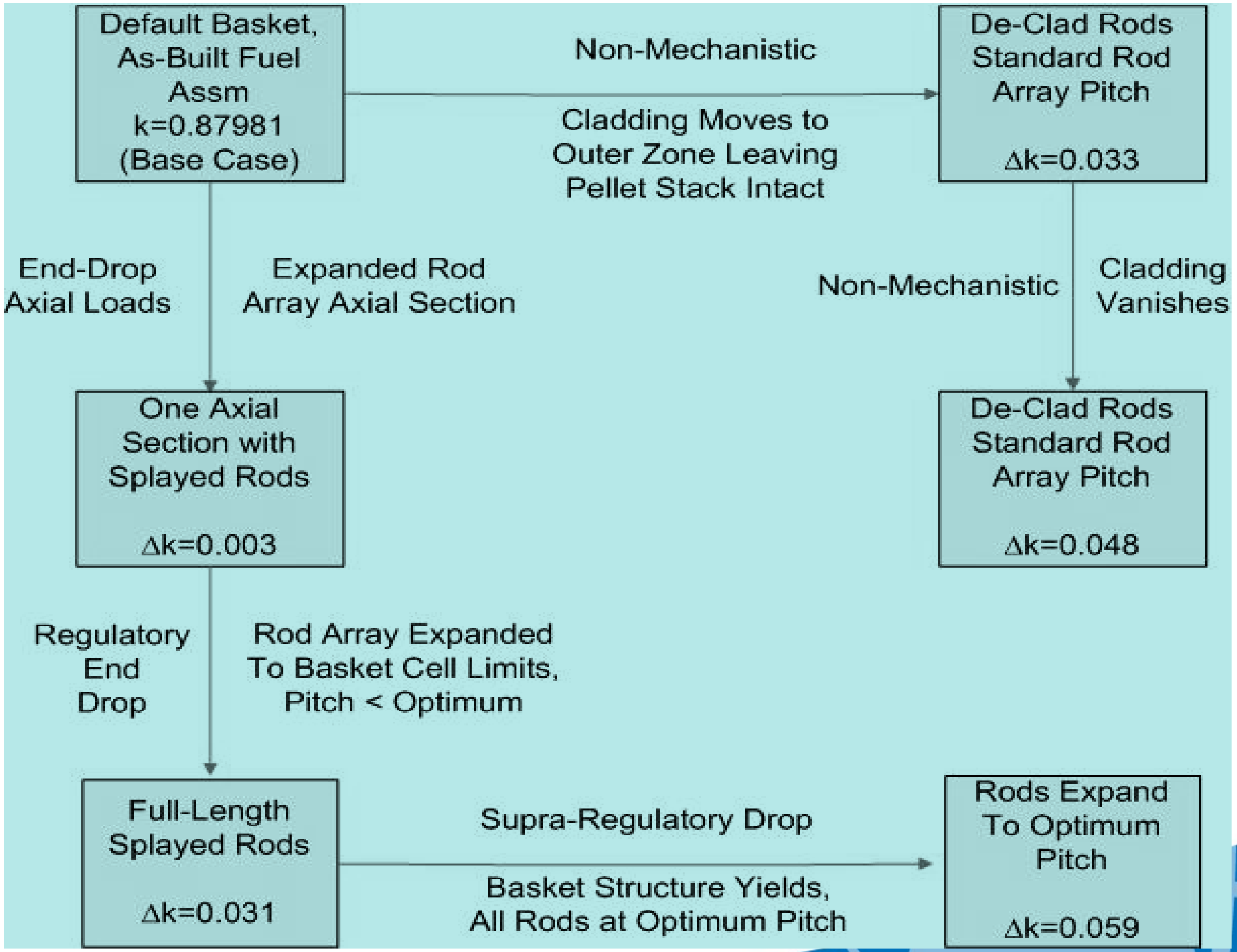
NUREG/CR-6835 and EPRI report 1015050:

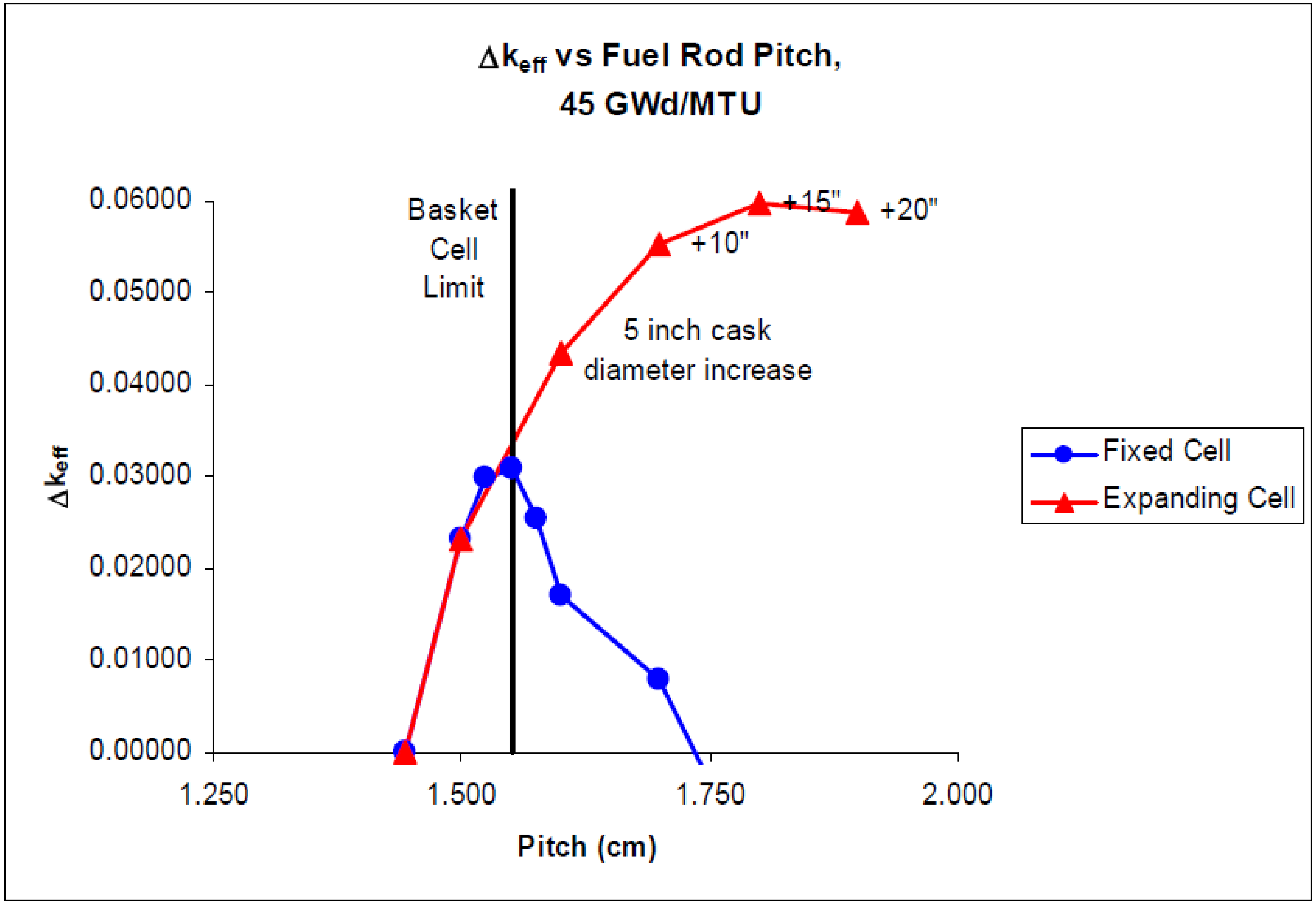
- Fuel reconfiguration due to
  - Collapse of fuel rods causing the fuel pellets to fall to the bottom or side of the cask
  - Breach of cladding causing pellets fall to the middle part of the package (holdup by grid spacers)
- Fuel reconfiguration causes:
  - source concentration
  - increase in self-shielding
- Impacts are:
  - *Cask design dependent*
  - *Cask landing position dependent*

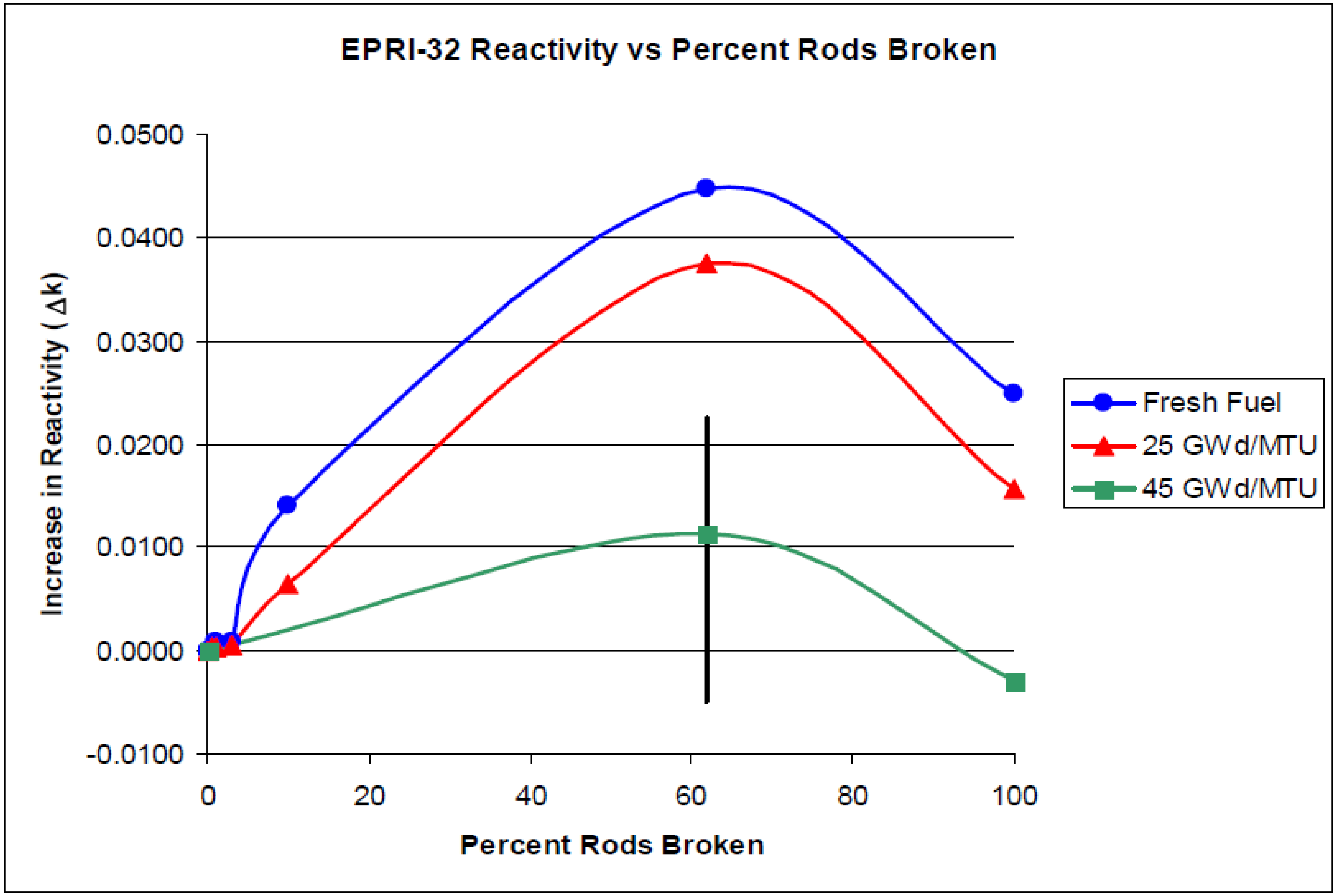
Concluding Remarks

- Fuel reconfiguration, both lattice expansion and compression, may lead to increase in cask k_{eff}
- Fuel reconfiguration may lead to increase in cask dose rates
- The knowledge in cladding material properties of high burnup fuel is limited
- Applications for transportation, and/or storage, of high burnup spent fuels might be able to use analyses to evaluate the potential impacts on both criticality and shielding safety of the casks.
- Need to consider both mechanical and non-mechanistic lattice deformation

The Criticality Effects of Fuel Reconfiguration




Δk_eff vs Fuel Rod Pitch,
45 GWd/MTU
Δk_eff
0.06000
0.05000
0.04000
0.03000
0.02000
0.01000
0.00000
1.250
1.500
1.750
2.000
Pitch (cm)
Basket
Cell
Limit
5 inch cask
diameter increase
+10"
+15"
+20"
Fixed Cell
Expanding Cell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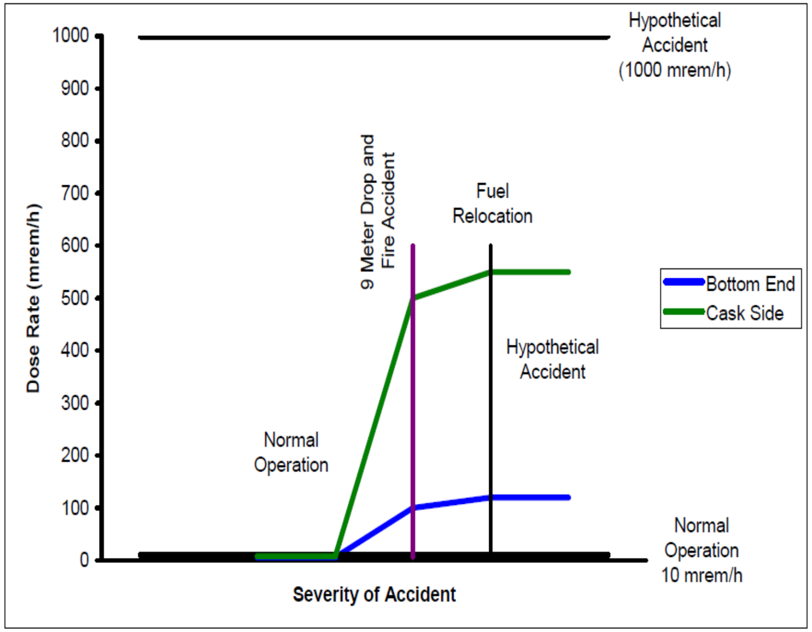
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
-0.0100
Increase in Reactivity (Δk)
0
20
40
60
80
100
Percent Rods Broken
Fresh Fuel
25 GWd/MTU
45 GWd/MTU

Cask Radiation (Dose Rate) Impact

EPRI Report 1015050:

- Impact to dose rate due to fuel reconfiguration (non-mechanistic):
  - "The effect of geometric dose rate falloff is less pronounced for the cask cylindrical side than it is for the cask ends"
  - The impact to 2-meter dose rate is about 10%



Cask Radiation (Dose Rate) Impact

NUREG/CR-6835:

- Impact to dose rate due to fuel reconfiguration (non-mechanistic):
  - Peak side surface dose rate is lower
  - Total dose rates in the lower side regions are increased