



Sensitivity Studies on UNF Cladding Structural Integrity under NCT Loading

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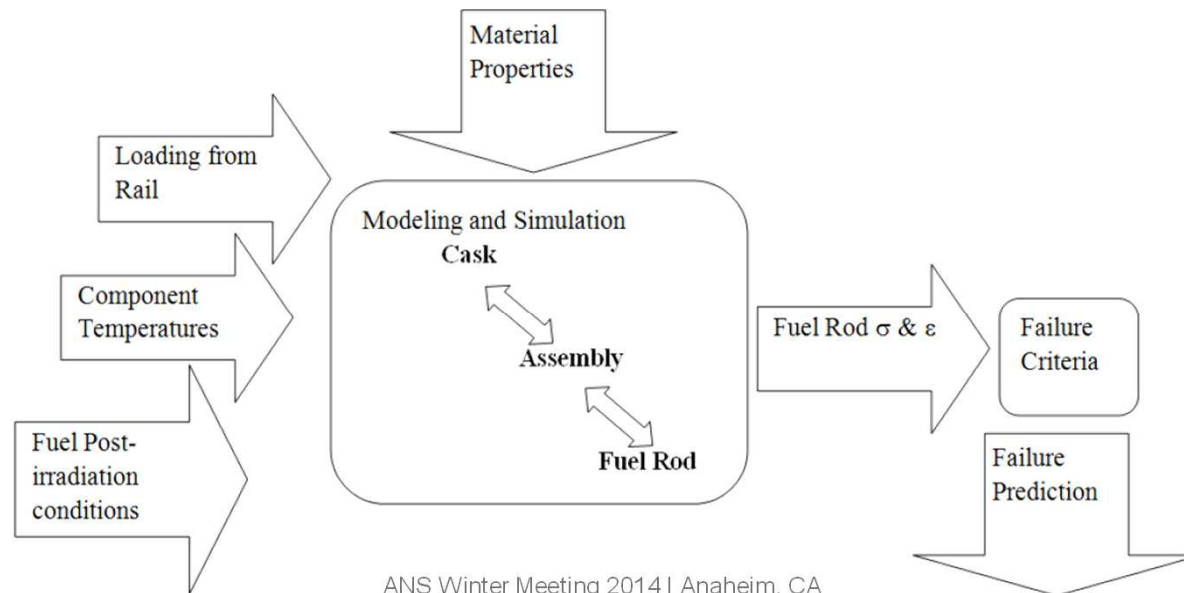
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- ▶ Background & Motivation
- ▶ Sensitivity Study Overview
- ▶ High Sensitivity Parameters
 - Cladding elastic modulus
 - Spacer grid stiffness
 - Spacer grid location
 - Gap between assembly and cask support structure
- ▶ Moderate Sensitivity Parameters
- ▶ Low and No Sensitivity Parameters

- ▶ US NRC regulation requires **UNF maintain its integrity during handling and transportation** for: restaging fuel and moving it for treatment or recycling; or moving it to a geological repository or other storage
- ▶ A Modeling & Simulation (M&S) initial demonstration was performed to demonstrate structural integrity of UNF cladding [1].
- ▶ Goal: to demonstrate that enough information, including experimental support and modeling and simulation capabilities, exists and/or can be generated to establish a preliminary determination of UNF structural performance under normal conditions of transport (NCT).
- ▶ For initial demonstration configurations were selected to cover the most existing configurations (17x17 PWR assembly, GBC-32 cask).
- ▶ Initial demonstration predicted that the cladding did not experience enough damage to lose its structural integrity.

Modeling Approach

- ▶ Rail car excitation inputs provided by TTCI
- ▶ Cask-level, assembly-level, and rod-level models pass information back and forth
- ▶ Other inputs include material properties, post-irradiation fuel conditions, and temperatures.
- ▶ Failure criteria evaluated using the information from the model extrapolated to a hypothetical 3000 mile transport.



► Three levels of modeling

■ Cask-level modeling

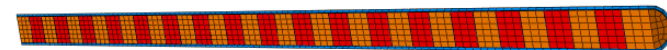
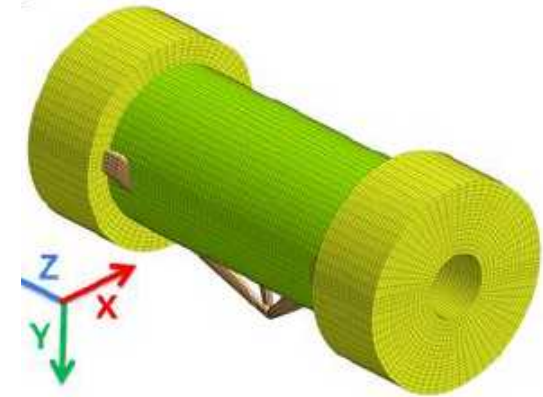
- Inputs rail car excitation data from TTCl into cask through cradle
- Has detailed model of structural components of GBC-32 cask (impact limiters, neutron shield, basket, spacer blocks, etc.)
- Uses simplified sub-models of assemblies
- Outputs assembly-level excitation

■ Assembly-level modeling

- Inputs assembly-level excitation from cask-level model and material properties from rod-level model to the detailed assembly model
- Has detailed model of Westinghouse 17x17 OFA with springs, dimples, spacer grids, top and bottom nozzles, etc.)
- Outputs stresses and strains for damage evaluation

■ Rod-level modeling

- Inputs post-irradiation fuel and clad properties.
- Evaluates response of detail single fuel rod under different conditions include a range of pellet-pellet and pellet-clad interfaces.
- Outputs range of composite fuel rod material properties, tension stress concentration factor, and broadened excitation



Sensitivity Study Summary

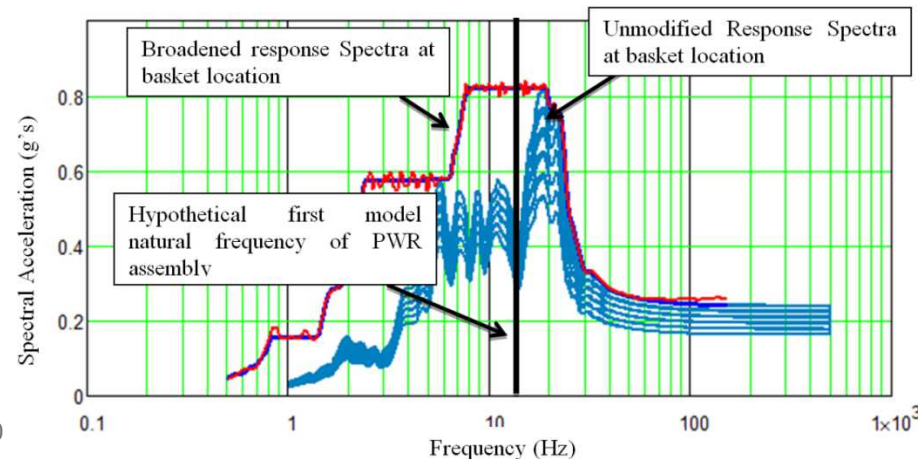
- ▶ There exist a number of uncertain inputs and assumptions.
- ▶ Several sensitivity analyses were performed to determine the influence of these parameters.

Sensitivity Analysis	Models Used to Explore Sensitivity	Sensitivity Result
Cladding elastic modulus	rod-level; assembly-level	High Sensitivity
Spacer grid stiffness	rod-level; assembly-level	
Spacer grid location	assembly-level	
Gaps between assembly and cask support structure	cask-level	
Fuel assembly basket location	assembly-level	Moderate Sensitivity
In-reactor fretting wear	rod-level	
Influence of control components	assembly-level	
Pellet-to-clad bonding	rod-level	
Fuel rod location in assembly	assembly-level	Low Sensitivity
Temperature distribution	assembly-level	
Fuel rod damping	rod-level	
Pin pressure influence	rod-level	
Cladding yield stress	assembly-level	No Sensitivity

Cladding Elastic Modulus: High Sensitivity

- ▶ The exact cladding material properties are uncertain due different levels of irradiation and interaction with pellets.
- ▶ Assembly-level study
 - Modal analyses were performed using LB, BE, and UB (properties created by rod-level analyses) fuel rod flexure stiffnesses
 - Found large difference in response frequency using LB stiffness
- ▶ Rod-level study
 - Assembly excitation (output from cask-level model) was *broadened* and *enveloped* to cover entire uncertainty in material properties.
 - When used in assembly-level model damage fraction increased.
 - Broadened and enveloped excitations were conservatively used in final evaluation for the initial demonstration.

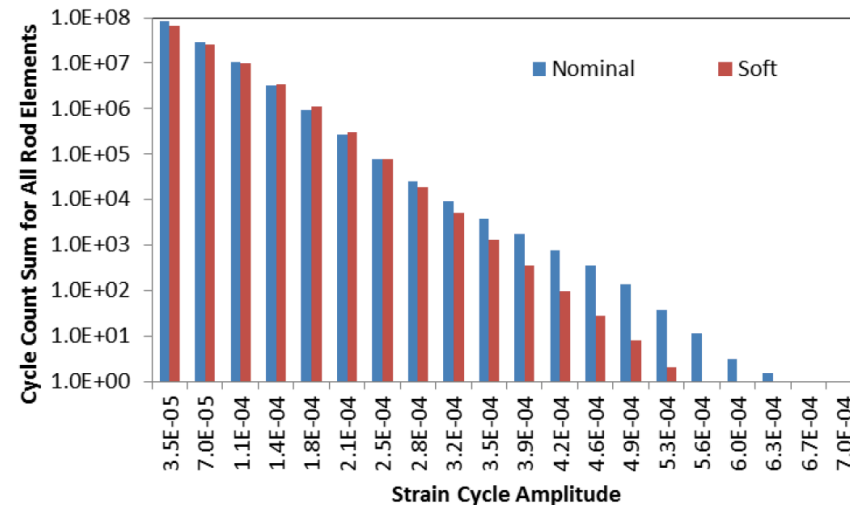
Mode #	Participating Component	Shape	Frequency (Hz)		
			BE cold	LB cold	UB cold
1	assembly	torsion	4.5	4.2	4.5
2/3	assembly	flexure	5.3	4.7	5.3
4	assembly	torsion	9.2	8.3	9.2
5/6	assembly	flexure	10.2	8.3	10.4
7	assembly	torsion	14.3	12.1	14.5
8/9	assembly	flexure	16.4	12.1	16.7
10	assembly	torsion	20.4	16.0	20.7
11/12	assembly	flexure	23.7	16.0	24.4
13	assembly	torsion	27.6	20.3	28.2
14/15	assembly	flexure	32.7	20.3	33.9
16	assembly	torsion	36.2	24.4	37.2
17/18	assembly	flexure	43.2	24.5	44.9
19	assembly	torsion	46.4	27.8	47.9
20+	fuel rod	flexure	48.8	27.9	50.5



Spacer Grid Stiffness: High Sensitivity

- ▶ The exact spring and dimple *configuration* and *relaxation conditions* in the spacer grids is complex.
- ▶ Rod-level analyses of spacer grid slots showed that by adjusting the shell thickness, the shell models could achieve similar displacements as a detailed spring and dimple model.
- ▶ Assembly-level analyses using 1/10 \times , 1 \times , and 10 \times spring and dimple stiffnesses showed:
 - Modal frequencies changed. Relaxed (1/10 \times) springs could shift the fuel rod response to a frequency that is more excited by the railcar loading.
 - Transient dynamic analyses showed that the relaxed springs reduce the cumulative number of higher strain amplitude cycles.

Mode #	Participating Component	Shape	Frequency (Hz)		
			BE cold (1 \times)	BE cold (1/10 \times)	BE cold (10 \times)
1	assembly	torsion	4.5	3.9	
2/3	assembly	flexure	5.3	4.7	6.4
4	assembly	torsion	9.2	8.0	6.8
5/6	assembly	flexure	10.2	8.9	
7	assembly	torsion	14.3	12.8	13.6
8/9	assembly	flexure	16.4	14.8	13.7
10	assembly	torsion	20.4	18.5	20.5
11/12	assembly	flexure	23.7	21.8	21.7
13	assembly	torsion	27.6	25.6	27.9
14/15	assembly	flexure	32.7	30.9	30.3
16	assembly	torsion	36.2	34.2	36.1
17/18	assembly	flexure	43.2		39.5
19	assembly	torsion	46.4		44.7
20+	fuel rod	flexure	48.8	41.4	67.1



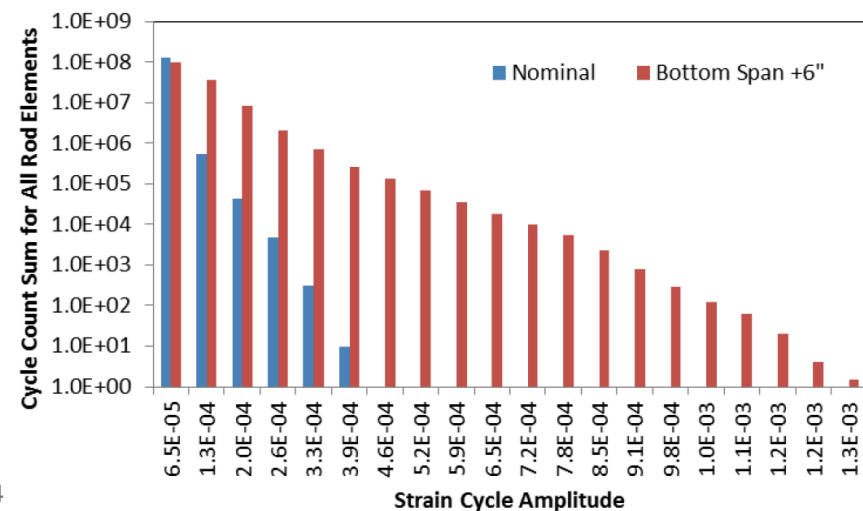
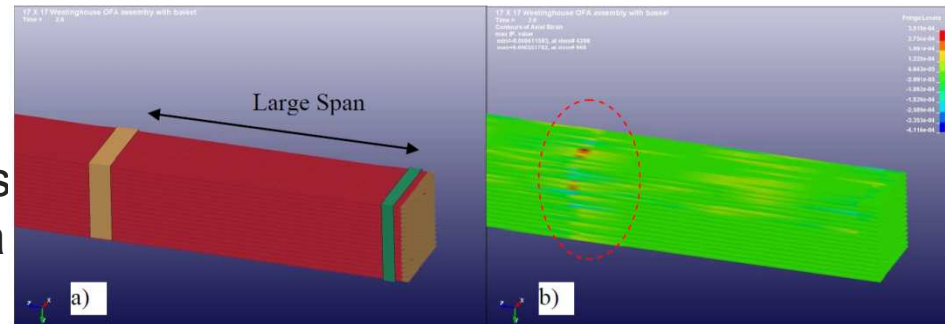
Spacer Grid Location: High Sensitivity

► Assembly-level model was modified by increasing the bottom span by 6 inches.

■ Modal analyses showed small difference in lower mode frequencies (assembly deformation modes) but a 29% decrease in higher mode frequencies (rod flexure modes).

■ Under transport excitation

- The rods at the grid at the upper end of the larger span showed the largest strains
- The cumulative number of larger amplitude strain cycles (which leads to more damage) increased significantly.

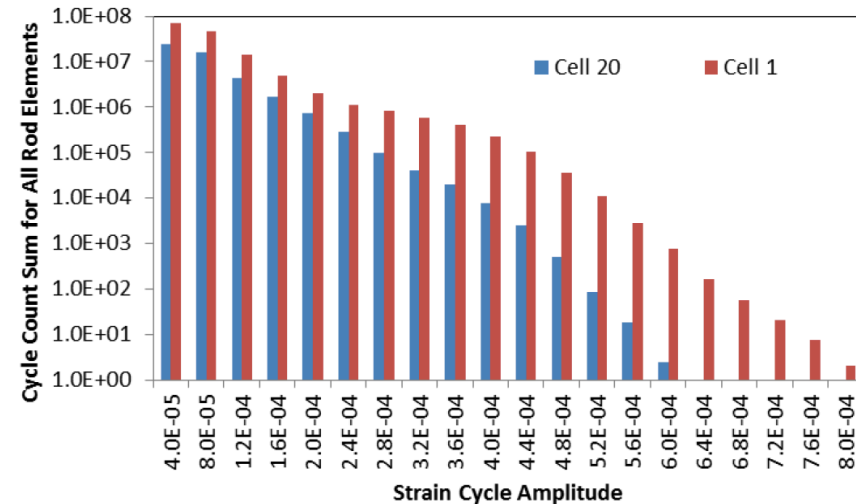


Gaps Between Assembly and Cask Support Structure: High Sensitivity

- ▶ The actual geometric configurations of casks filled with used fuel assemblies will vary.
- ▶ A cask-level sensitivity study was performed to investigate the effect of increasing the clearances between all components (assembly to basket, basket to canister, and canister to cask)
- ▶ The large gap model and the nominal cask model, under the same railcar excitations, demonstrated significant differences in results.
- ▶ In general larger clearances between components result in increased excitation levels at each fuel assembly and therefore larger clearance configurations can generally be considered more severe.

Fuel Assembly Basket Location: Moderate Sensitivity

- ▶ The assembly-level results compared the cumulative cyclic strain at cell 20 (near the center of the basket) and cell 1 (near the outer corner of the basket)
- ▶ Significant differences reported in the maximum strain and the cumulative cyclic strain at higher amplitudes.
- ▶ Location effect accounted for in final Initial Demonstration through broadened and enveloped excitations.



In-reactor Fretting Wear & Pellet-to-clad Bonding: Moderate Sensitivity

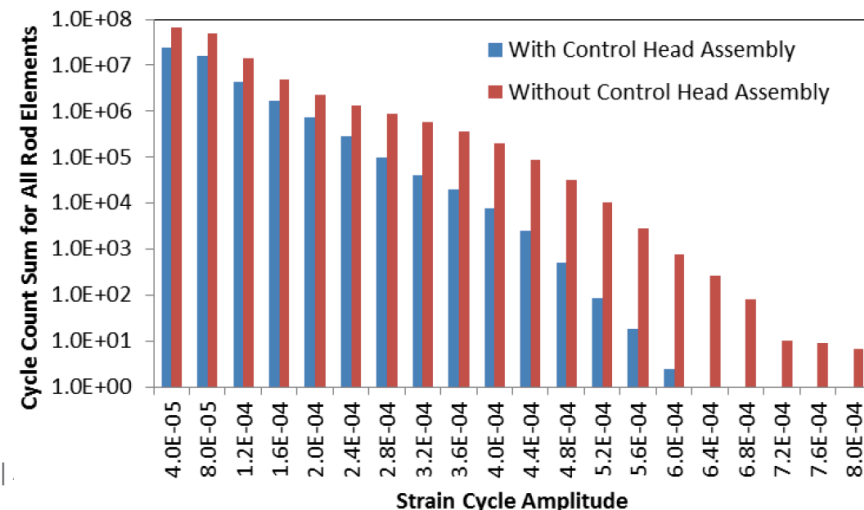
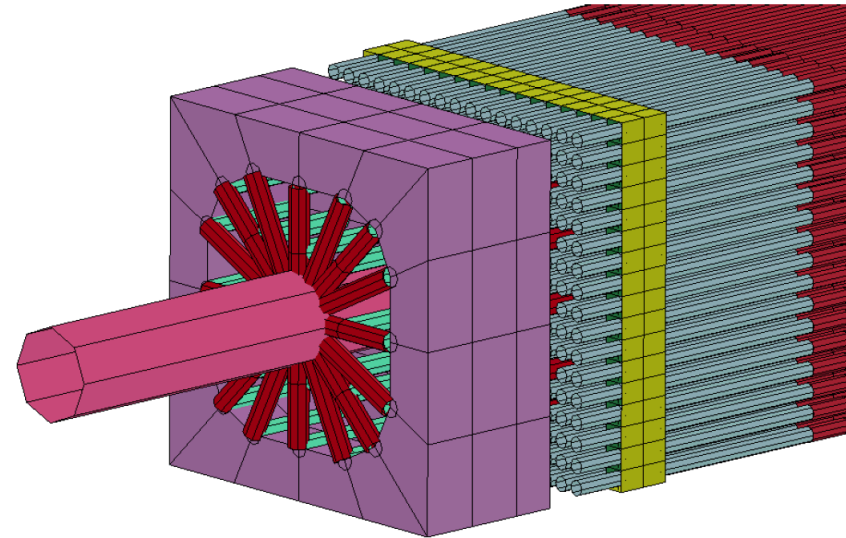
- ▶ Rod level sensitivity studies performed:
 - Fretting wear and pellet-to-clad bonding conditions found to effect the bending stress in the rods
 - A bending stress multiplier is recommended to account for this effect (1.38 for bonding, 1.41 for wear)
 - This multiplier was used in the damage calculation in the initial demonstration.
 - Internal pressure has low sensitivity (discussed later)

Model Number	Coefficient of Friction	Fuel Pellets Axially Contained	Internal Pressure Included	Wear Included	Finer Meshed	Stress Difference
1	0	yes	no	no	no	3.6 %
2	1.5	yes	no	no	no	-1.3 %
3	0	no	no	no	no	34.5 %
4	1.5	no	no	no	no	15.3 %
5*	0	no	yes	no	no	0.4 %
6*	0	no	no	no	yes	37.6 %
7*	0	no	no	yes	no	38.0 %
8*	0	no	yes	yes	no	2.8 %
9*	0	no	no	yes	yes	40.9 %

* Model parameters selected based on the results of earlier models.

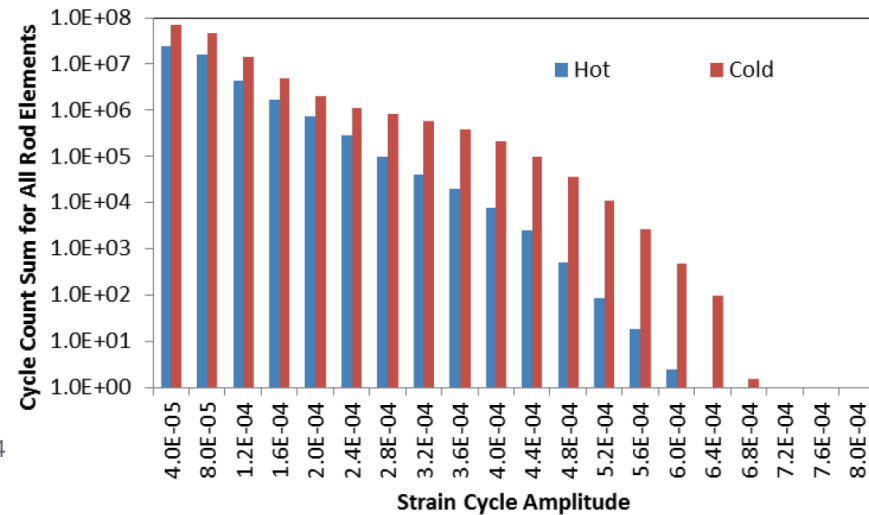
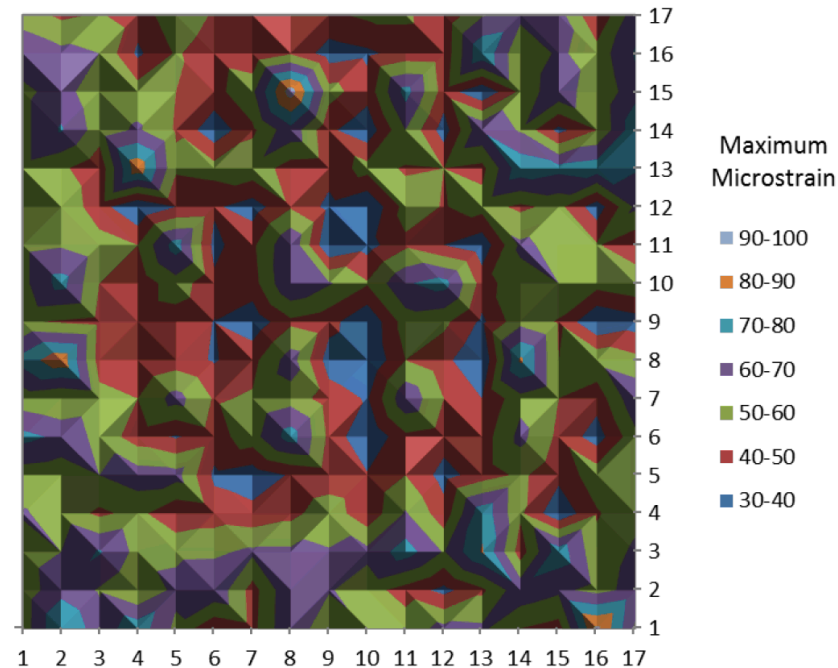
Influence of Control Components: Moderate Sensitivity

- ▶ Many used fuel assemblies have additional activated hardware such as control components that will have additional mass (assembly features) and stiffness (control rods).
- ▶ Assembly-level analyses compared cases with control components (+82 kg) to without:
 - Modal analyses showed little effect from control head components.
 - Transient dynamic analyses showed significantly more strain cycles at higher amplitudes in the case without the control head assembly.



Fuel Rod Location in Assembly & Temperature Distribution: Low Sensitivity

- ▶ Assembly-level analyses
- ▶ Rod location
 - Maximum element strains plotted vs rod location → no clear distribution of strains.
- ▶ Temperature distribution
 - Modal analyses using LB/BE/UB rods at hot (up to 641K) and cold (down to 302K) showed changes to the modal frequencies were small, with a difference of no more than 3%.
 - Transient dynamic analyses showed the cumulative number of strain cycles increased slightly at higher strain levels



Fuel Rod Damping & Pin Pressure Influence: Low Sensitivity

▶ Rod-level analyses

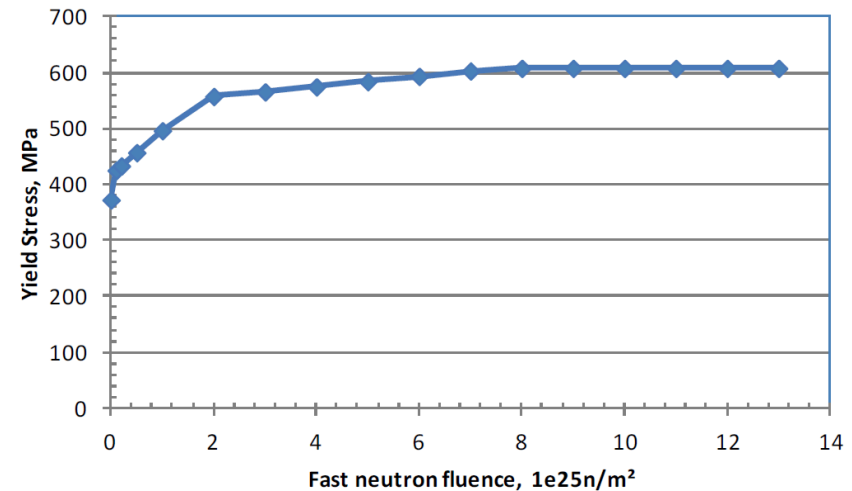
■ Internal pin pressure

- Influence reduces the stress concentration caused by pellet-to-clad bonding and in-reactor fretting wear.
- Not included in final initial demonstration analyses

■ Damping was determined to be minimal in the fuel rods. However, the damping determined from the rod-level analyses was included in the assembly-level model.

Cladding Yield Stress: No Sensitivity

- ▶ Part of cladding failure criteria includes effects from plastic strain.
- ▶ Cladding yield stress varies based on irradiation
- ▶ Full range of yield stress from irradiated to unirradiated are well above expected cladding bending stress – no plastic strain ever induced by loading.
- ▶ For other cask, railcar, and assembly configurations this may not be the case.



- ▶ The parameters with the most significant influence on the structural integrity of the used fuel cladding are:
 - Cladding elastic modulus (accounted for in initial demonstration by broadened and enveloped excitations)
 - Spacer grid stiffness
 - Spacer grid location
 - The gaps between assembly and cask support structure
- ▶ These results should be considered when guiding future research
 - Where to focus data collection, experiments (ORNL recent results), and future modeling

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In-reactor fretting wear	
Influence of control components	
Pellet-to-clad bonding	
Fuel rod location in assembly	Low Sensitivity
Temperature distribution	
Fuel rod damping	
Pin pressure influence	
Cladding yield stress	No Sensitivity

References

1. H. ADKINS, K. GEELHOOD, B. KOEPEL, J. COLEMAN, J. BIGNELL, G. FLORES, J.A. WANG, S. SANBORN, R. SPEARS, N. KLYMYSHYN, “Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Demonstration of Approach and Results on Used Fuel Performance Characterization,” FCRD-UFD-2013-000325, United States Department of Energy (2013).

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