Used Fuel Disposition (UFD) Transportation Sensitivity Analysis

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
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SUMMARY

This report fulfills the M3 milestone, M3FT-14IN0813013, Transportation Sensitivity Analyses for Fuel Assemblies, under Work Package Number FT-14IN081301.

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology, has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development activities related to storage, transportation, and disposal of used nuclear fuel (UNF) and high-level radioactive waste. The mission of the UFDC is to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of UNF and wastes generated by existing and future nuclear fuel cycles. The UFDC Storage and Transportation staffs are responsible for addressing issues regarding the extended or long-term storage of UNF and its subsequent transportation. The near-term objectives of the Storage and Transportation task are to use a science-based approach to develop the technical bases to support the continued safe and secure storage of UNF for extended periods, subsequent retrieval, and transportation.

It is important to demonstrate there is a low probability of failure of high burn-up (HBU) UNF during normal conditions of transportation (NCT). Establishing high confidence low probability of failure (HCLPF) of UNF during transportation and extended storage requires a combination of numerical modeling and simulation and experimental tests.

The response of UNF to NCT is a function of the frequency content of the input motion (i.e. rail motion, truck motion), stiffness and mass of the entire package (i.e. rail car, cask cradles, cask, cask internal components), stiffness and the mass of the fuel assemblies. Yielding of the fuel during NCT is unlikely since maximum transportation-induced strains will likely be lower than the yield strength of the fuel. The larger concern is cyclic fatigue, specifically the growth of localized cracks in the fuel clad during hundreds of thousands of cycles during rail transportation that can lead to failure.

This report presents:

- A comparison and analysis of the numerical results from *Adkins 2013* and experimental testing results from *Wang 2014* that suggests:

> There may be cyclic fatigue concerns associated with transportation of UNF

- Sensitivity studies performed using numerical analysis of Westinghouse 17x17 OFA

> The relaxed grid spacer springs present the potential to create the highest strains during NCT.

- Non-destructive examination x-ray work performed on INL 15x15 dummy to determine its adequacy for shaker table tests.

> NDE of the INL dummy assembly shows the fuel rods are solid steel rod and this assembly is not suitable for vibration analysis testing.

- A long term vision for developing HCLPF of high burn-up fuel cladding during NCT

> Demonstrating HCLPF of high burnup requires coupling of numerical models with experimental testing

Experimental testing coupled with finite element models will develop HCLPF to show fuel cladding can remain intact during NCT and extended storage. Numerical studies are needed to determine the effects that will change fuel rod and fuel assembly response. Experimental tests are needed to build confidence in the numerical models. Once important sensitivities are identified (i.e. those sensitivities that shift high burnup fuel rod response towards the peak response of the input motion) then experimental tests can be performed to determine the effects these sensitivities have on high burnup fuel during NCT (demonstration tests). These demonstration tests can then be used to validate numerical studies and provide a basis for transportation of high burnup UNF during NCT.

CONTENTS

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Acronyms

3D	3 dimensional
BE	best estimate
DOE	Department of Energy
DOF	degree of freedom
EPRI	Electric Power Research Institute
FEA	Finite Element Analysis
FY	fiscal year
HBR	H. B. Robinson
HCLPF	high confidence in low probability of failure of high-burnup
INL	Idaho National Laboratory
IP	Imaging Plate
MOX	Mixed Oxide
NA	North Anna
NCT	normal conditions of transportation
NDE	non-destructive examination
OFA	Optimized Fuel Assembly
ORNL	Oak Ridge National Laboratory
PPC	pellet-pellet-clad
PWR	pressurized water reactor
UB	upper bound
UFD	used fuel disposition
UFDC	Used Fuel Disposition Campaign
UNF	used nuclear fuel
UO	uranium oxide
V&V	verify and validate

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1. INTRODUCTION

The basis for transportation of high burn-up UNF has not been developed. If retrievability of UNF is important and cladding is the barrier than it is important to demonstrate that there is a high confidence in low probability of failure of high-burnup (HCLPF) UNF cladding during transportation and extended storage. This will ensure retrieveability, if necessary, and maintain fuel cladding as the containment barrier during normal conditions of transportation (NCT). Establishing HCLPF of fuel cladding during transportation and extended storage will require a combination of numerical modeling and simulation and experimental tests.

Demonstration of HCLPF of high burn-up UNF cladding is complicated because it requires an understanding of the evolution of the fuel material properties and material states throughout its life cycle. To demonstrate HCLPF it is necessary to couple numerical analysis with experimental work. Initial numerical methodology should be developed. This methodology should couple the structural dynamic behavior with the material properties and states of high burn-up fuel cladding. Numerical sensitivity studies should be performed to limit the number of experimental tests needed. Experimental tests should be performed to verify and validate (V&V) structural dynamic behavior at the pellet-pellet-clad (PPC) interface and the thermal mechanical behavior of the pellets and clad. Finally, a high burn-up rod test should be performed to demonstrate HCLPF of high burnup fuel during NCT. This test would also provide data that would be used to V&V numerical models.

This document will:

- Layout a long term vision for developing HCLPF of high burn-up fuel cladding during NCT
- Compare numerical results from *Adkins 2013* with experimental testing results from *Wang 2014*
- Document sensitivity studies performed this year using numerical analysis of Westinghouse 17x17 OFA models
- Present non-destructive examination x-ray work performed on Idaho National Laboratory (INL) 15x15 dummy to determine its adequacy for shaker table tests.

2. Long Term Vision and Important Sensitivities

To minimize the number of experimental tests, numerical sensitivity studies should be performed. These sensitivity studies, using numerical models, should be used to determine what sensitivities have detrimental effects on fuel rod vibration during NCT. The necessary numerical and experimental tasks should be presented as a series of activities that achieve the long-term goal.

2.1 Long Term Vision

Figure 2.1-1 provides a high level overview of a path that successfully demonstrates HCLPF during NCT and maintaining fuel cladding integrity and retrievability during storage. Ultimately a hybrid test, which includes coupling numerical modeling with high burnup fuel rod testing, real time, should be performed. This test will also provide data that will be used to validate numerical codes that couple fuel performance and structural dynamics. Activity number four shown in Figure 2.1-1 describes a hybrid test that can be used to demonstrate HCLPF for multiple postulated rail transport trips. Figures 2.1-2 – 2.1-4 show the proposed hybrid test concept. Figure 2.1-2 shows the conceptual transportation configuration for a high burnup fuel package including rail car, cask, basket, and assemblies. Ultimately the concern is cyclic strains at the PPC interface (as shown by the red regions in the figure).

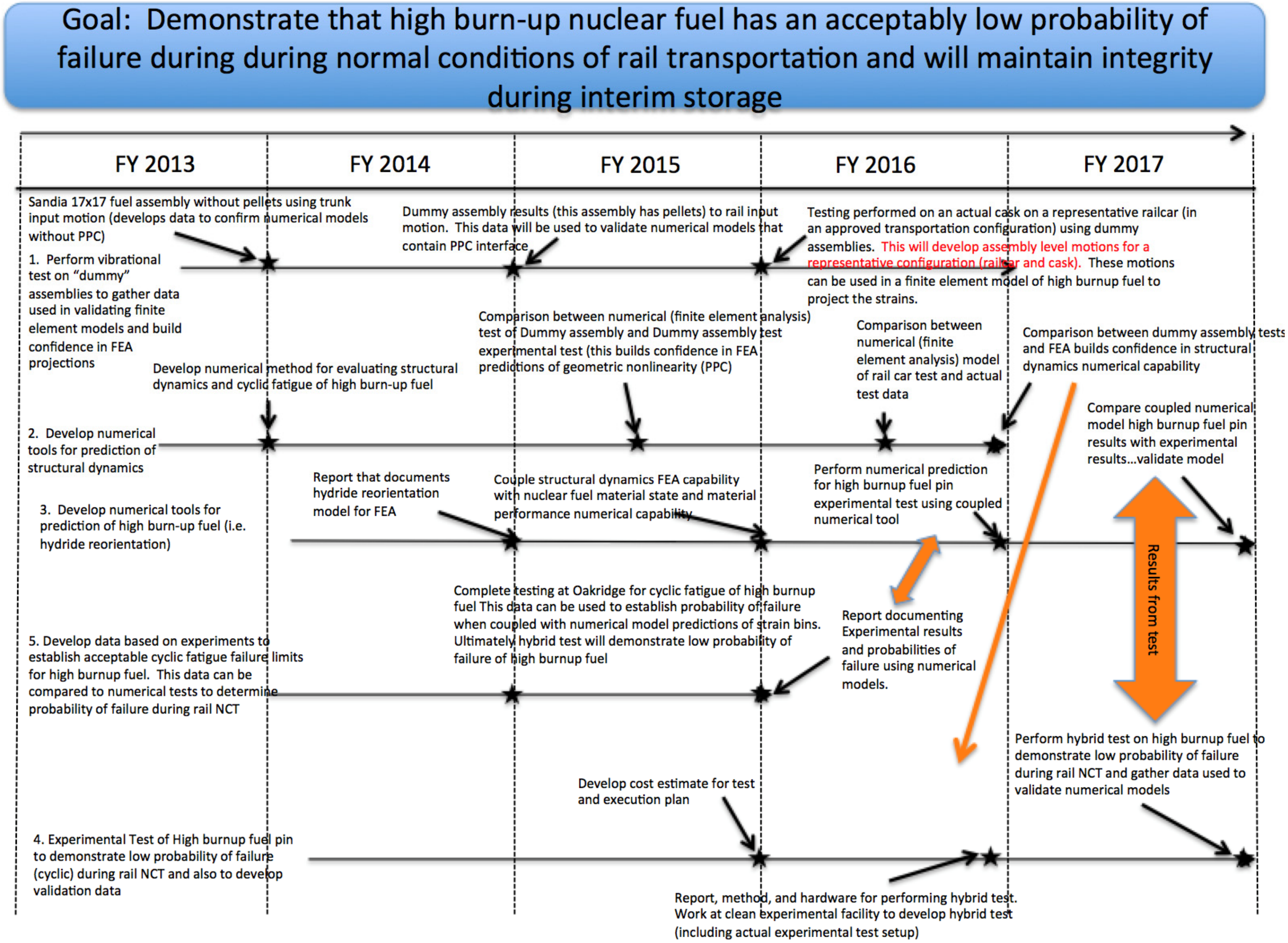

Figure 2.1-1. Conceptual layout of activities to develop high confidence low probability of failure of high burnup fuel cladding

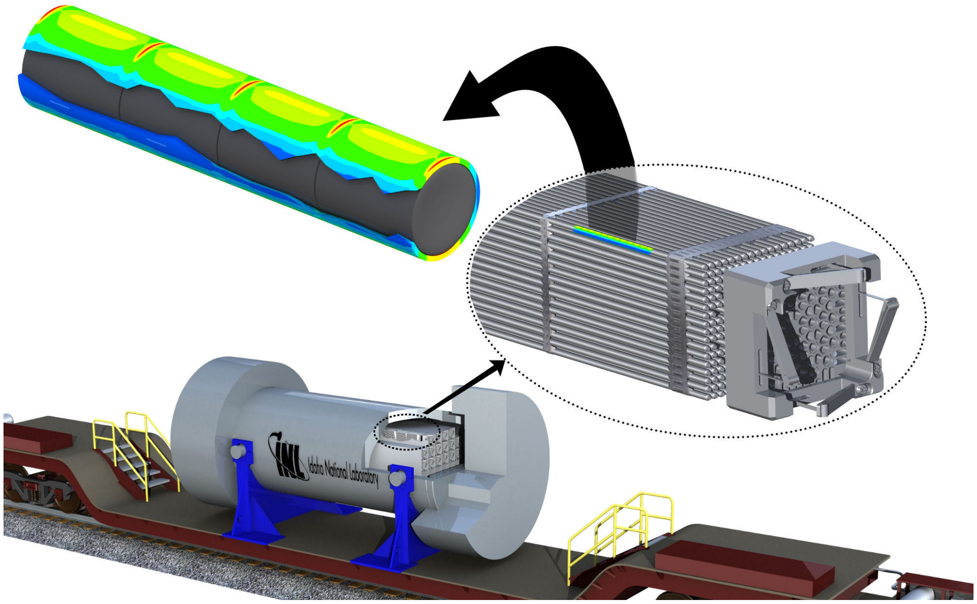

Figure 2.1-2: Conceptual high burnup fuel transportation package. This is the package that should be simulated in experimental testing.

Figure 2.1-3: Conceptual hybrid test set-up for experimental testing of high burnup fuel rod (note the rod would be in a hot-cell). This test configuration simulates the package in Figure 2.1-2.

Figure 2.1-3 shows the hybrid test configuration that could be used to simulate the rail transportation package configuration shown in Figure 2.1-2. A numerical finite element model would simulate the structural dynamics of package response using a number of different rail motions. This model would then feed real-time displacement time-history data to linear actuators that are attached to a high burn-up fuel rod in a hot cell. The numerical simulations would drive the high burn-up fuel rod in-cell such that the motions on this rod would be the same motion as if it were in the actual package configuration. This would produce cyclic strains at the PPC interface as shown in Figure 2.1-4.

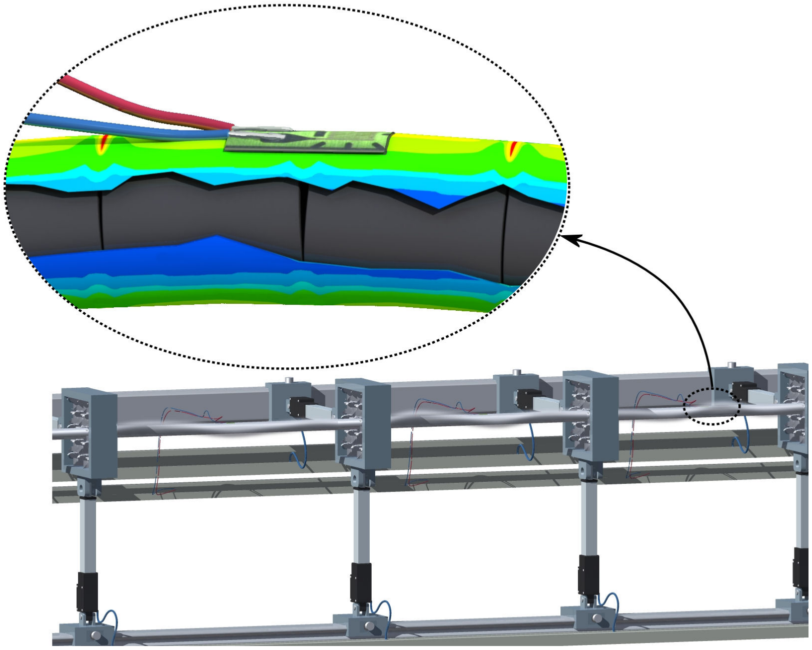

Figure 2.1-4: Measured strains during hybrid testing of high burn-up fuel rods.

2.2 Sensitivity Studies

Dynamic response of high burnup fuel assemblies during NCT is a function of the frequency content of the input motion, the material properties and material states of the UNF. If the frequency content of the large amplitude portion of the input motion (rail transportation) aligns with the natural frequency of a high burnup fuel assembly, resonance can occur causing higher strains at the PPC interface. The accumulation of these strains over a 3000-mile rail transport can cause cyclic fatigue concerns. One effect that likely contributes to cyclic fatigue concerns is the concentration of hydrides at the PPC interface that is also the location of increased strains.

At a high level three effects can create cyclic fatigue concerns during rail transportation of high burnup UNF. These are frequency content of input motion, UNF material properties at the time of transportation, UNF material state at the time of transportation. A number of sensitivities should be studied to understand the impact of these effects on UNF cyclic fatigue. Some sensitivities to be considered are:

- Bonding between the PPC Interface (material state)
- Pellet condition, cracked or uncracked (material state)
- Pellet geometry, such as pellet chamfers at the PPC interface. This geometry in the localized area may have a dramatic effect on cyclic strains. (material state)
- Hydride reorientation, concentration at the PPC interface (material state)
- Axial thermal profile along the length of fuel rods (material property and material state)
- Axial rod growth in reactor which thins the rod and changes natural frequency (material state)
- Relaxation of grid spacer springs (material state)

- Material properties of the irradiated cladding (material property)
- Frequency content of the input motion (input motion)
- Pellet cracking (material state)
- Fuel rod bambooing, variation in cladding thickness at the PPC (material state)
- Couple effect of the material properties and material states listed above

The thermal profile along a nuclear fuel rod varies along its length. Localized areas near the PPC interface (where pellet chamfers create small gaps between pellets) are cooler than the clad that is more intimately contacted by the fuel pellets (Figure 2.2-1). These cooler areas of clad have the highest concentration of hydrides (due to the Soret effect). These hydrides are oriented in a circumferential manner around the clad as a result of the stress profile generated by the high temperature drop across the clad during in-core service. During vacuum drying, the fuel heats up due to gamma heating (vacuum is a poor heat conductor) and some hydride dissolves as a result of the corresponding increase in hydrogen solubility in the clad as it heats up. When the cask is finally filled with helium, the fuel begins to cool as the gamma heat can be transferred and rejected from the cask. As the clad cools, new hydrides precipitate, however, there is only the hoop stress caused by the gas pressure in the fuel rod to drive the hydride orientation. This hoop stress causes the new hydrides to form in a radial orientation (across the clad and perpendicular to the stress). Some recent papers and analysis work indicate that reoriented hydrides tend to concentrate around the PPC interface due to the change in thermal profile at this local interface (Figure 2.2-1 showings numerical studies performed at INL). This local interface is also the location of the highest strains during NCT.

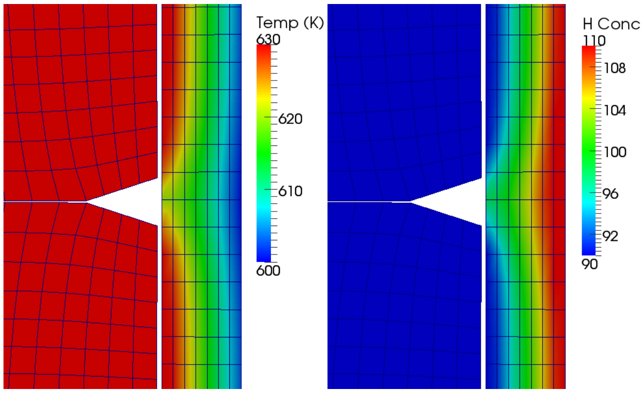

Figure 2.2-1: High burn-up fuel pin model showing PPC interface with temperature distribution on the left and hydrid concentration on the right

The missing link between experimental shaker table results [*McConnell*] and modeling and simulation work [*Adkins*] to date is the coupling of hydride concentration at the PPC interface with structural dynamics. It is important to understand whether the coupling of these two parameters decreases the cyclic fatigue strength of high burnup fuel. This should be investigated since the risk to cladding failure during NCT is crack growth around the PPC interface (this is the location of highest strains (Figure 2.2-2) and hydrides). Figure 2.2-2 shows FEA analysis results of a detailed 3D high burn-up fuel rod under load. This image shows maximum stresses (strains) located at the PPC interface. This hypothesis has been confirmed by cyclic pure bend testing performed by Oak Ridge National Laboratory (ORNL) [*Wang*].

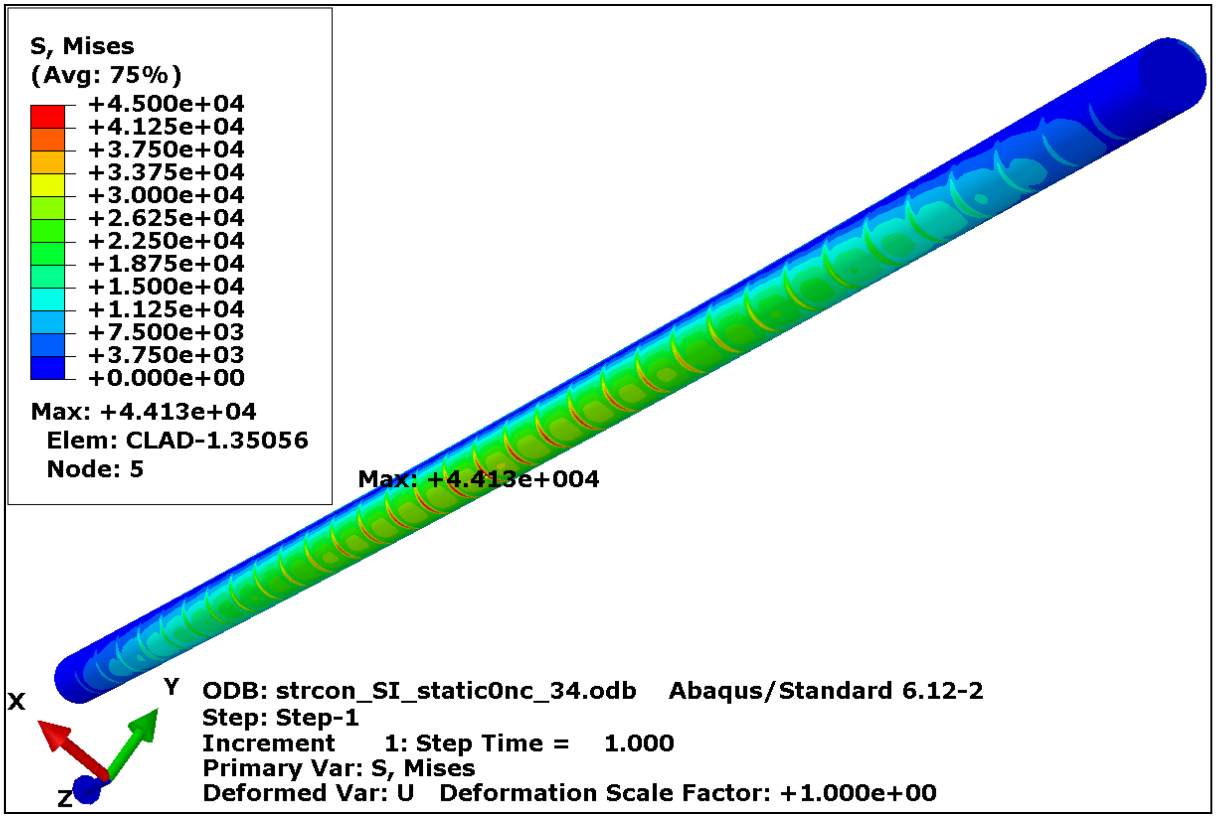

Figure 2.2-2: UNF rod showing high stresses (strains) in the area at the PPC interface.

2.3 Comparison of Numerical Studies with High Burnup Fuel Experimental Results

A numerical modeling effort was performed in fiscal year (FY) 2013 [*Adkins 2013*] to develop a methodology for numerically evaluating the damage ratio of high burnup fuel during rail NCT. The findings of the structural dynamic numerical evaluations that used a 17x17 OFA high burnup fuel assembly (using the best estimate stiffness, during a 3000-mile rail transport) are presented in Figure 2.3-1. The damage ratios are based on a 3000-mile rail transport and are compared with experimental data as shown in that figure. The damage ratio accounts for material property uncertainty, as indicated by the red dots. This figure, documented in *Adkins 2013,* was produced before pure bending tests of high burnup fuel rods were completed at ORNL.

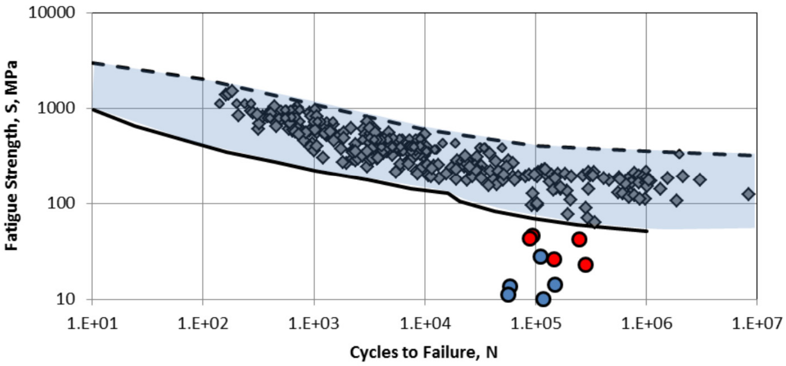

Figure 2.3-1: Projected fatigue strength of best estimate 17x17 OFA fuel assembly for a 3000 mile rail transport

Pure bend tests of high burnup fuel rods have recently been completed at ORNL and these tests are documented in *Wang*. *Wang* documents the cyclic fatigue of three types of fuel, 1) H. B. Robinson (HBR), 2) North Anna (NA), and 3) Mixed Oxide (MOX). This report produced data points on a strain amplitude versus number of cycles to failure curve (Figure 2.3-2).

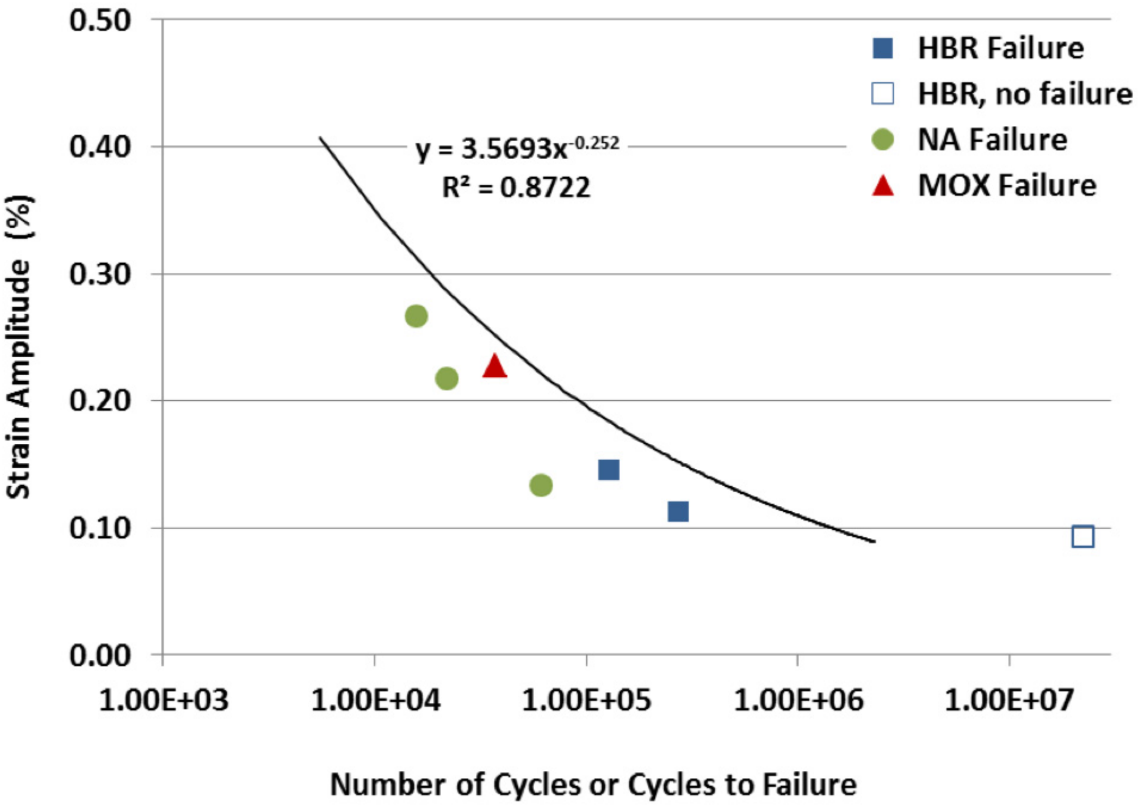

Figure 2.3-2: Strain amplitude versus number of cycles to failure

The *Wang* report provides a S-N trend curve fit based on HBR only. However, there are important differences between the HBR, NA, and MOX fuel rods. The most significant difference is the HBR is from a 15x15 fuel assembly, which has a cladding thickness of 0.76-mm, and the NA is from a 17x17 fuel assembly, which has a cladding thickness of 0.57-mm. This is an important difference since the cladding thickness likely has an impact on cyclic fatigue as well as pellet-clad interaction. Therefore, when comparing experimental transportation results (such as documented in *McConnell*) and numerical results (documented in *Adkins 2013*) with the ORNL data it is important these results are compared with the appropriate data points. Since both *McConnell* and *Adkins* use an equivalent 17x17 clad thickness these results can be compared with the NA tests from ORNL. Plotting only the NA failure points from the ORNL report produces the blue points and power trend curve shown in Figure 2.3-3. Also, standard deviation curves were plotted based on these three data points. Next, the projected fatigue strength of the 17x17 OFA fuel rods from *Adkins* (red dots in Figure 2.3-1) is plotted on Figure 2.3-3. This Figure 2.3-3, which plots ORNL NA experimental data with *Adkins* numerical modeling results, shows potential cyclic fatigue concerns with high burnup 17x17 fuel rods during NCT.

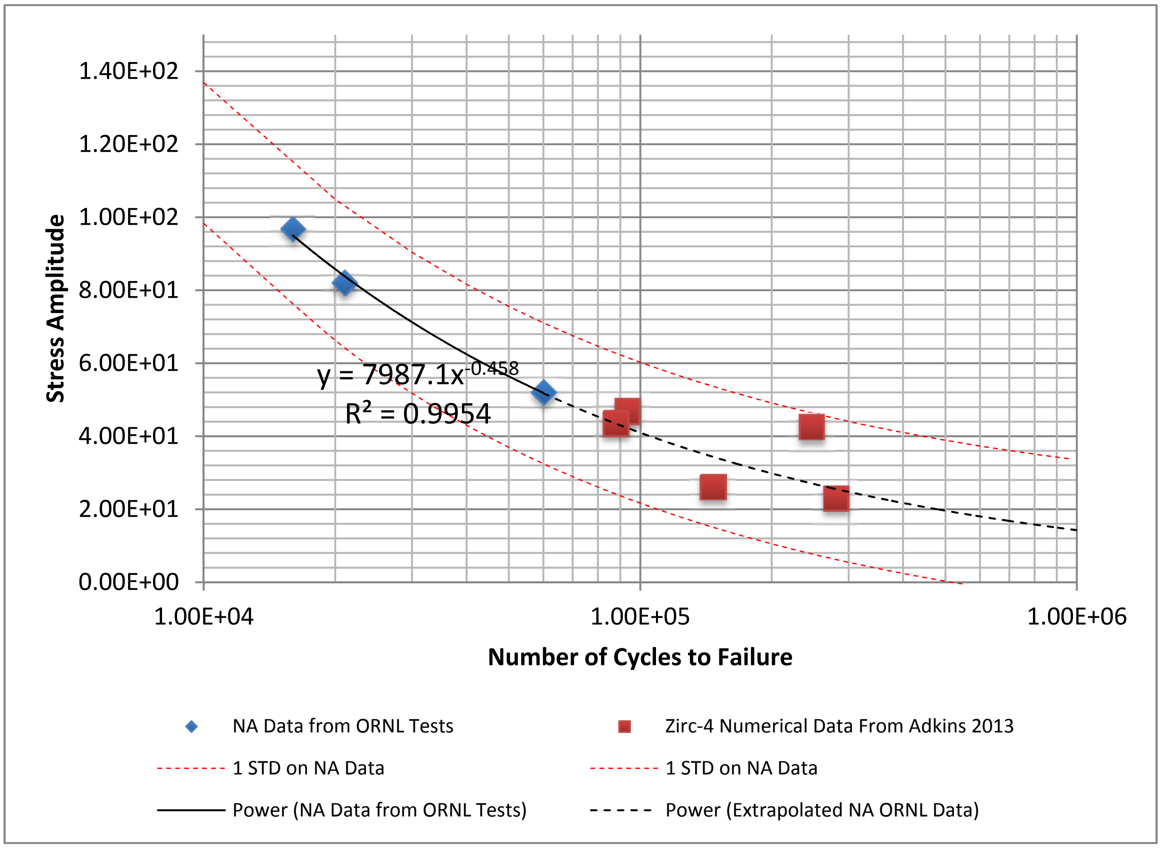

Figure 2.3-3: NA ORNL experimental data plotted with projected fatigue strength of high burnup fuel from *Adkins*.

Based on the comparison of numerical results with experimental results shown in Figure 2.3-3 it is important to understand the sensitivities that effect structural dynamics of high burnup fuel rods during NCT. The sensitivities that cause higher strains during NCT have the potential to create cyclic fatigue concerns. Therefore it is recommended that additional numerical simulations be performed to assess the coupled effect of UNF material properties and material states. Also, it is recommended that additional experimental testing be performed at lower strain (stress) amplitudes. These tests would provide the link between the model and data to confirm whether the cyclic fatigue concerns are valid.

3. Numerical Sensitivity Studies using 17x17 Westinghouse OFA Model

Sensitivity studies are important since they can be used to understand structural dynamic behavior of high burn-up UNF during NCT and reduce the number of experimental tests needed to describe UNF behavior. Numerical sensitivity studies can be used to determine the sensitivities that cause UNF to experience higher strains during NCT. This allows experimental testing to focus on only the sensitivities that cause higher strains during NCT.

The numerical models documented in this section utilize the same 17x17 Westinghouse OFA fuel assembly model developed and analyzed in *Adkins*. Using this fuel assembly four specific sensitivities were studied, 1) clad bambooing (this might only be the case for older fuel and long length pellets), 2) clad thinning (a few items that could contribute to rod thinning are, axial rod growth, clad corrosion, fretting), 3) pellet fracture, and 4) the effect of a relaxed spring on the natural frequency (shifts down).

The geometric and material property details of the 17x17 Westinghouse OFA assembly are as documented in *Adkins*, with the following exceptions. First, the LS-DYNA model was converted to an ABAQUS model. Second, various fuel rod geometrical parameters were modified to account for fuel rod thinning, clad bambooing, and pellet fracture. By varying these parameters it was hoped to conservatively bound potential geometric fuel rod configurations that would be produced in reactor and during wet and dry storage.

3.1 NUMERICAL SENSITIVITY STUDIES

The fuel rod level model described in *Adkins 2013* utilized a deterministic approach, which analyzed a lower bound (LB), upper bound (UB), and best estimate (BE) case for the fuel rod. This report noted that there is a wide range of uncertainty in the material properties for irradiated fuel rods as well as uncertainty in the fuel rod material state (which includes pellet cracking, clad bambooing, clad corrosion, clad cracking due to hydride formation, and pellet-cladding interface). This sensitivity study focuses on the effects that fuel rod material state has on the dynamic response of a fuel rod.

A suite of models for various fuel rod material states was created using ABAQUS. A process identical to that described in *Adkins* was used to extract the dynamic response of the fuel rod for each model. The effect of each material state on the dynamic response of the fuel rod is compared using the time-history response, flexural rigidity, and viscous damping.

The objective of these sensitivity studies was to determine which material states have the greatest impact on the dynamic response of the Westinghouse pressurized water reactor (PWR) 17 x 17 fuel assembly (increase strains on the fuel rods). Due to the uncertainty of the severity of each material state, various models were created for each material state. Table 3.1-1 describes the fuel rod models that were analyzed. The “base case” in Table 3.1-1 refers to the best estimate model in *Adkins*.

The base case has a model friction coefficient of 0.1 and circumference tie between the pellet and the cladding. The fuel pellets are composed of uranium oxide (UO_2), are 12.879 mm in length, 7.844 mm in diameter, and have a density of 10292 kg/m^3. The cladding is composed of zircaloy-4, has a length of 450.76 mm, inner diameter of 8.001 mm, wall thickness of 0.5715 mm, and has a density of 6587 kg/m^3. All material states described in Table 3.1-1 are variants of this base case.

Table 3.1-1. Dynamic response properties of various material state models for the BE case

Material state	Severity	Time-history response	Flexural rigidity (Pa*m^4)	Viscous damping (% critical)
Clad bambooing	1x clad wall thickness	See Figure 3	21.03	0.001718%
	2x clad wall thickness	See Figure 3	10.04	0.012010%
Clad thinning	20% clad thinning	See Figure 4	41.49	0.002324%
	40% clad thinning	See Figure 4	38.63	0.002066%
Pellet fracture	Horizontal fracture in all pellets	See Figure 5	43.79	0.108320%
	Vertical fracture in all pellets	See Figure 5	44.72	0.265800%
Base case	-	See Figures 3 through 5	45.06	0.001358%

The numerical modeling results presented in Table 3.1-1, show that clad bambooing has the greatest impact on flexural rigidity (fuel rod stiffness) and pellet fracture has the greatest impact on damping. The fuel rod bamboo FEA shown in Figure 3.1-2 produces a gap between the PPC interfaces. This gap could also be caused by other phenomena such as a missing pellet surface as documented in Electric Power

Research Institute (*EPRI*). Clad thinning has less of an impact on flexural rigidity than gaps (in this case modeled as bambooing) around the PPC interface. This is due to the pellet-clad interaction being circumferentially tied, which causes most of the fuel rod stiffness to be developed from the fuel pellets as opposed to the clad. This also explains the effect that clad bambooing has on the stiffness as this phenomena effectively reduces the pellet area that is circumferentially tied to the clad.

Figures 3.1-1 and 3.1-2 show the CAE models developed for the base case, and clad bambooing, respectively. The clad thinning and pellet fracture material states are very similar to the base case with the exception of either thinner clad or a slip plane through the center of each pellet (for the case of pellet fracture).

Figures 3.1-3 through 3.1-5 show the time-history response of a node at the mid-point of the clad for each material state compared to the base case. The dynamic response for these figures was induced using the following steps:

- Apply uniform acceleration due to gravity (g) to whole model in a static step.
- Apply an additional sinusoidal acceleration equal to 0 at the ends of the rod and 0.4*g at the clad mid-point (see Equation-1) in a static step.
- Remove the acceleration described in step-2 using a dynamic step and record the resulting dynamic response over a minimum of 10 cycles.

$$a(Z) = 0.4 * \sin\left(\pi \times \frac{Z}{L_{clad}}\right) \qquad \text{(Equation-1)}$$

$$where\ a = acceleration, Z = length\ along\ clad, and\ L_{clad} = total\ clad\ length$$

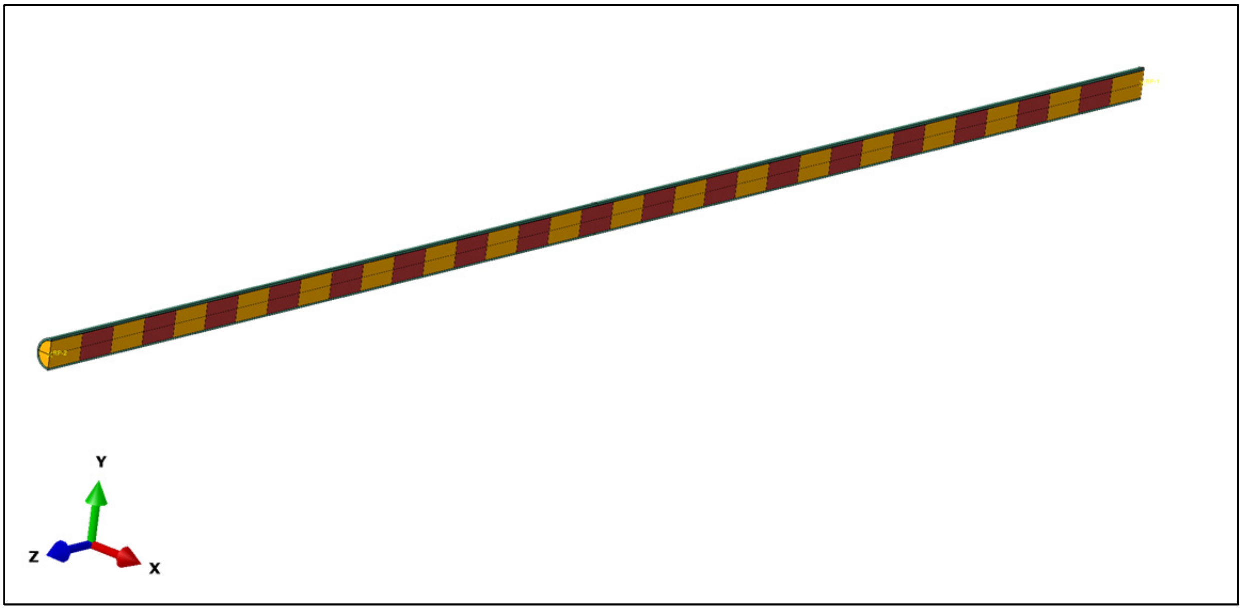

Figure 3.1-1. Base case CAE model. Clad is shown in green and pellets are shown in red and orange.

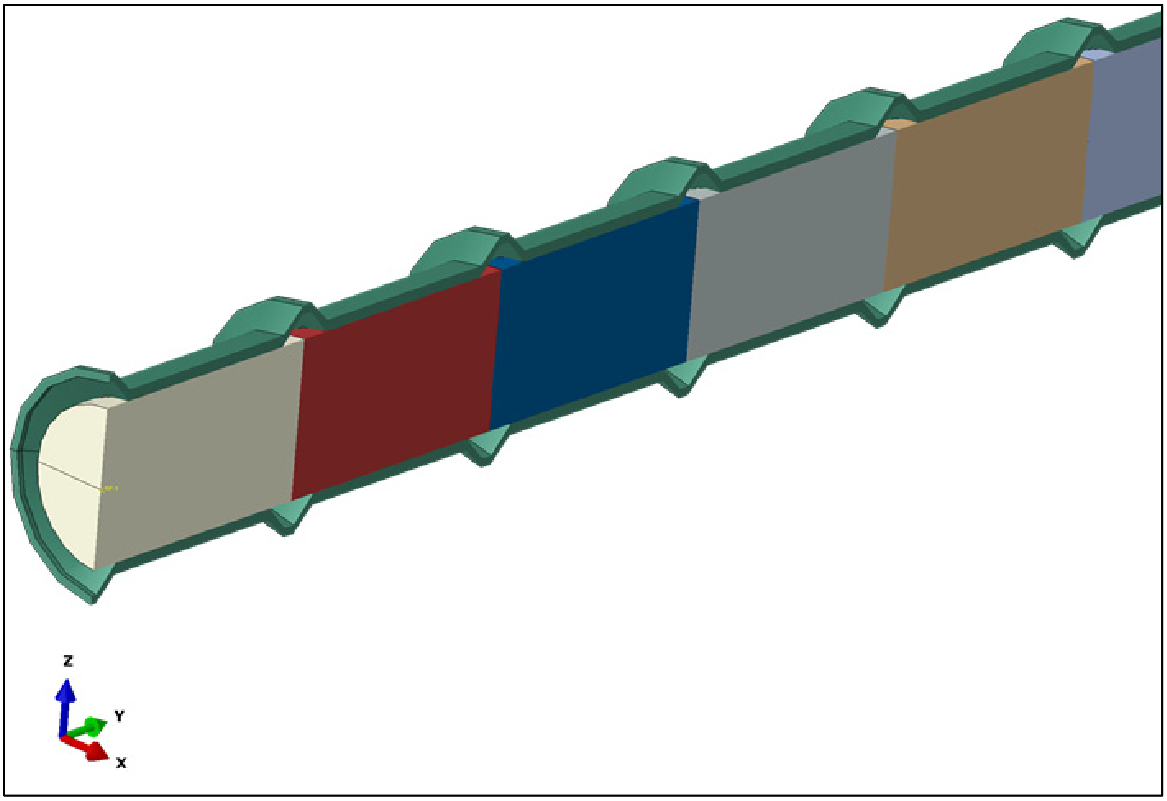

Figure 3.1-2. Diagram depicting how the clad bambooing was modeled.

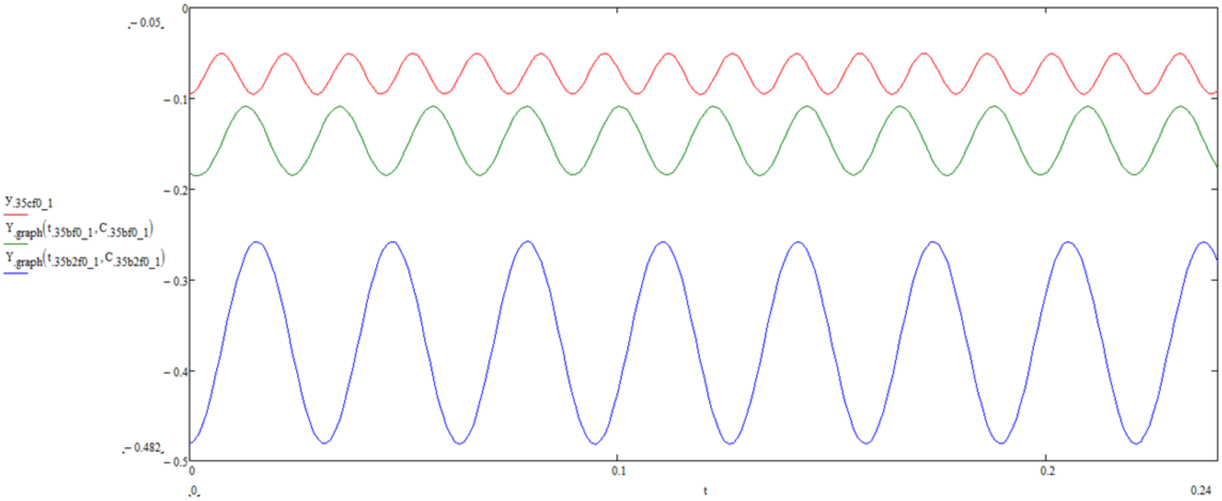

Figure 3.1-3 Time-history response for base case (red), clad bambooing 1x clad thickness (green), and clad bambooing 2x clad thickness (blue).

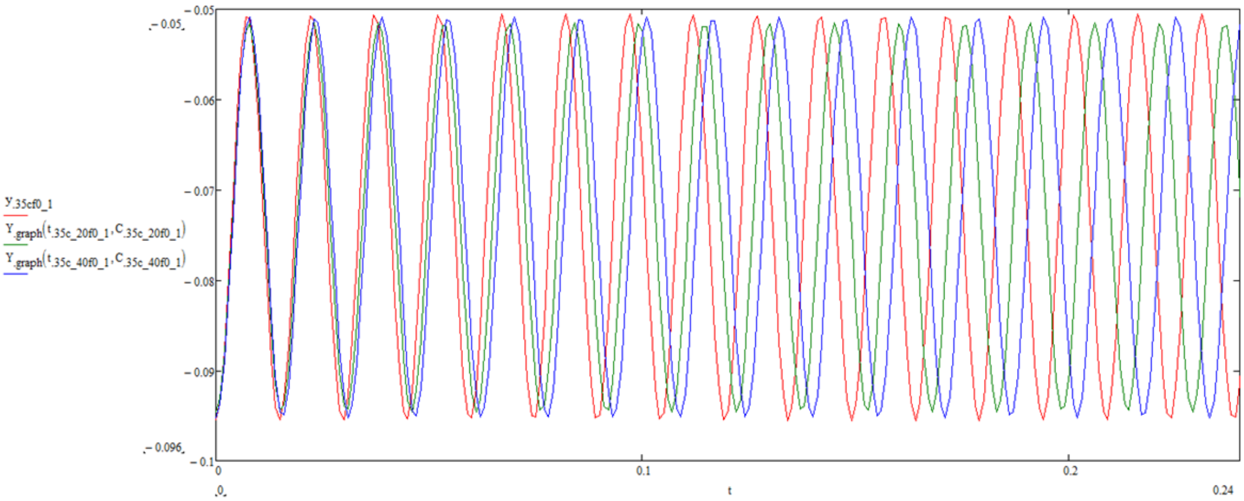

Figure 3.1-4. Time-history response for base case (red), 20% clad thinning (green), and 40% clad thinning (blue).

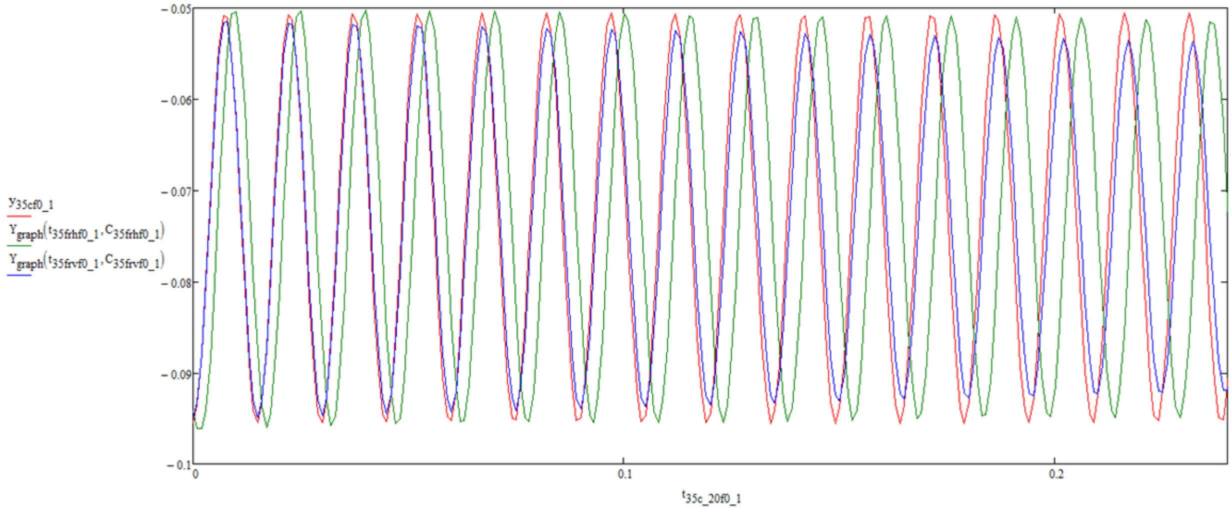

Figure 3.1-5. Time-history response for base case (red), horizontal pellet fracture (green), vertical pellet fracture (blue).

To compare the effect that each rod level material state model (see Table 3.1-1) has on the dynamic response of the Westinghouse PWR 17 x 17 assembly, a modal analysis was performed on the assembly model, shown in Figure 3.1-6, for each material state of the rod. To determine if these sensitivities will produce an amplified structural response (and increased strains), the response of the assembly (cumulative effective mass) was plotted against broadened rail car motion. The resulting cumulative effective mass over a frequency range of 0 to 110 Hz for each material state was then plotted against the input spectral acceleration for each degree of freedom (DOF). This type of plot is useful in determining how frequency shifts (due to differing rod material states) will affect the dynamic response of the assembly model. For example, if the assembly responds strongly at a frequency that corresponds with the peak of the input spectrum, then shifting the frequency of the assembly either up or down will be beneficial. In addition to the rod material states, one model run was performed with the springs on a single spacer relaxed.

Figure 3.1-7 shows the input spectral acceleration for each DOF. Figures 3.1-8 through 3.1-13 plot the cumulative effective mass versus frequency and the spectral acceleration for each DOF and each material state.

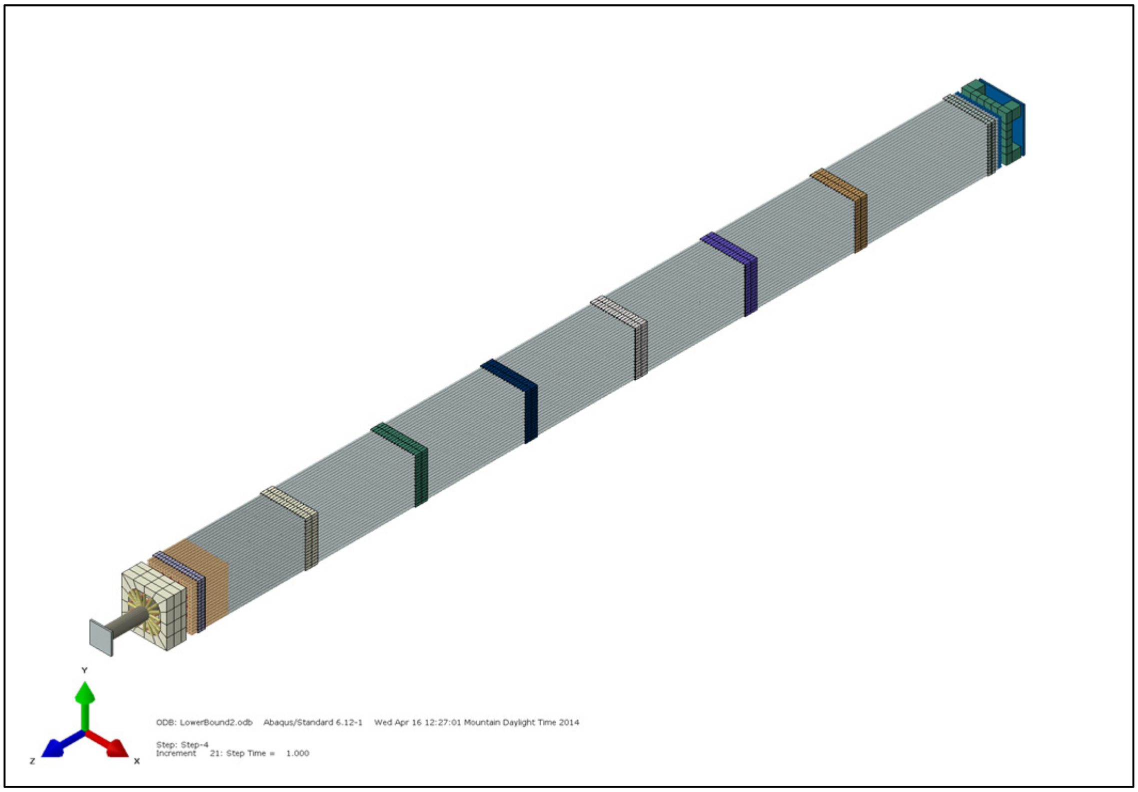

Figure 3.1-6. Model of the Westinghouse PWR 17 x 17 assembly created in Abaqus 6.12-2 (converted from the LS-DYNA model documented in *Adkins*).

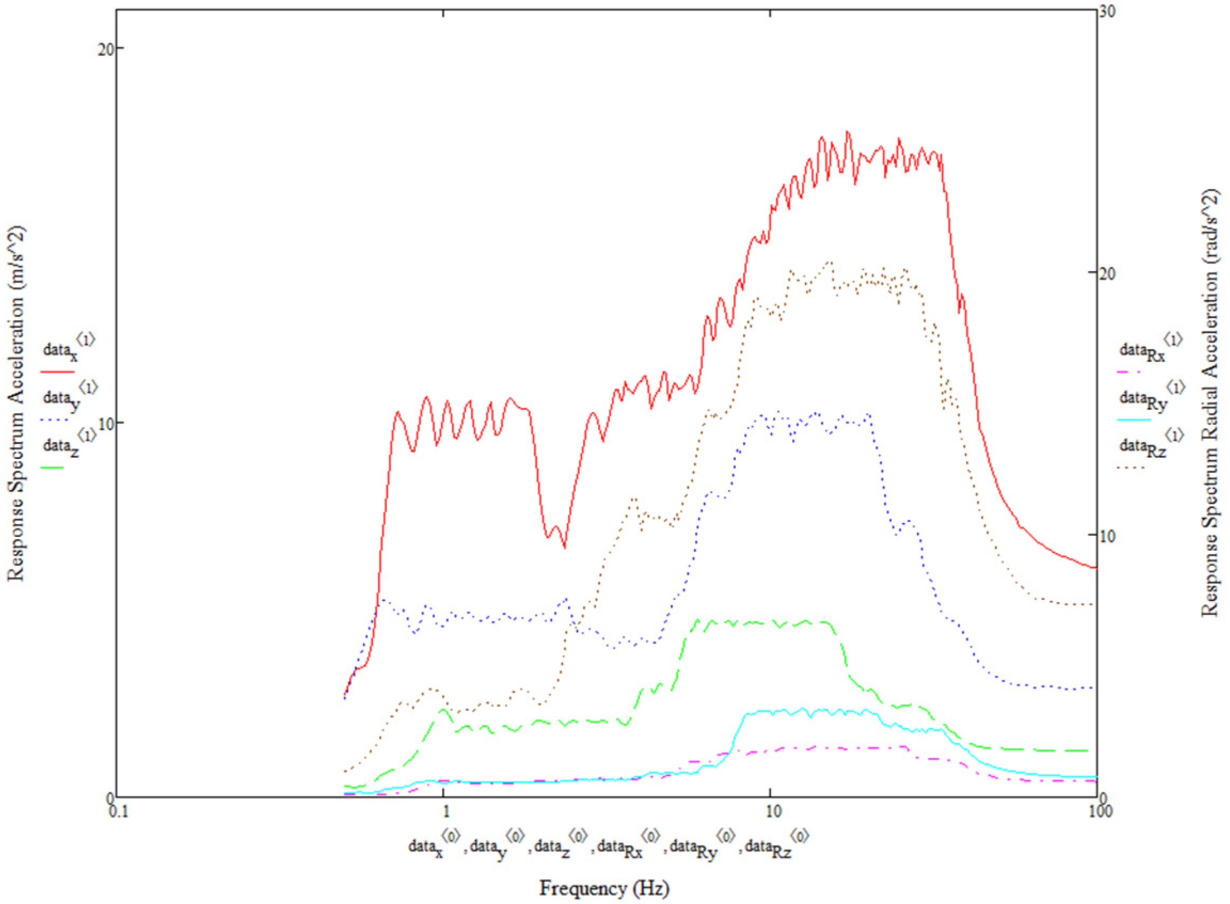

Figure 3.1-7. Input spectral accelerations for each DOF.

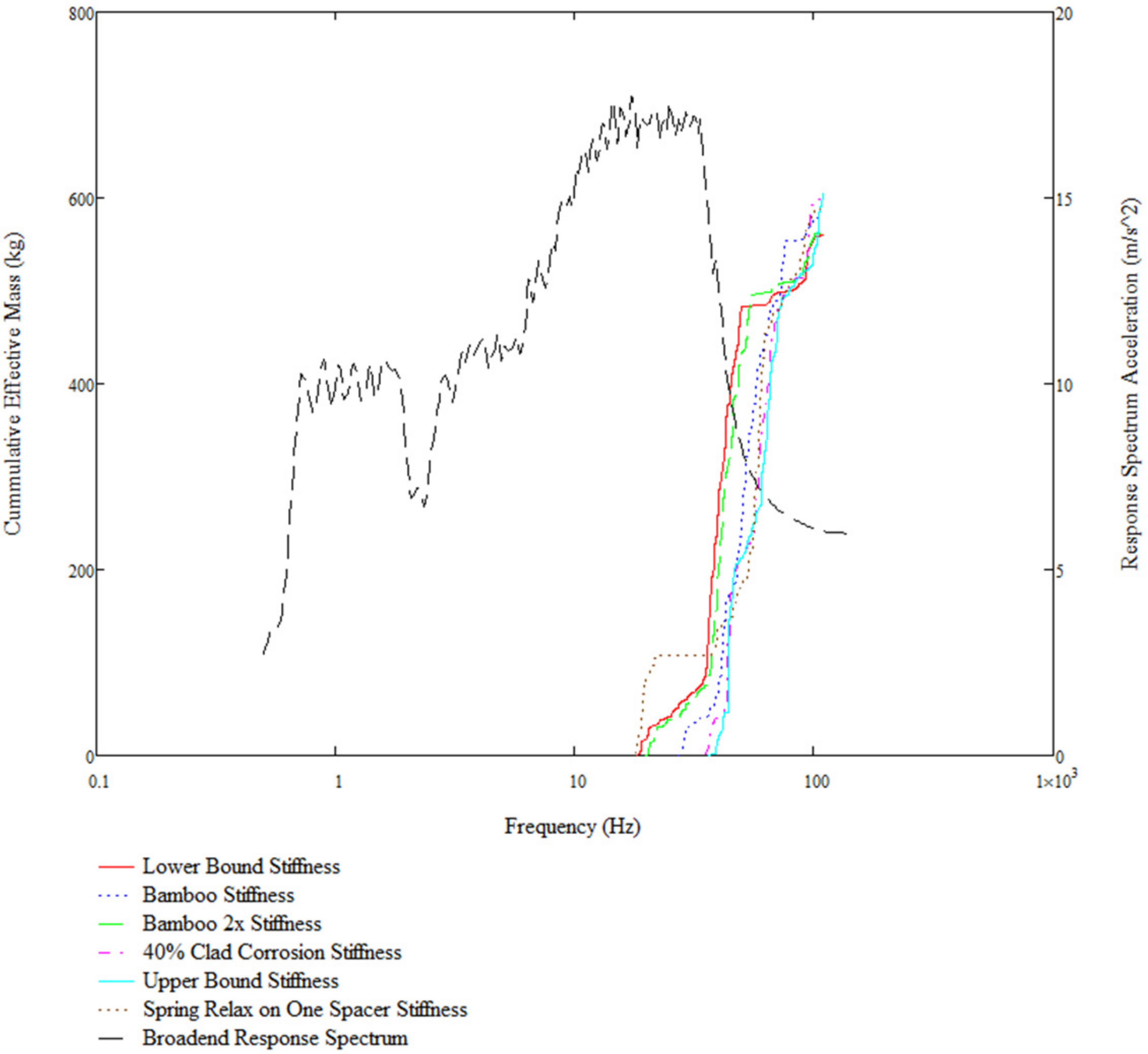

Figure 3.1-8. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the “x” translational DOF.

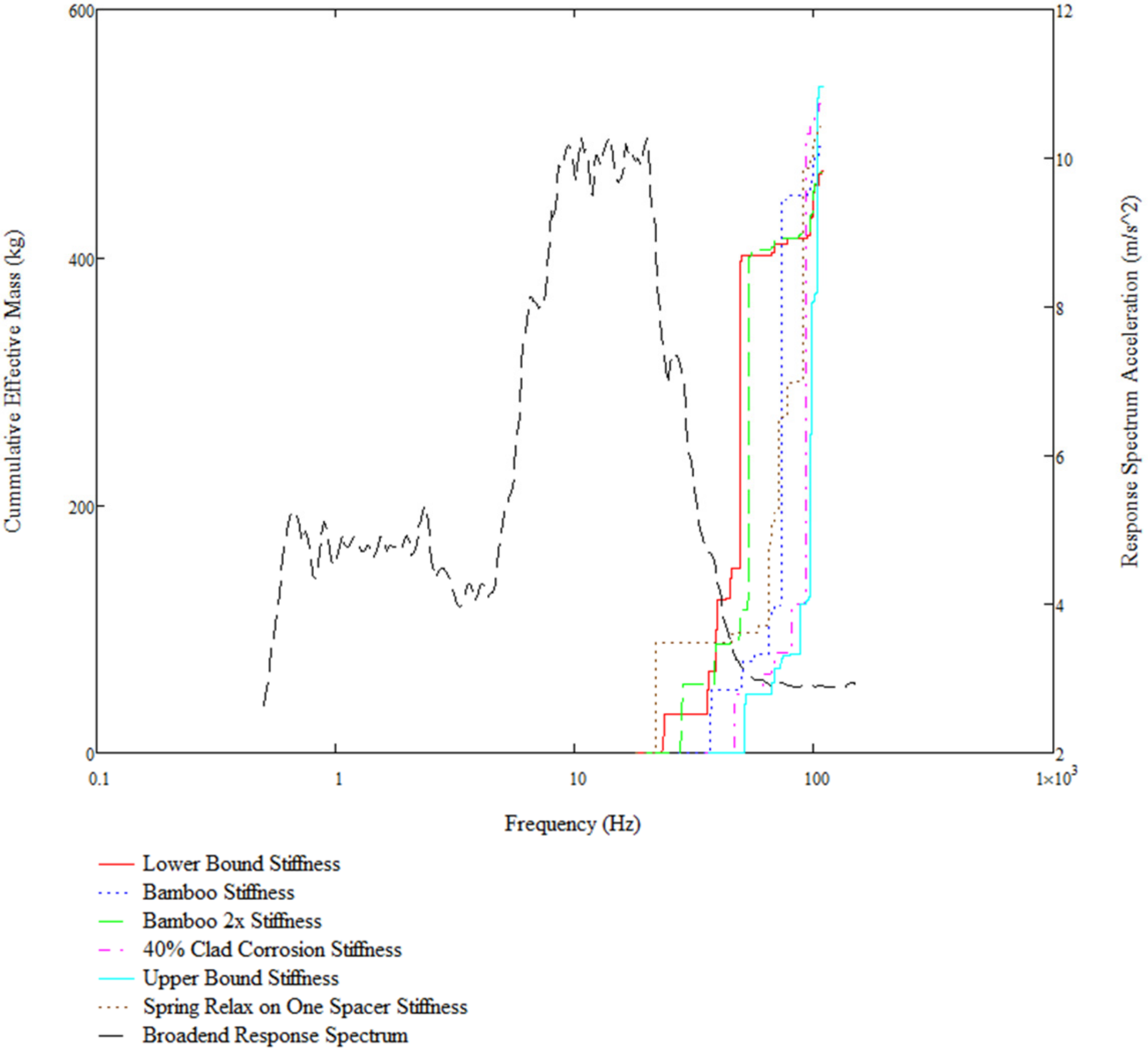

Figure 3.1-9. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the "y" translational DOF.

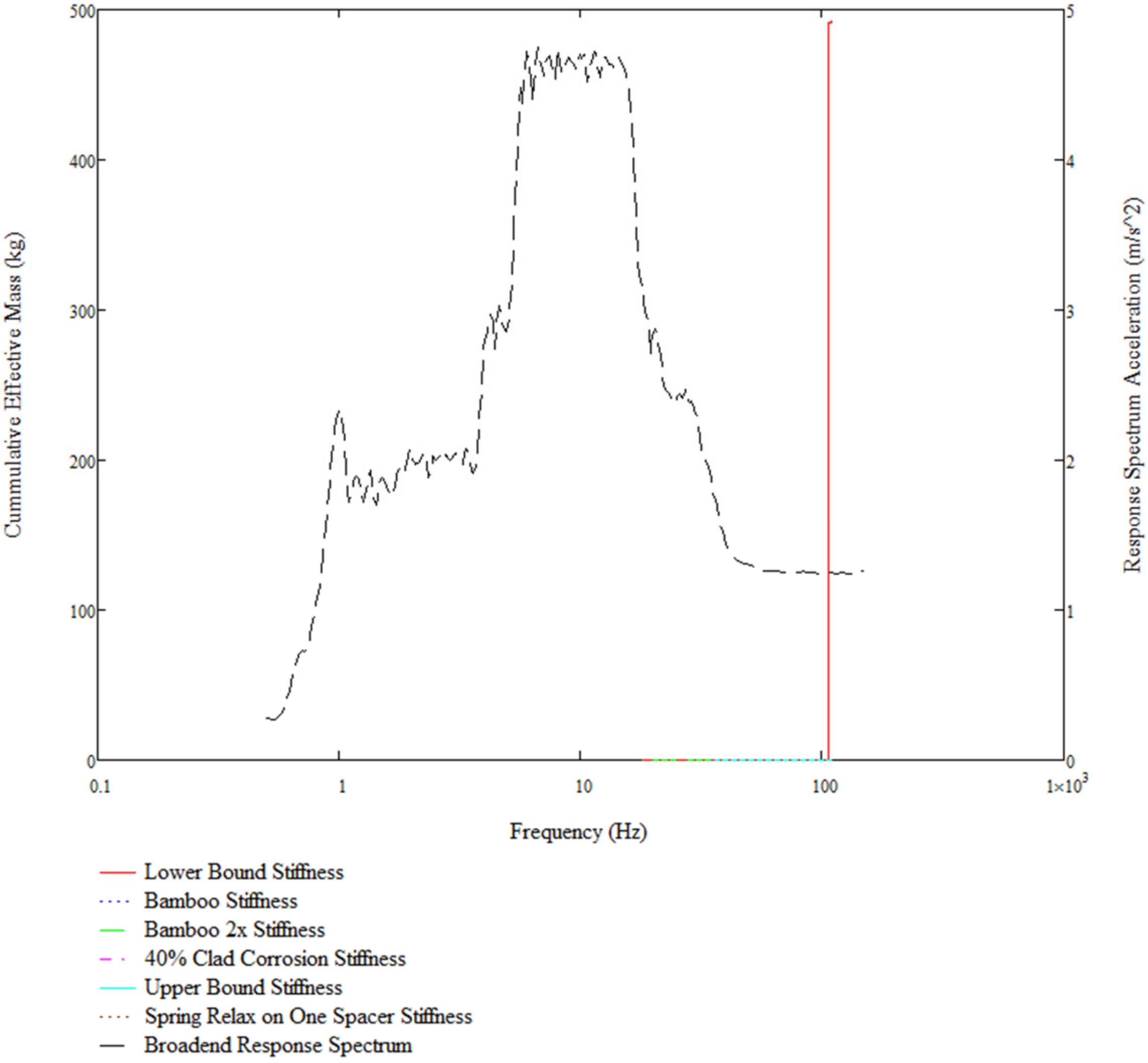

Figure 3.1-10. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the “z” translational DOF.

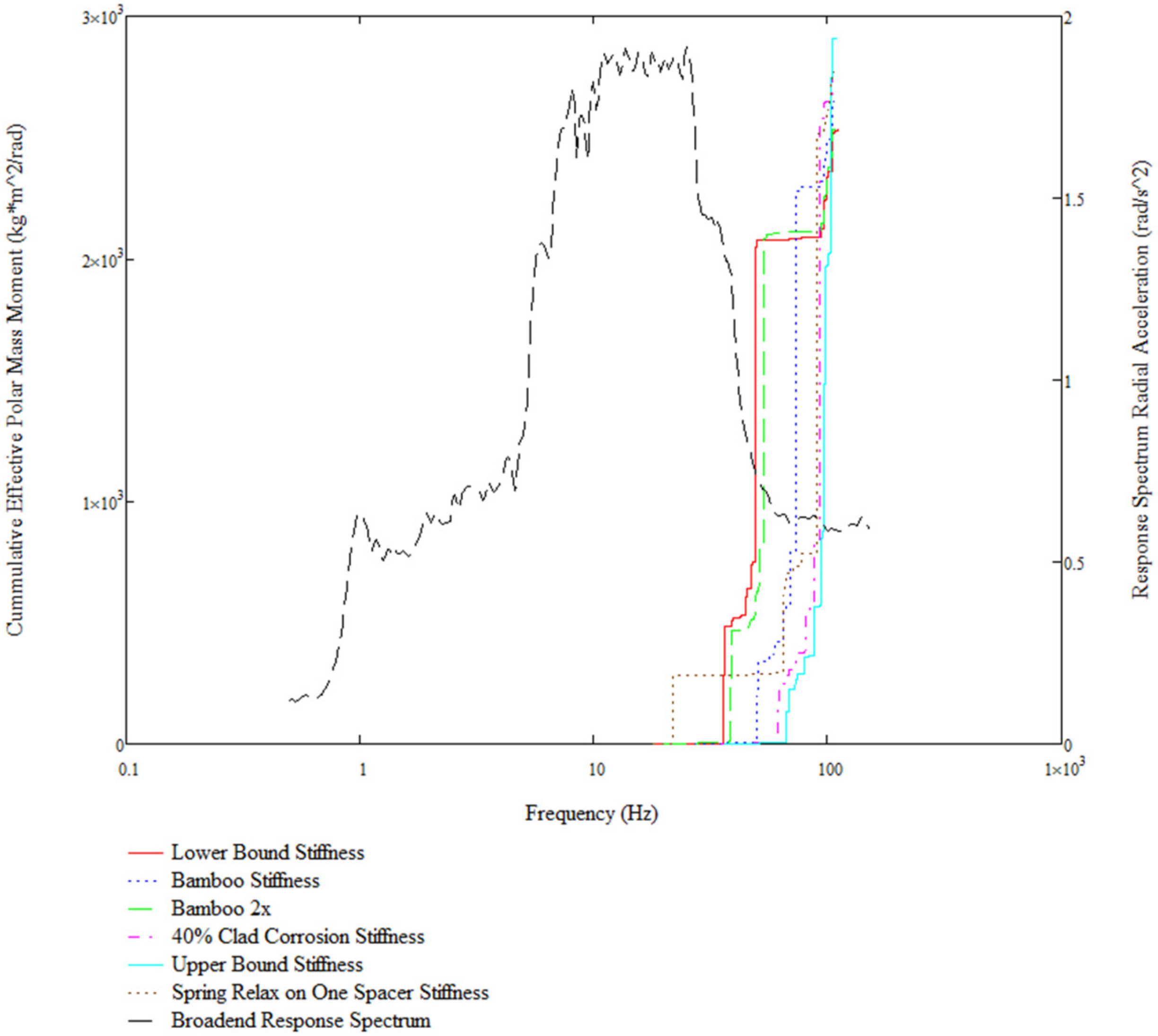

Figure 3.1-11. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the “x” rotational DOF.

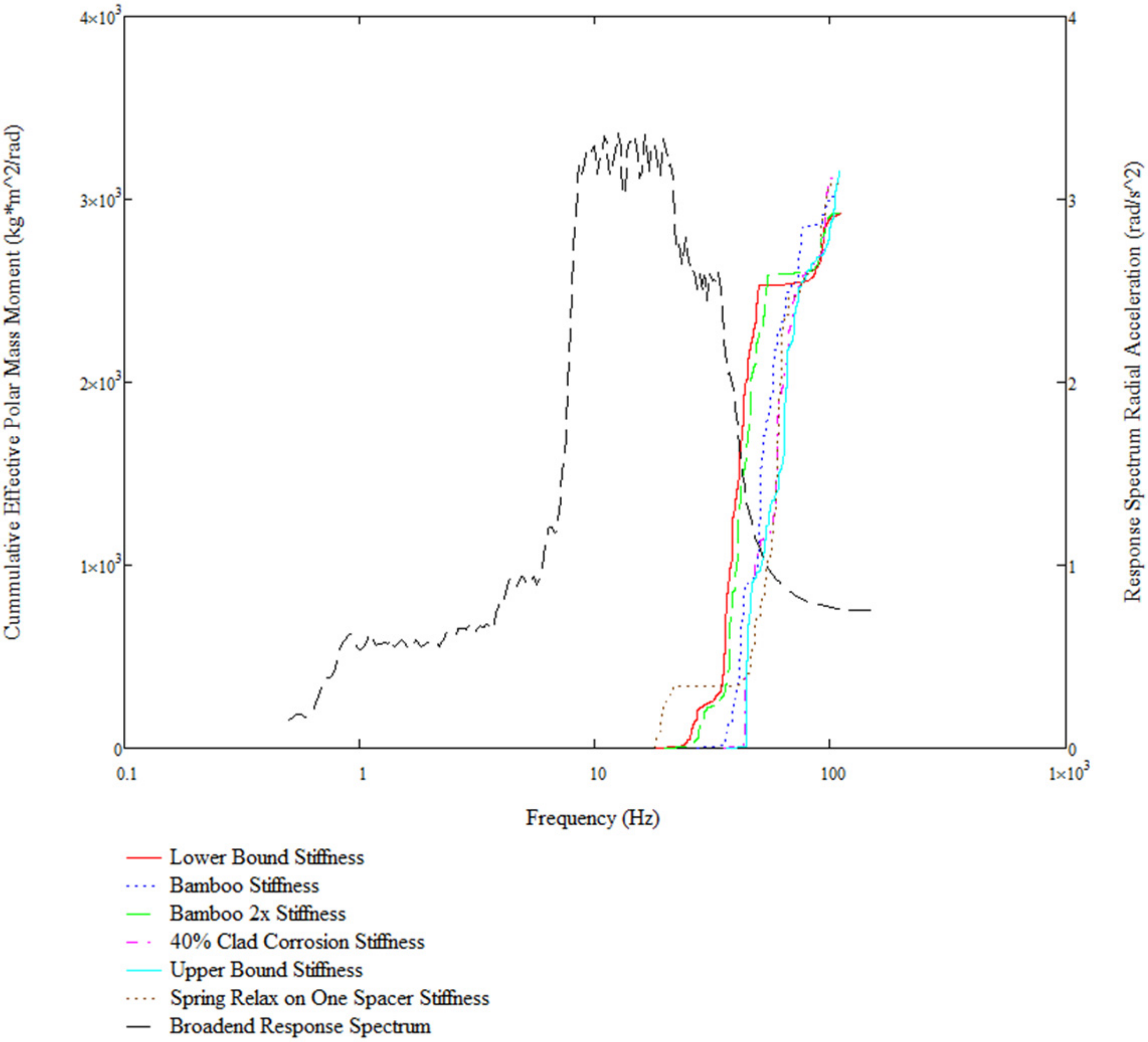

Figure 3.1-12. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the “y” rotational DOF.

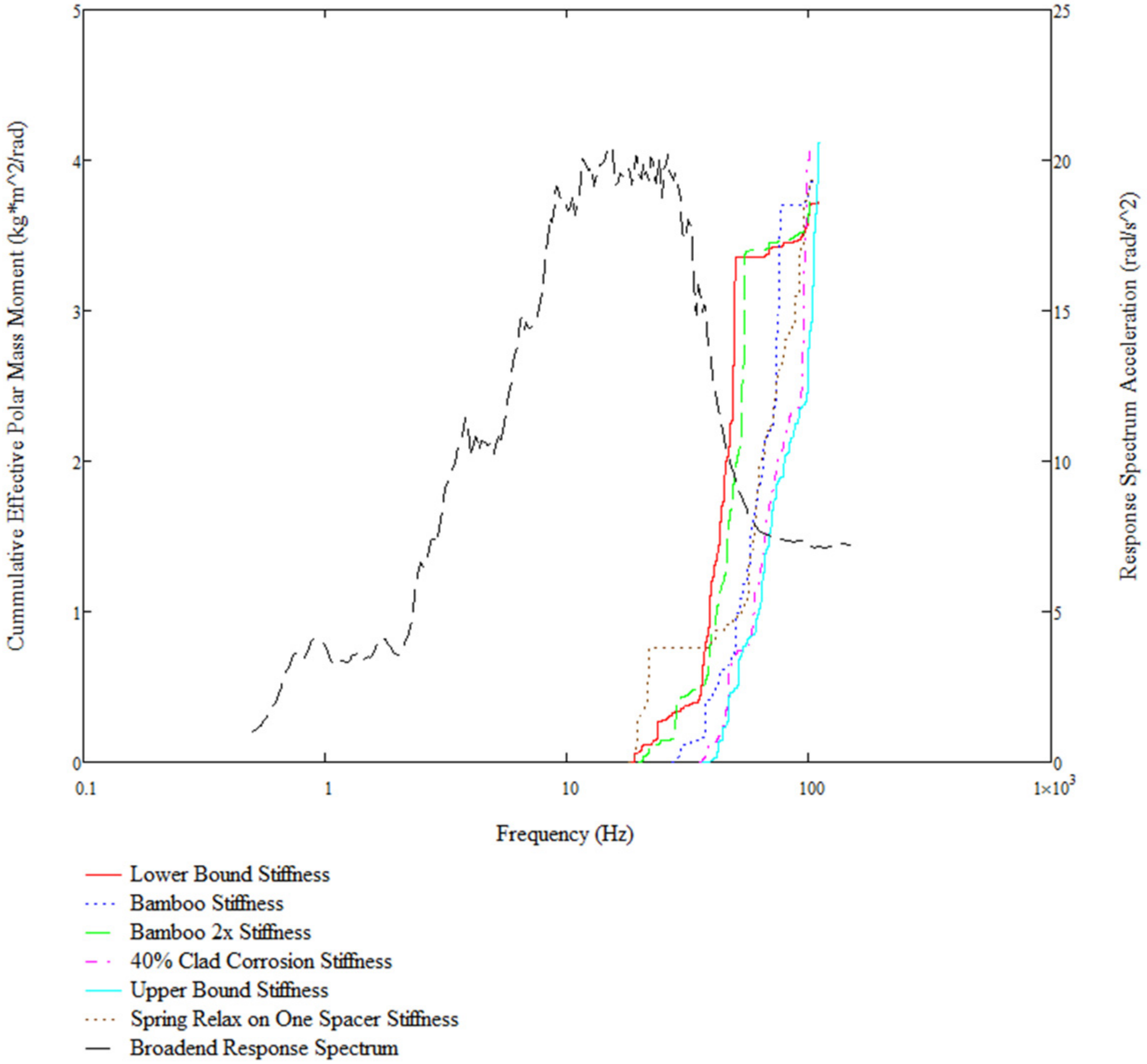

Figure 3.1-13. Plot comparing the cumulative effective mass for each material state with the input spectral acceleration for the “z” rotational DOF.

The above plots show that the sensitivity that produces the biggest frequency shift down into the large amplitude portion of the broadened rail motion is spring relaxation.

4. Proposed Testing using INL Dummy Assembly

INL has a Westinghouse 15x15 dummy Optimized Fuel Assembly that it wanted to use in experimental shaker table tests. These tests would gather data that would be used to validate the capability of numerical models to capture dynamic response at the PPC interface (Figure 2.1-1 activity 1). Strain gages were to be placed on the assembly in the location of the PPC interface and results gathered. These strain results would be compared to numerical tests using identical inputs. This comparison would be utilized to identify areas of the FEA model where initially approximated properties (e.g. modulus of elasticity, friction, etc.) can be adjusted to better match the actual properties of the assembly and thus produce a validated FEA.

For the INL dummy assembly shaker table test to have value it was important to understand whether or not this assembly contained pellets. If the assembly had pellets then it was important to know where the PPC interface was and place strain gages at this interface. Since design drawings were not available for this assembly, non-destructive examination using an x-ray machine was performed to determine PPC interface (if any).

4.1 Non-Destructive Examination

Non-destructive examination (NDE) was performed using a x-ray scanning machine. One of the setups is shown in Figure 4.1-1 along with the INL dummy assembly (still in its wooden box).

Figure 4.1-2 shows the x-ray generator pointing directly at the imaging plate (IP) at the bottom of the fuel assembly. This image was taken to determine what was in the bottom of the fuel rods and plenum tubes. The image shown in Figure 4.1-3 shows that threads are located in the bottom of the fuel rods (likely to simulate the threads in actual 17x17 fuel assembly's for the end caps) and the plenum tubes have threads. From this image it appears that the plenum tubes are empty.

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Figure 4.1-1: X-ray scanning setup for NDE tests

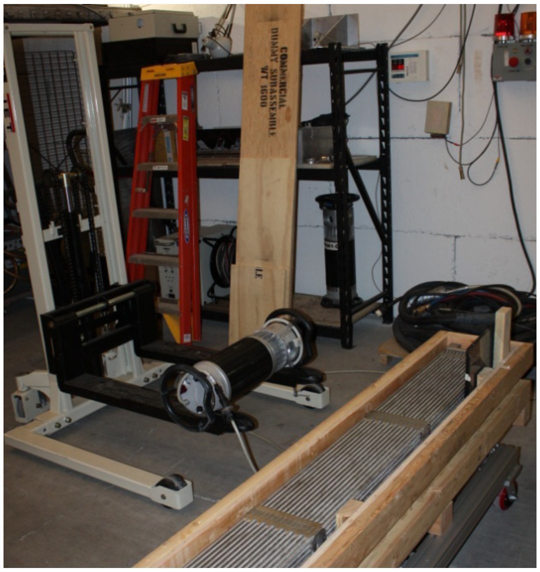

Figure 4.1-2: X-ray scanning setup bottom image capture

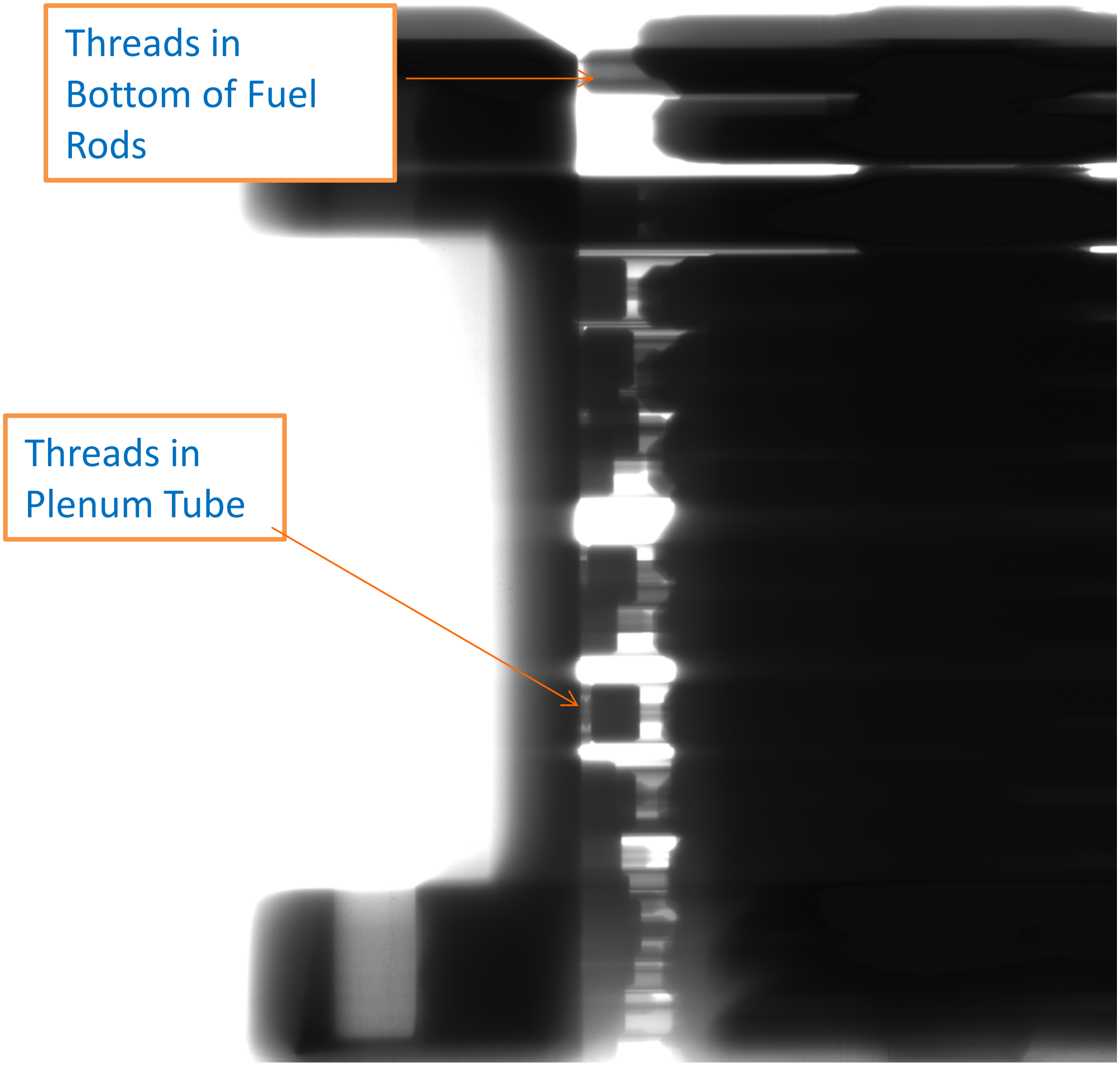

Figure 4.1-3: Bottom image of INL dummy fuel assembly showing threads in fuel rods and plenum tubes

Figure 4.1-4 is an additional bottom image. This image was collected with the IP behind the bottom nozzle on the fuel assembly and the x-ray generator at an angle. The intent was to see better detail of the fuel rod that was moved down and one plenum tube.

- This image shows threads in the fuel rods at the bottom of the bundle. The way the threads appear in the image indicates that the rods are solid.
- The image shows what appears to be threads and/or a bolt where the plenum tubes attach to the base of the bundle. The way the threads/bolt appear in the image indicates that the plenum tubes are hollow.

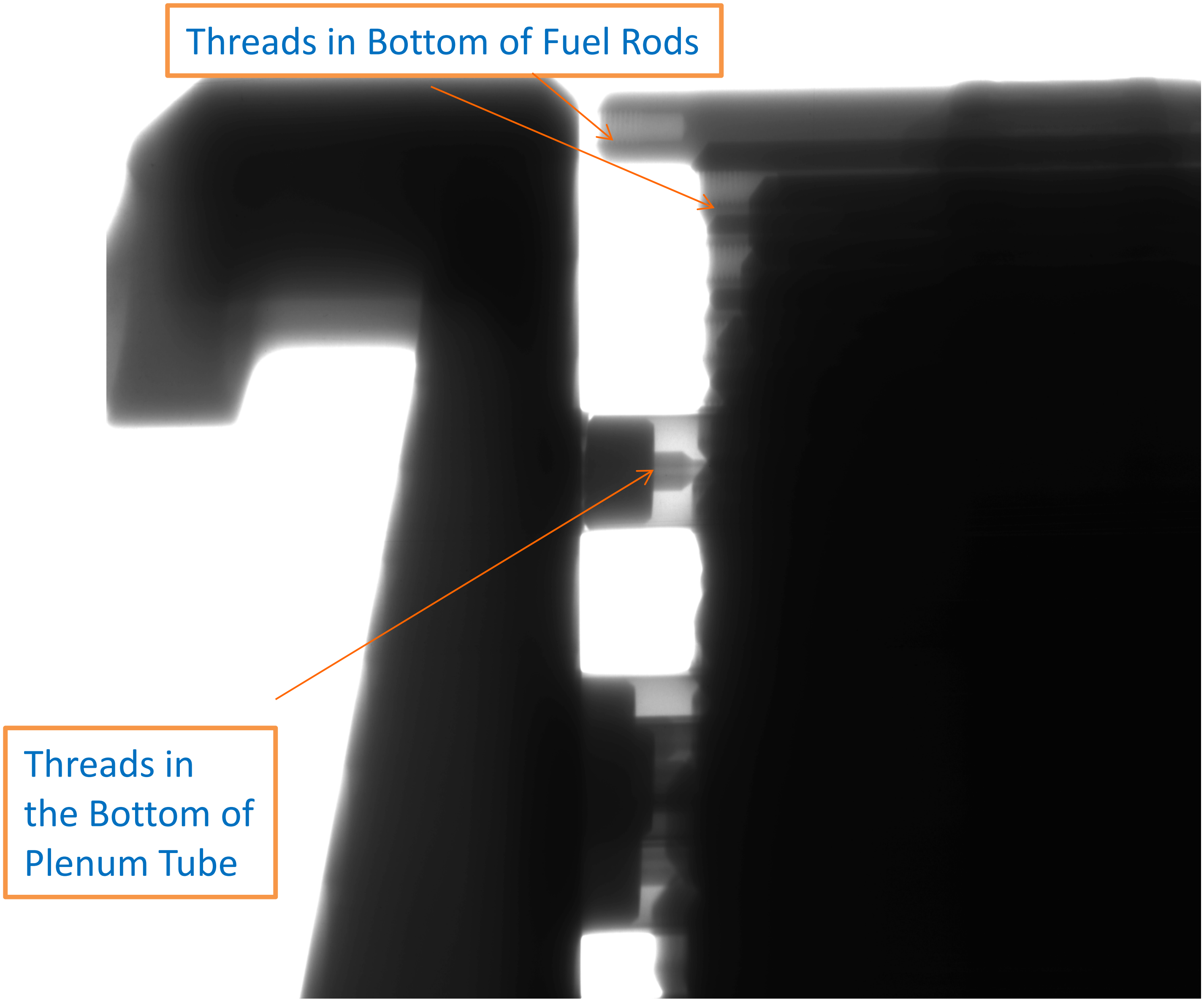

Figure 4.1-4: Additional bottom image of INL dummy fuel assembly showing threads in fuel rods and plenum tubes

Figure 4.1-5 shows an image captured at the top of the fuel assembly. This image was collected with the IP behind the top nozzle on the fuel assembly and the x-ray generator at an angle. The intent was to see better detail of one fuel rod by moving that rod up and one plenum tube.

- The image shows no indication of a cap welded on the end, indicates the rods are solid (machined end versus welded end).
- The varying gray values in the Plenum tube attached to the top of the bundle indicates the plenum tubes are hollow.

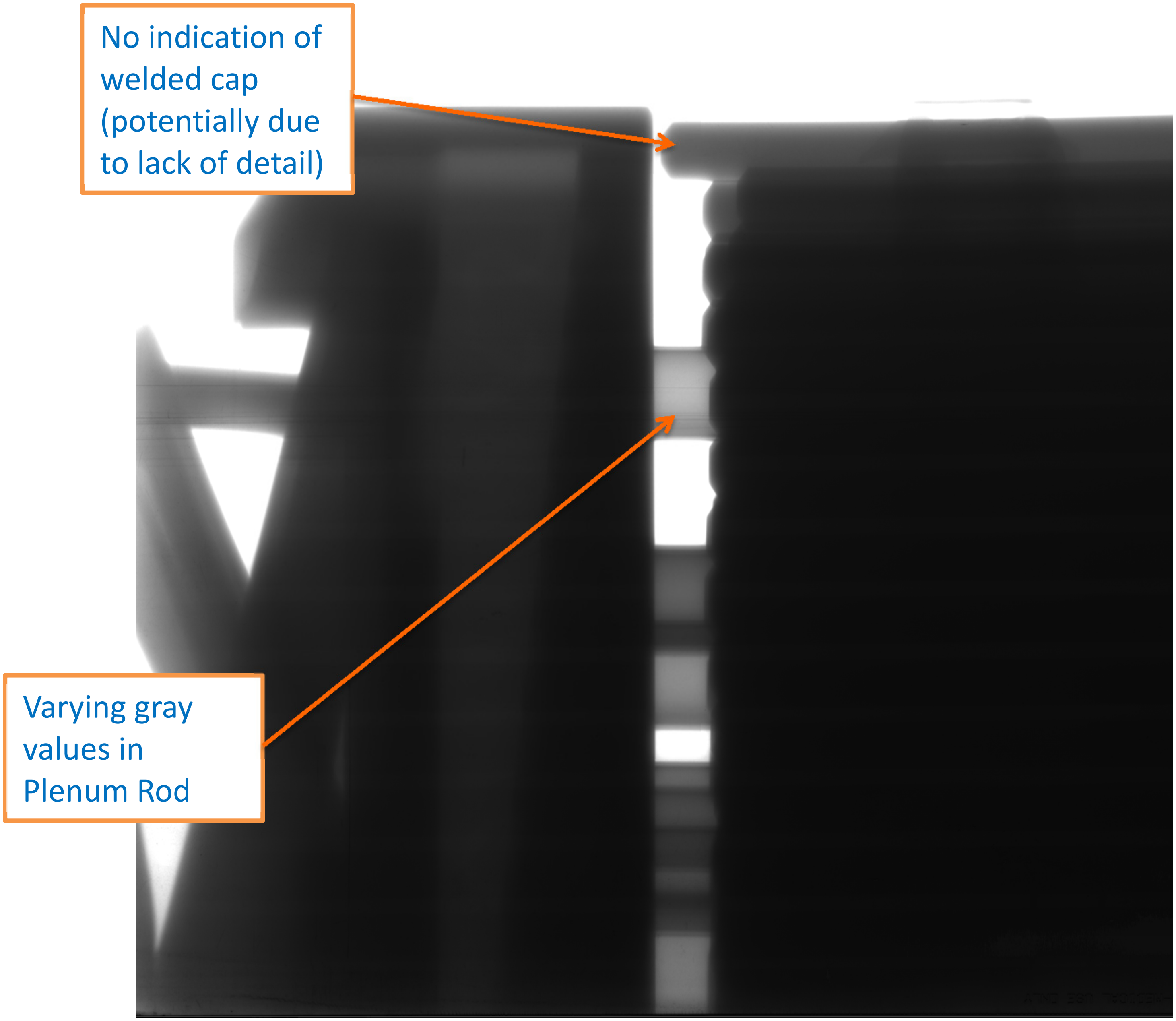

Figure 4.1-5: Additional bottom image of INL dummy fuel assembly showing threads in fuel rods and plenum tubes

5. Results and Conclusions

- A comparison and analysis of the numerical results from *Adkins 2013* and experimental testing results from *Wang 2014* that suggests:

There may be cyclic fatigue concerns associated with transportation of UNF

- Sensitivity studies performed using numerical analysis of Westinghouse 17x17 OFA

The relaxed grid spacer springs present the potential to create the highest strains during NCT.

- Non-destructive examination x-ray work performed on INL 15x15 dummy to determine its adequacy for shaker table tests.

NDE of the INL dummy assembly shows the fuel rods are solid steel rod and this assembly is not suitable for vibration analysis testing.

- A long term vision for developing HCLPF of high burn-up fuel cladding during NCT

Demonstrating HCLPF of high burnup requires coupling of numerical models with experimental testing

Experimental testing coupled with finite element models is needed to develop HCLPF to show fuel cladding can remain intact during NCT and extended storage. Numerical studies are needed to determine the effects that will change fuel rod and fuel assembly response. Experimental tests are needed to build confidence in the numerical models. Once important sensitivities are identified (i.e. those sensitivities that shift high burnup fuel rod response towards the peak response of the input motion) then experimental tests can be performed to determine the effects these sensitivities have on high burnup fuel during NCT (demonstration tests). These demonstration tests can then be used to validate numerical studies and provide a basis for transportation of high burnup UNF during NCT.

6. References

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