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Dynamic Testing Procedures for Performance Assessment of Nuclear Fuel Rods

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DYNAMIC TESTING PROCEDURES FOR PERFORMANCE ASSESSMENT OF NUCLEAR FUEL RODS

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Honors Thesis

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Executive Summary

Existing transportation probabilistic risk assessment for spent nuclear fuel in the United States is based on short-term (decades) on-site storage at power plants before transport. Updated risk assessment estimates will be required as extended on-site storage (centuries) and higher burnup levels in fuel become standard. Nuclear fuel rods under these two conditions are more brittle than rods from short-term storage and intermediate burnup due to several mechanisms, including hydrogen embrittlement. Development of risk assessment requires characterizations of dynamic behavior of these degraded rods under transportation scenarios. This Honors thesis provides an initial literature review for a larger project that will investigate the dynamic response of fuel rods under vibration due to normal transportation only. The literature review covers testing procedures, methods for modeling pellet-cladding interaction, and methods for inducing hydrogen embrittlement in sample fuel rod specimens. Moreover, recommendations are provided for testing procedures for a rod sample on the uniaxial shake table at the University of New Hampshire. Recommendations include the use of acceleration data from truck transportation studies by Magnuson (1977 and 1978) modified to serve as appropriate shake table input. Another recommendation is the construction and use of a specialized "U-frame" for reversal bending fatigue tests on a segment of the sample rod, similar to work done by Wang et al. (2013) at Oak Ridge National Laboratory. The necessities of more transport acceleration data, a greater quantity of sample specimens, and in-depth study of flexural stiffness due to pellet-cladding interaction are outlined in the description of future work.

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Introduction

Transportation of spent nuclear fuel poses potential hazards to public safety due to the potential for criticality accidents. Therefore, probabilistic risk assessment is important to estimate the extent of the hazard for a given transportation plan. Risk assessment is based on probabilistic analyses of many different potential failure modes. Spent fuel is transported by truck or more often by rail in purpose-built transportation casks (Figure 1). These casks protect fuel assemblies from damage during transport and form an additional layer of shielding to contain radiation. Existing probabilistic risk assessment for transportation of spent nuclear fuel rods is based on short-term storage of spent fuel at power plants. Short-term storage for spent fuel from power plants usually occurs on-site in pools which act both to cool the fuel assemblies and to provide some shielding. Increasingly, dry storage casks are being used on-site as pool capacities are reached (United States Nuclear Regulatory Commission, 2014). Dry storage casks provide protection and shielding similar to transportation casks, and some casks are dual-purpose for both dry storage and transportation.

Figure 1: Spent nuclear fuel rail transportation cask (U.S. Department of Energy)

Existing probabilistic risk assessment was created with the expectation that on-site fuel storage of a particular fuel assembly would last for only a few decades. The assembly would then be transported to a long-term repository. Funding for the proposed repository at Yucca Mountain in Nevada ended in 2010, so there are now no official plans for a repository in the United States. The consequence of having no long-term storage facility is that on-site storage must continue until such a facility is constructed. This will significantly increase the demand for on-site storage from decades to centuries, which will become a challenge for nuclear power plants.

The condition of spent fuel during transport after an extended storage interval will not be the same as after short-term storage of only a few decades. Fuel rods in storage are subject to many degradation mechanisms including delayed hydrogen embrittlement, delayed hydride cracking, low temperature creep, and stress corrosion cracking. As a result, the fuel rods are more brittle after extended storage than after short-term storage, so existing transportation risk assessment procedures do not apply to this condition.

Nuclear fuel consists of 8.19 mm diameter uranium dioxide pellets stacked inside a fuel rod. Rods are also referred to as cladding. Fuel rods are made of specialized metal alloys known by commercial names, such as Zircaloy-4 (often abbreviated Zr-4). Rods are 9.50 mm in diameter with a 0.57 mm wall thickness. This leaves an approximate 0.08 mm gap, which is filled with helium (Buongiorno, 2011). Typical fuel assemblies are 4 m long and consist of rods arranged in an array, typically 17x17 rods. Rods are supported at intervals by spacer grids and the fuel assemblies are capped by nozzle assemblies. Grid intervals vary, though many are 21 inches. Some other specifications vary by manufacturer as well. Cladding and pellet dimensions are summarized in Table 1. Illustrations of a typical assembly, a typical rod, and a pellet are shown in Figure 2.

Table 1: Typical PWR fuel cladding and pellet dimensions (adapted from Buongiorno, 2011)

Component	Parameter	Dimension	
Zircaloy-4 Cladding	Outer Diameter	9.50	mm
	Inner Diameter	8.36	mm
	Wall Thickness	0.57	mm
	Length	4.0	m
UO_2 Pellet	Outer Diameter	8.19	mm
-	Radial Clearance	0.08	mm

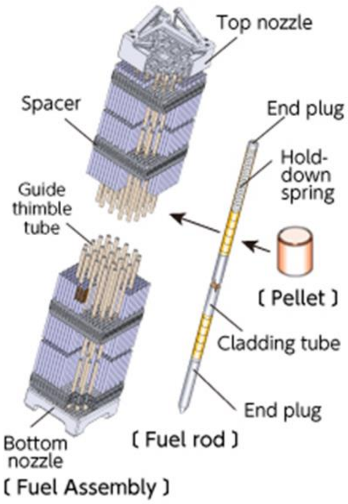

Figure 2: Typical PWR fuel assembly and fuel rod (Mitsubishi Nuclear Fuel Co., Ltd.)

In addition to extended storage, fuels are also being used in reactors for longer periods than originally planned. Spent fuels in this condition is known as *high burnup* (HBU) fuel. HBU fuel rods are more brittle than intermediate burnup rods. High burnup fuel also tends to have a greater mechanical and thermal interaction between the inner surface of the rods and outer surface of the pellets, which affects the mechanical properties of the overall pellet-cladding system. The extent of this interaction has not yet been adequately quantified. Future transportation probabilistic risk assessment must account for this interaction since, unlike existing probabilistic risk assessment, must account for high burnup fuels.

The need for a “technical basis for asserting that aged, high-burnup fuel can withstand normal conditions of transport” is mentioned specifically by McConnell et al. (2103) after describing how safety in the transportation of low burnup fuels after short-term storage has both a technical basis and actual successful shipments to support it. The development of new transportation risk assessment will require characterization of the behavior of degraded high burnup fuel rods under transportation conditions. These include both normal transportation and extreme events such as collisions. In February 2014, a project was awarded funding by the Nuclear Energy University Programs (NEUP) of the U.S. Department of Energy (DOE). One component of this project will require dynamic testing of degraded and non-degraded rod samples. Test results will eventually be used to evaluate the risk of failure of degraded fuel rods during normal conditions of transport after extended storage. This project, *Risk Assessment of Structural Integrity of Transportation Casks after Extended Storage: Aging Effect on the Cask Components Mechanical Performance*, is led by Dr. Luis Ibarra at the University of Utah, Dr. Ricardo Medina at the University of New Hampshire, Dr. Haori Yang at Oregon State University, and Justin Coleman at Idaho National Laboratory. Dr. Medina is the advisor for this Honors thesis.

Scope

This Honors thesis is focused on recommending procedures for the dynamic testing component of the overall project. The most substantial part of this thesis is a literature review for testing methods. This is followed by initial recommendations for testing methods for a sample fuel rod on the uniaxial shake table at the University of New Hampshire. The testing is to be conducted to evaluate performance under normal transport conditions only; extreme events are not considered. The testing is intended to be non-destructive since only one sample rod is available to the research time. The recommendations will include support conditions and loading protocols. Also within the scope is a literature review for methods of modeling the pellet-cladding interaction (PCI), as well as previous work to induce degradation due to hydrogen embrittlement. The first rounds of actual dynamic tests are expected to be performed during Fall 2014, so the testing itself is beyond the scope of this thesis.

Literature Review

Following are literature reviews for works relevant to testing procedures, PCI modeling techniques, and fuel cladding degradation methods that may be considered or adapted for use in the current project.

Testing Procedures

Many of the recent dynamic tests for nuclear fuel components are focused on the fuel assembly as a whole. Klymyshyn et al. (2013) at Pacific Northwest National Laboratory (PNNL) developed a finite element model of a fuel assembly and compared its response to base motion with results from laboratory tests at Sandia National Laboratory (SNL). The assembly was held in a square tubular basket mounted on the shake table using a 60 inch expander plate (Figure 3). This was intended to simulate how the assembly lies horizontally in a transport cask. In these tests, applied acceleration time histories were comprised of 50 components with frequencies from 3 Hz to 600 Hz. These were shock loadings with total durations of about 6.4 seconds. In the laboratory setup the fuel assembly was able to lift off the holding basket during the motion, just as could happen inside a transportation cask. Acceleration responses of the shake table (blue) and the center of gravity of the fuel assembly (red) are presented in the frequency domain (Figures 4 and 5). The team concluded that for frequencies up to 100 Hz, the fuel assembly and shake table have similar acceleration responses because contact is maintained between the fuel assembly and the basket. At higher frequencies the responses are less correlated, potentially due to loss of contact between the fuel assembly and basket. The clearly-defined frequencies in the shake table acceleration correspond to component frequencies used to construct the table motion.

Figure 3: Sandia National Laboratory shaker with expander and basket (McConnell et al., 2013)

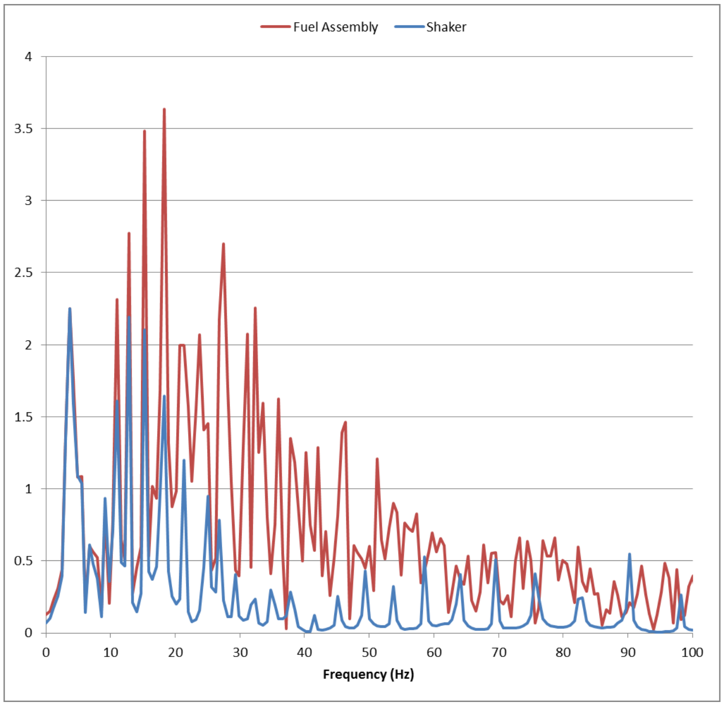

Figure 4: Acceleration spectra, 0-100 Hz, from fuel assembly shake testing (Klymyshyn et al., 2013)

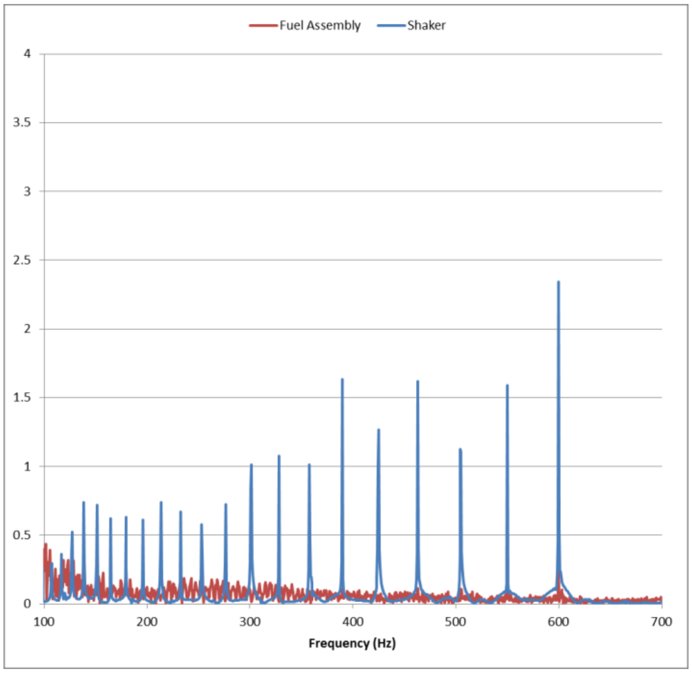

Figure 5: Acceleration spectra, 100-700 Hz, from fuel assembly shake testing (Klymyshyn et al., 2013)

Another finding from the PNNL team that is of importance to the current project is the boundary conditions used in the finite element model. Rod supports at grid spacers were modeled as springs between the shell elements representing the grid spacer and the beam elements representing the cladding (Figure 6). Based on results from static load tests, the team concluded that only varying the stiffness of these springs in their model could not make the model's behavior match the experimental data. Though development of a model is beyond the scope of this thesis, this issue will need to be addressed in the model that is developed for the parent project.

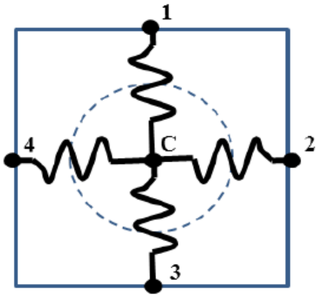

Figure 6: Grid spacer rod support in ANNL finite element model (Klymyshyn et al., 2013)

The report from the laboratory tests for which the PNNL model was developed provides more information about the overall response of the fuel assembly. This study (McConnell et al., 2013) used surrogate copper tubes in a 17x17 array, except in 3 grid locations were Zircaloy-4 rods were used. Copper tubes had thicker side walls than actual fuel rods to match the mass and stiffness (and thus natural frequency) of the Zircaloy-4 rods. Both the copper and Zircaloy-4 rods were filled with lead rods to simulate the mass and stiffness of uranium oxide fuel pellets. Specifications for the copper and lead rods are presented in Table 2. Neither the size of the openings in the spacer grid nor the radial clearance between the rods and spacer grid openings are specified in the report.

Input excitations for the SNL tests were determined from two studies by Magnuson in 1977 and 1978. In these studies, a 22-ton spent fuel transportation cask and a 28-ton cask were each subjected to a 700-mile truck transport journey at speeds varying from 0 to 55 mph. Data was collected from accelerometers attached to the exterior of the casks. Shocks and normal vibration were both of interest. The resulting shock spectra from the two casks are given in Figures 7 and 8. The vibration spectra are given in Tables 3 and 4. As noted by McConnell et al. (2103), most spent fuel will be transported by rail, not truck, so test input should be constructed from rail acceleration data when such data becomes available.

Table 2: Surrogate tube dimensions from Sandia National Laboratory shaker tests (McConnell et al., 2013)

Component	Parameter	Dimension
Copper Tube	Outer Diameter	9.525 mm
	Inner Diameter	7.925 mm
	Wall Thickness	0.8 mm
Lead Rod	Outer Diameter	7.11 mm
-	Radial Clearance	0.41 mm

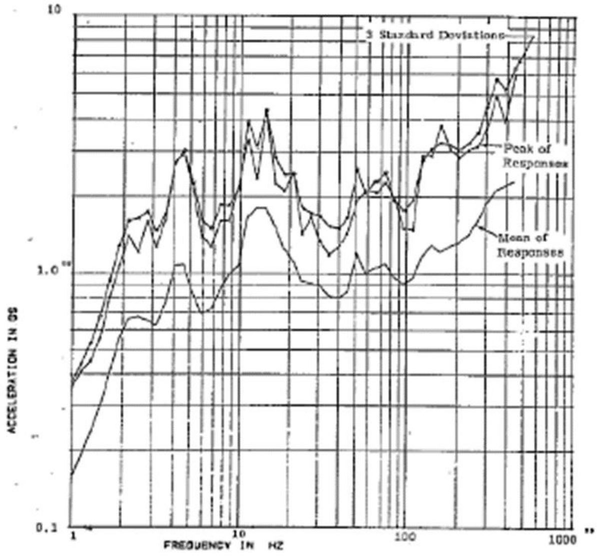

Figure 7: Shock spectrum for 22-ton spent fuel transportation cask (Magnuson, 1977)

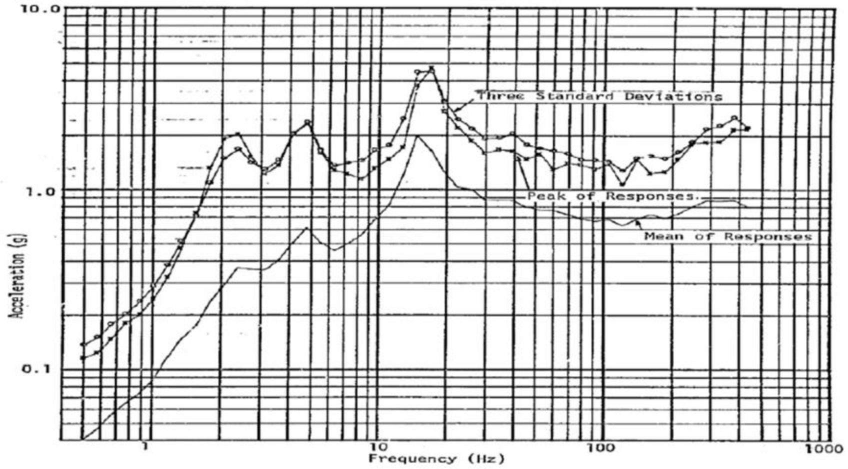

Figure 8: Shock spectrum for 28-ton spent fuel transportation cask (Magnuson, 1978)

Table 3: Vibration data from 22-ton spent fuel transportation cask (Magnuson, 1977)

	Input to Cargo (g)		
	99% Level of 0 to Peak Amplitude		
Fequency Band Hz	Longitudinal Axis	Transverse Axis	Vertical Axis
0 - 5	0.14	0.14	0.27
5 - 10	0.19	0.19	0.19
10 - 20	0.27	0.27	0.27
20 - 40	0.10	0.27	0.27
40 - 80	0.14	0.14	0.52
80 - 120	0.07	0.10	0.52
120 - 180	0.07	0.10	0.52
180 - 240	0.05	0.10	0.52
240 - 350	0.05	0.10	0.52
350 - 500	0.05	0.05	0.14
500 - 700	0.04	0.04	0.07
700 - 1000	0.03	0.07	0.07
1000 - 1400	0.01	0.04	0.05
1400 - 1900	0.01	0.05	0.05

Table 4: Vibration data from 28-ton spent fuel transportation cask (Magnuson, 1978)

	Input to Cargo (g)		
	99% Level of Zero-to-Peak Amplitude		
Fequency Band Hz	Longitudinal Axis	Transverse Axis	Vertical Axis
0 - 5	0.27	0.10	0.52
5 - 10	0.14	0.07	0.27
10 - 20	0.19	0.19	0.37
20 - 40	0.10	0.07	0.19
40 - 80	0.10	0.10	0.37
80 - 120	0.07	0.10	0.37
120 - 180	0.07	0.10	0.52
180 - 240	0.05	0.10	0.52
240 - 350	0.07	0.14	0.52
350 - 500	0.05	0.07	0.37
500 - 700	0.05	0.02	0.10
700 - 1000	0.05	0.02	0.10
1000 - 1400	0.14	0.05	0.10
1400 - 1900	0.03	0.02	0.10

Input from shock data will not be used for the current project, but may be important for future work. The input from random vibration data used for the SNL most relevant to the current project. The report for that project explains how the input is derived for the vertical direction, since that is the direction with the greatest accelerations for both cask sizes. The team used both sets of data from Magnuson (1977 and 1978) to envelope the input since cask weights vary. Magnuson's data was converted from *99% level of 0 to peak amplitude* (*ZPA*) to Acceleration Spectral Densities (ASDs) by the following equation, where each *FR* is a bound of the particular frequency bandwidth:

$$\boldsymbol{ASD} = (\boldsymbol{ZPA} + \mathbf{3})^{\mathbf{2}} + (\boldsymbol{FR}(\mathbf{2}) - \boldsymbol{FR}(\mathbf{1})) \qquad \textbf{(Eq 1)}$$

The team then introduced "ramps" to the resulting ASDs because shaker control systems cannot replicate shaker stepped spectra. The acceleration spectral densities for each of Magnuson's two data sets (green and blue) and the SNL team's input (red) are presented in Figure 9. Breakpoints in the input are given in Table 5.

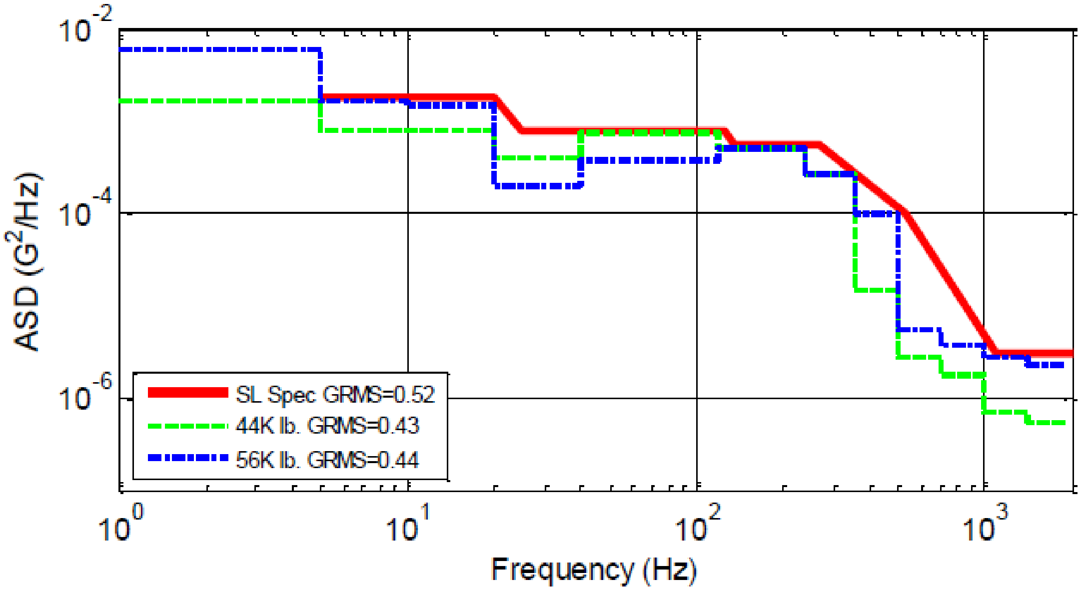

Figure 9: Random vibration test input ASD (McConnell, et al., 2103)

Table 5: Breakpoints in random vibration test input (McConnell, et al., 2103)

Fequency Hz	**ASD** (G^2/Hz)
5	0.27
20	0.14
25	0.19
125	0.10
135	0.10
265	0.07
530	0.07
1100	0.05
2000	0.07

An important issue discovered during the shaker tests at SNL was localized mechanical wear on rods due to the grid spacers. This occurred in the actual Zircaloy rods, not just the copper surrogates. It is possible that localized wear could potentially cause fuel rod failure before excessive strains from shock or fatigue due to bending under random vibration cause failure. The shaker tests were only run for durations of approximately one minute, while a transportation event would often consist of tens of hours of travel time during which wear could occur.

The SNL tests used three accelerometers on the shake table at center and extreme points of fixity between the table and the fuel assembly. Rods of interest were instrumented with strain gauges and accelerometers at midspan between spacer grid locations and accelerometers only at the spacer grids. This arrangement of accelerometers provides a record of the actual input from the table to the assembly, the input to the rods as transmitted by the spacer grids, and the response of the rods. The strain gauge location at midspan is one of the most likely locations for yielding to occur in the rods, another being the support locations.

A team at Oak Ridge National Laboratory (ORNL) (Wang, Wang, Bevard, Howard, & Flanagan, 2103) developed a U-shaped frame that allows for the testing of rods under reversal bending. Their purpose is to perform fatigue tests on stainless steel surrogate fuel rods and eventually actual

Zircaloy-4 rods. The frame consists of two 152.4 mm rigid stainless steel arms connected by stainless steel linkage (Figure 10). Aligned with the hinge points on each arm are holes into which the ends of the sample rod are press-fit. Teflon layers (visible as white bands around the sample in the image) are used as lining in the holes to prevent local damage to the rod specimens. Applying force at the arm ends to open or close the frame results in pure moment in the gage section of the sample. In their setup, the specimen is six inches long with two inches at each end press-fit into the holes, leaving a two-inch gauge section.

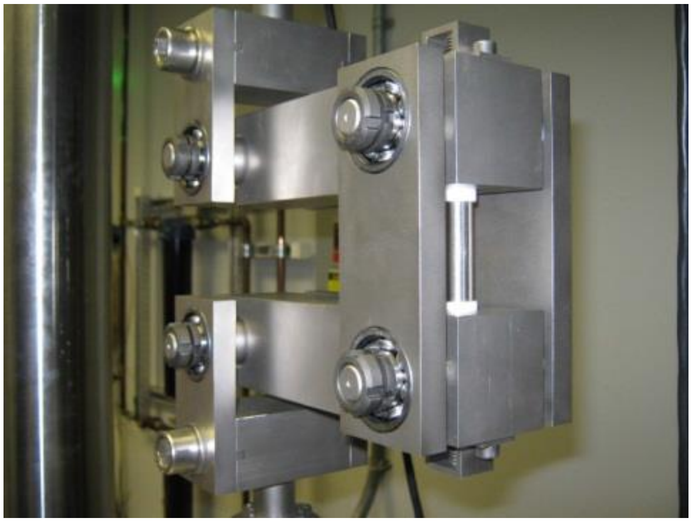

Figure 10: Reversal bending U-frame at ORNL (Wang, Wang, Bevard, Howard, & Flanagan, 2103)

The team's initial tests on surrogate stainless steel rods involved cycling samples through reversal bending at 2 Hz. The servo-hydraulic load frame used to apply the bending to the U-frame was run in displacement-control mode (±3 mm) and load-control mode (±100 N, ±200 N, and ±300 N) for different samples. Sample curvature was determined through measurements taken from three linear variable differential transformers (LVDTs) attached to the sample such they each recorded lateral translation of the rod. One LVDT was attached at midspan on the specimen while the other two were placed symmetrically toward either end of the gauge section of the specimen. After cycling to each power of ten cycles (10^1, 10^2, 10^3, etc.) a quasi-static bending test was performed to measure the flexural rigidity of the rod. This test procedure is summarized in Figure 11, which is reproduced from their report. The decrease in flexural rigidity of one sample from its initial state at $N = 1$ cycle to failure at $N \approx 4.5 * 10^4$ cycles is shown in Figure 12. Data from these tests could be used to develop a hysteretic model for fuel rods, which could be used to predict rod integrity for transport events of different durations. For further reading on types of hysteretic models, see *Hysteretic Models that Incorporate Strength and Stiffness Deterioration* (Ibarra, Medina, & Krawinkler, 2005).

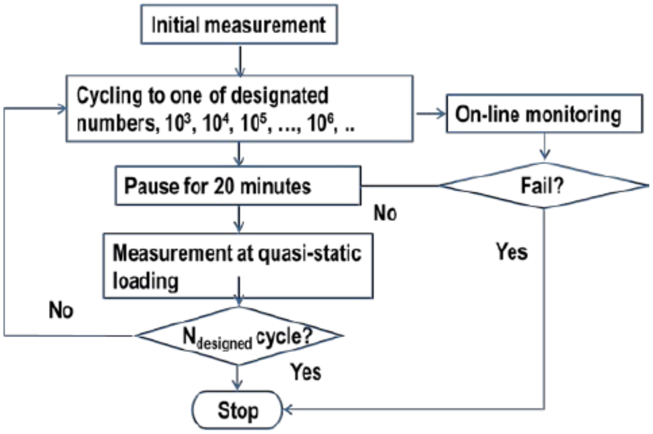

Figure 11: Procedure for ORNL reversal bending tests (Wang, Wang, Bevard, Howard, & Flanagan, 2103)

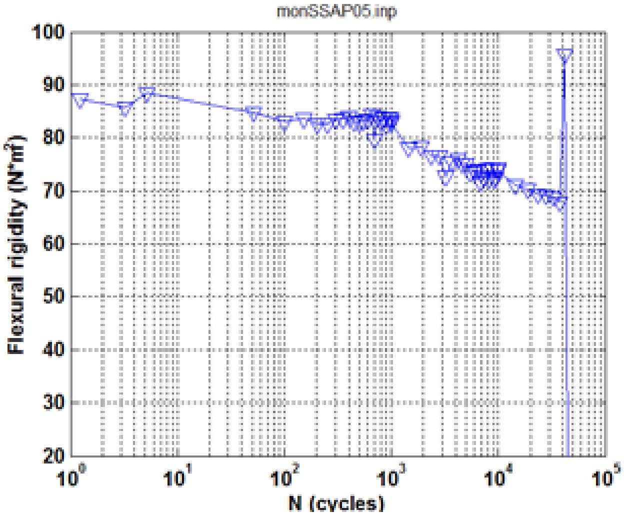

Figure 12: Flexural rigidity decrease in one sample during ORNL reversal bending tests (Wang et al., 2013)

For shake table testing of an individual rod, the support conditions are important to obtain a reasonable simulation of truck transport conditions for individual rods. A study on buckling of fuel rods under impact (Bjorkman, 2010) modeled the spacer grid supports as rollers for the purpose of analysis. This model is for analysis of buckling due to impact loading, not transverse support motion, but this supports the notion that spacer grids do not provide significant rotational restraint at the rod locations they support. This is somewhat consistent with the finite element model constructed by Klymyshyn et al. (2013) which provided only translational restraint at the spacer grid. The Bjorkman paper is actually intended to show that the weight of fuel pellets must be considered in buckling analysis. The paper derives the theory for a critical inertial load for buckling but does not report any experimental results.

Pellet-Cladding Interaction (PCI)

One of the most significant effects of the high burnup condition on a fuel rod is an increase in the degree of PCI. Daum (2007) presents transverse micrographs from Argonne National Laboratory that illustrate this condition (Figure 13). The left side of Figure 13 shows a defined gap (black) between the fuel (dark gray) and Zircaloy-4 cladding (light gray) in an intermediate burnup condition. The right side shows a bond between the fuel and cladding in the high burnup condition. Both micrographs were taken at room temperature.

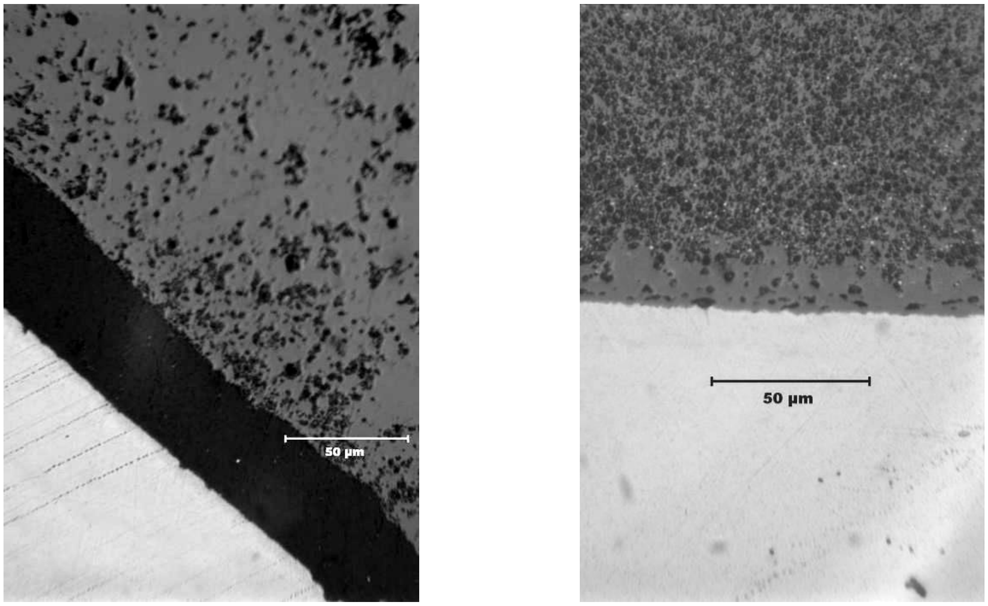

Figure 13: Pellet-cladding gap in intermediate burnup fuel (left) and bond in high burnup fuel (right) (Daum, 2007)

Daum refers to Retel et al. (2004) for quantification of this interaction. Six parameters were considered in that study, including the coefficient of friction between the pellets and cladding as well as the amount of cracking in the pellets, which also increases in the high burnup condition. The team determined a "reasonable extreme" of 0.8 for the pellet-cladding coefficient of friction. They concluded that the most important parameters relating to the stresses in the cladding are pellet fragmentation and the opening of radial cracks in the pellets during the life of the fuel rod. The study was conducted using variation of parameters and a fuel rod behavior code known as *CYRANO3* rather than experimental data. The results were validated using a different code known as *Code_Aster*. Jernkvist (1995) considered pellet-cladding friction coefficients in excess of 1.00 when modeling PCI-induced rod failure due to power ramping in-service. However, this occurs at high temperatures and is likely not the same as what would be found after rods have cooled to storage temperatures. Ranjan and Smith (1980) also investigated cladding stresses due to PCI but did not determine a practical value for the maximum friction coefficient.

Several methods have been used to simulate PCI during experimental testing of fuel rods. Wang et al. (2103) at Oak Ridge National Laboratory used three conditions when evaluating the flexural rigidity of the cladding-pellet system for use in reversal bending tests. In all three cases the dummy fuel rods were stainless steel, not Zircaloy. The first condition was a control specimen consisting of an empty rod. The second condition was a rod filled with aluminum oxide pellets to model the geometry and approximate mass of fresh fuel pellets. The third condition was a rod filled entirely with epoxy to model the PCI in spent fuel. The study found that despite the lower stiffness of epoxy compared to aluminum oxide, the overall system was stiffer with the epoxy due the bond. The rod samples were subjected to quasi-static cyclic loading, so the mass of the pellets was not critical. For dynamic testing the epoxy alone would not accurately model the inertial mass of the fuel or simulate cracking in the pellets.

Recent dynamic tests have largely ignored the issue of PCI. McConnell et al. (2103) considered the use of solid molybdenum rods to model fuel in a shaker test of an entire surrogate fuel assembly. However, they determined that it would be cost-prohibitive to implement this approach for the entire 17x17 array of 4-meter rods. Thus, PCI was disregarded for the test, though lead rods were used to simulate the mass. Finite element modeling performed at PNNL for the SNL tests (Klymyshyn et al., 2013) did not physically model any PCI. The SNL team did consider an assumed 10 percent increase in stiffness due to PCI. Their report extensively evaluates the effects of the interaction between the cladding and the spacer grid, but acknowledges that PCI may have an even greater effect on the dynamic behavior of the fuel assembly.

Degradation Methods

Hydrogen embrittlement of fuel rods is caused by the formation of radial, longitudinal, and tangential hydride crystals in the cladding. As explained in a report from Argonne National

Laboratory (ANL) on embrittlement in high burnup PWR assemblies (Billone, Burtseva, Han, & Liu, 2013), radial hydrides the precipitate during cooling of the fuel rods are of the greatest concern to the structural integrity of the rods. The report first summarizes previous work at ANL on as-irradiated fuel rods. Before storage, most hydrides present in the rods are oriented transverse (tangential) or longitudinal to the rod, not radial (Figure 14). The as-irradiated rods are subjected to a “radial-hydride treatment” (RHT) which induces precipitation of radial hydrides by simulating the temperatures and hoop stresses associated with storage. This results in the formation of radial hydrides in addition to the existing hydrides in other orientations (Figure 15). The team used a peak temperature of 400 °C for RHT on all six of their Zircaloy samples with peak hoop stresses of 140 MPa on two of the samples and 110 MPa on four of the samples.

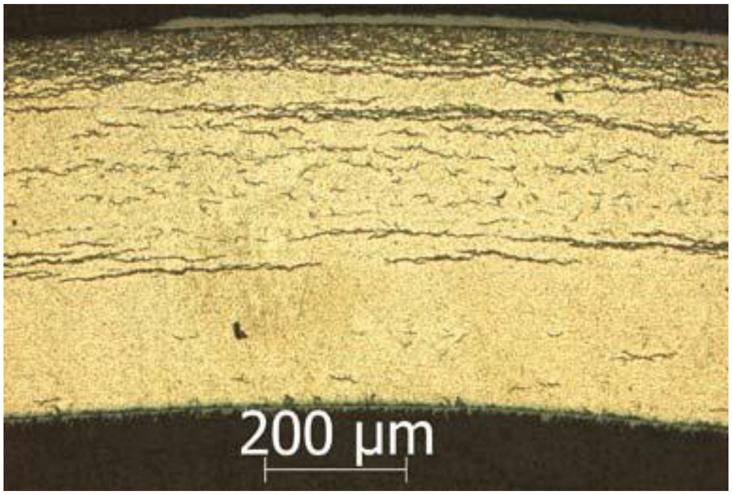

Figure 14: As-irradiated Zr-4 cladding transverse hydrides (Billone, Burtseva, Han, & Liu, 2013)

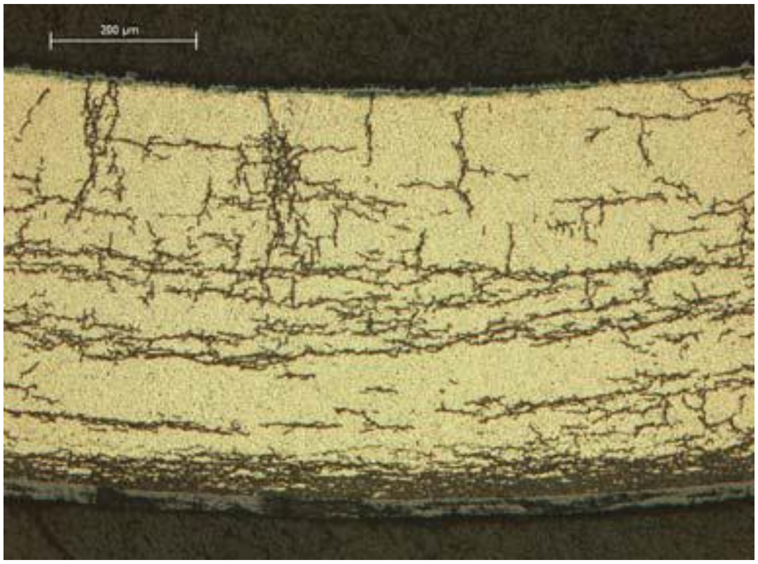

Figure 15: Zr-4 cladding with radial hydrides (Billone, Burtseva, Han, & Liu, 2013)

Daum (2007) used hydrogen charging processes to induce formation of transverse and longitudinal hydrides. Formation of radial hydrides was intentionally avoided by conducting the procedures under stress-free conditions. One of the processes is proprietary to Nuclear Development Corporation of Japan and was conducted by that corporation. That process produced hydrides in a rim near the outer surface of the rod. The other hydrogen-charging process was performed at ANL and produces a uniform distribution of hydrides from the inner to outer surfaces of the cladding. A schematic of this latter process, which uses a three-zone furnace and an applied 30% hydrogen-70% helium gas mixture, is shown in Figure 16.

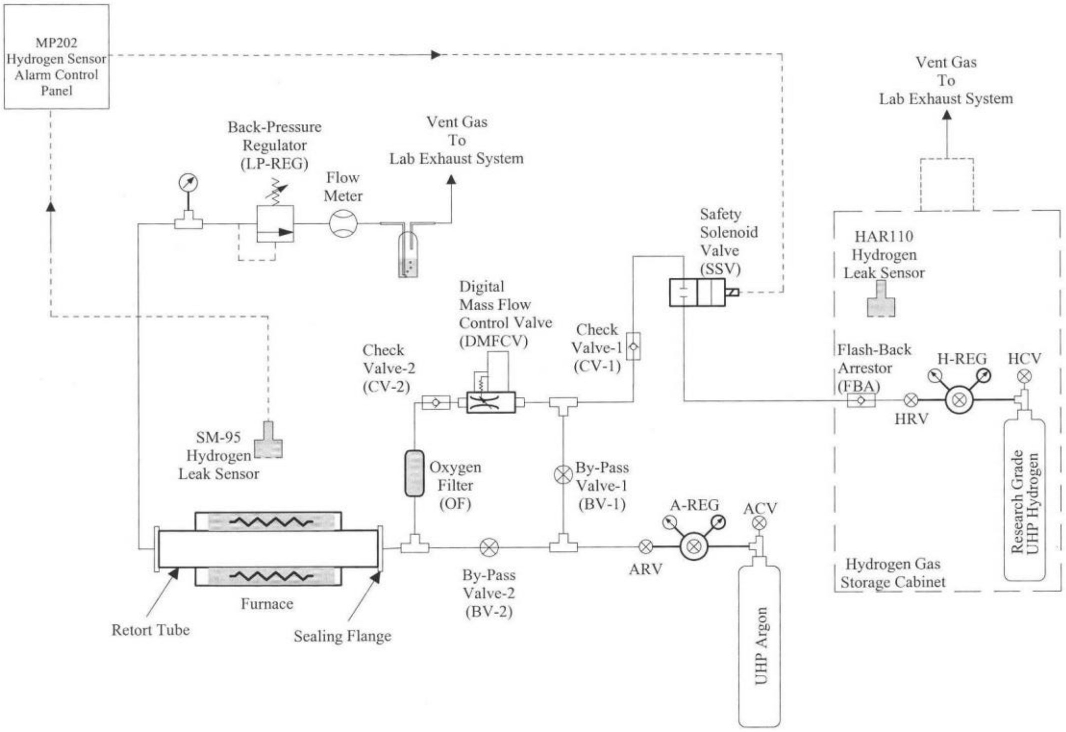

Figure 16: Schematic of the hydrogen charging furnace system at Argonne National Laboratory (Daum, 2007)

Apparatus and Samples

The available sample in this research is a single 68-inch section of a Zircaloy-4 rod. The sample contains surrogate fuel pellets made of steel. A preliminary decision has been made to cut this sample into three 21-inch sections. This sample length corresponds to the length between typical spacer grids in a fuel assembly. This will leave an additional five-inch section less the kerf widths from the cuts.

The testing apparatus is a seismic shake table located in Kingsbury Hall at the University of New Hampshire (UNH) in Durham, New Hampshire. The shake table is pictured in Figure 17 supporting a shear building model. This table is capable of uniaxial shaking at frequencies up to 100 Hz, but experience has determined a practical operating limit of 20 Hz.

In addition to shaking structures and samples mounted on the table itself, it is also possible to use the table to drive additional testing apparatus secured nearby if adequate connecting linkages are fabricated. An example of such an apparatus would be a reversal bending frame similar to that described by Wang et al. (2103). Load frames of various sizes are also available for use in the same facility as the shake table.

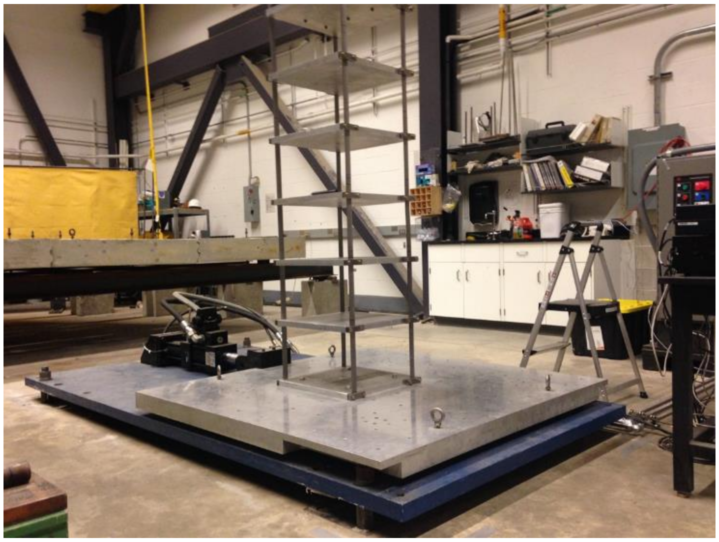

Figure 17: Uniaxial shake table at the University of New Hampshire

Recommendations

Prior to cutting the 68-inch rod into shorter samples, preliminary testing should be performed to characterize the behavior of the rod in its initial state. The rod should be subjected to transverse quasi-static loading in a load frame with simple support conditions in order to determine its stiffness. A U-frame for bending the full-length specimen in pure moment would be preferable to this arrangement, but cost and effort for construction of a U-frame would be disproportionate to its importance in the project. The rod is slender enough (with a slenderness ratio on the order of 300) that shear effects may be ignored, making this a reasonable method for determining the approximate bending stiffness. This may be used to calibrate the computer model of the rod. If the chosen PCI modeling system is removable, such as steel pellets, it can be put in place and the quasi-static load case repeated, then removed before degradation is induced if that process will damage the . The results of this test will allow for better calibration of the pellet-cladding computer model. Experimental data can also be used to quantify the change in stiffness due to PCI modeling and potentially provide verification of estimated values. A calibrated computer model is important for predicting whether intended further tests will be destructive and will provide much needed information to finalize the design of additional experiments.

Before testing of cut segments begins, two of the three 21 inch rod samples should be subjected to the chosen process for inducing degradation. This will provide redundancy in the event that the degradation is unsuccessful or excessive in one of the samples. The other 21-inch sample should not be degraded because it will serve as a control case. All 21-inch samples should be used for shake table testing because their lengths correspond to the distance between grid spacers (supports) in a fuel assembly. The remaining section of rod, which will be 5 inches less the kerfs from the three cuts, is more appropriate for use in a reversal bending frame because of its short length. The testing plan following initial full-length specimen tests is summarized in Figure 18.

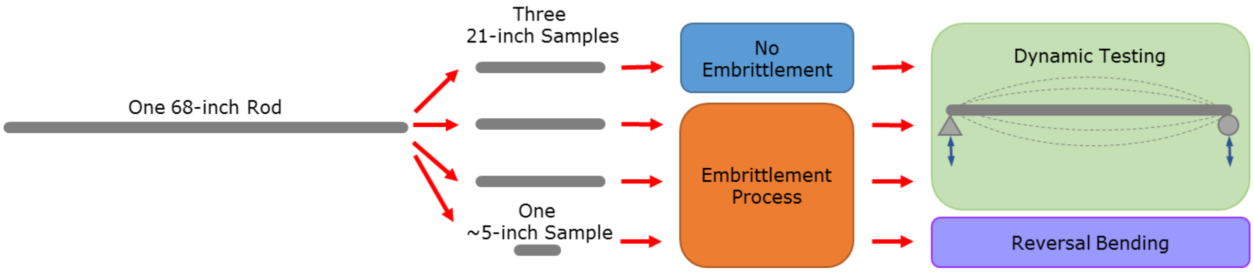

Figure 18: Testing plan for samples cut from one fuel rod

Dynamic Testing

For dynamic testing, supports must be constructed and affixed to the shake table in such a way that the fuel rods are supported in a similar fashion to how they are supported in a fuel assembly lying flat for transport. Supports will have to be stiffer than spacer grid openings to offset the decrease in boundary stiffness caused by having a single rod span rather than a continuous rod with multiple spans. The choice of PCI modeling method will also be critical because both the mass and stiffness of the pellet-cladding system affect the dynamic response; both properties influence the natural period of vibration. The mass of any strain gauges or accelerometers attached to the rod cannot be avoided.

Vertical displacement is of interest because vertical transit accelerations are the greatest in magnitude among accelerations recorded during normal transport conditions in the three orientations according to both data sets from Magnuson (1977 and 1978). In order to use the uniaxial shake table to model vertical transport excitation, the setup must be placed such that the rod samples are lying horizontally and perpendicular to the direction of motion. The disadvantage of this setup is that gravity is not parallel to the excitation. Contributions of gravity to stress in the rods should be accounted for at locations of peak displacement in the response to determine whether the total stress would cause yielding or failure.

The acceleration data from Magnuson's studies are the most relevant currently available for nuclear fuel transport. The conversion by McConnell et al. of these data to ASD therefore provides the most relevant input. However, much of the spectrum is beyond the 100 Hz maximum limit of the UNH shake table. Because of this limitation, the input must be capped at a maximum frequency of 100 Hz. One of the findings of the simulations at PNNL (Klymyshyn et al., 2013) is that for frequencies up to 100 Hz the accelerations at spacer grid points closely match shake table accelerations, so the input will not require modification to account for how it is propagated through the spacer grid in a real fuel assembly. Accelerations at the unsupported ends of the fuel assembly during the SNL tests are not relevant to the current project because in transport an assembly would be supported along its entire length rather than only 60 inches at mid span. Moreover, since the behavior over an entire transport scenario is of interest, the tests for each sample should have a total duration of at least several hours (transport may require tens of hours) rather than just one minute as in the SNL shaker test. The length of the time frame for this testing will be primarily dictated by the duty cycle of the shake table.

The test segment should be instrumented with an accelerometer at midspan and on each end at the supports. Accelerometers should also be placed on the table at locations where rod supports are affixed. The most important accelerometers are those on the rod itself for comparison of input at the rod ends with the response of the rod midspan. The table accelerometers may be used to show how table input is propagated to the rod supports, but this is less critical since the supports are artificial rather than actual spacer grids. The rod should also be instrumented with a strain gauge at midspan. If available, additional strain gauges should be placed on the rod immediately adjacent to supports. This is important because the supports will supply some rotational restraint which could cause yielding at the rod ends. Initial testing on the full 68-inch rod should also use this instrumentation arrangement.

Before any test input is used in the laboratory, it should be applied to a finite element model of the sample to check structural behavior and whether failure is to be expected. This model should include information about the change in the properties of the system with fatigue as determine from reversal bending tests, which is described next.

Reversal Bending

The five-inch sample is similar in length to the six-inch samples used by Wang et al. at ORNL for reversal bending tests, so a reversal bending U-frame of similar size and construction is appropriate. Holes for sample ends must be 1.5 inches deep instead of 2 inches to leave a two-inch gauge length. This frame should ideally be mounted horizontally to avoid gravity effects as in the original reversal bending study. However, none of the load frames at UNH are oriented horizontally, so a vertical orientation may be necessary. The drawbacks of adding this additional testing to the shake table tests are the increased fabrication cost, increased testing time, and an overall increase in the complexity of the project. The advantage is that results could potentially be compared to those from another study to evaluate the accuracy of the induced degradation for modeling real degradation. Also, this test prevents any segments of the original 68-inch sample rod from going to waste. The sample should be instrumented with three transverse LVDTs to measure curvature as in the ORNL study so comparison will be possible.

Many types of input are possible for the reversal bending system, including quasi-static and dynamic versions of monotonic and cyclic loading protocols. Examples of these with descriptions and example time histories are presented in Figure 19. Since normal transport is of interest and not extreme events such as collisions, monotonic dynamic loading (impact) is not appropriate. Since dynamic tests are already to be performed on the 21-inch segments, cyclic dynamic loading is unnecessary for this sample. What can be gained from reversal bending is quantification of the stiffness provided by the PCI modeling method. Like the ORNL reversal bending study, a monotonic quasi-static load could be applied to measure the flexural rigidity of the system, but unlike that study it will not be repeated after cycling because failure of samples is not desired in this study. Although it might be preferable to bend the rod to a curvature equal to the maximum curvature expected in the dynamic response due to transport, using the same loading conditions as the ORNL study would allow comparison to results from the first quasi-static tests from that study, before cycling loads on each sample. The ORNL study aims to next use the U-frame in a hot cell on real fuel rods. When their results are published they could provide verification that the degradation process used for the current project produces appropriate flexural rigidity..

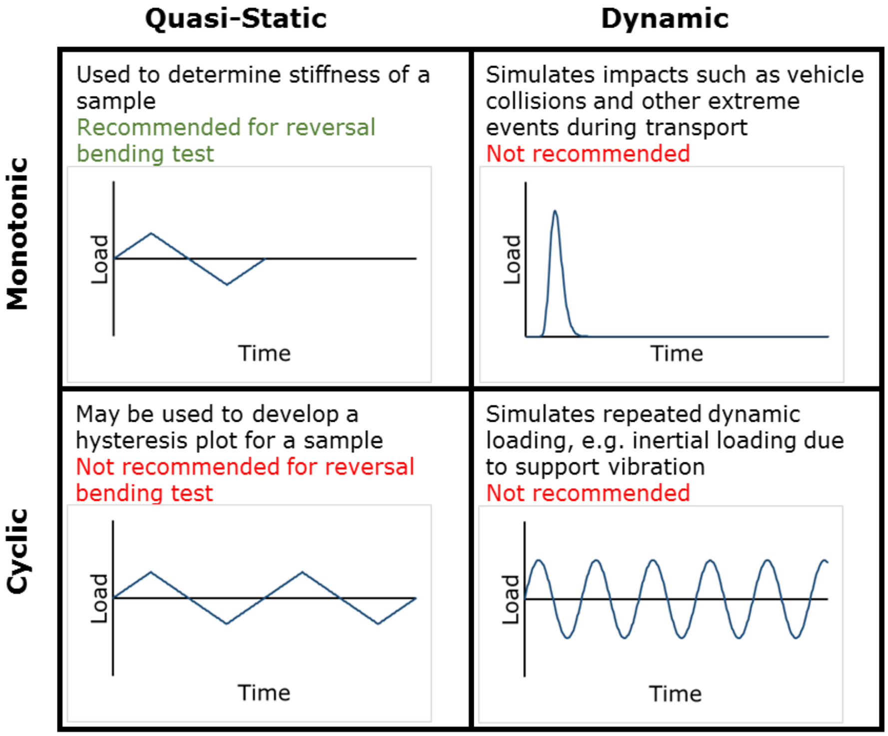

Figure 19: Possible test methods with typical load plots

Future Work

The next step in the current project will be to construct a finite element model of the sample rod and construct testing apparatus including supports for the full-length specimen and the reversal bending U-frame. Initial testing will then be performed on the full-length specimen and repeated with the PCI modeling system - if possible at that time. Test segments will then be cut from the original sample and utilized as set forth in the recommended test procedures.

For future testing, the most important improvement would be the use of acceleration data from rail transport to develop a loading protocol. Two-dimensional shake capabilities would also improve the testing by allowing investigation of biaxial bending responses under accelerations from both the vertical and transverse orientations relative to transport position. A shake table with a higher maximum operating frequency, such as 2000 Hz, would allow for application of higher frequencies in the input spectrum to more accurately simulate transportation conditions. A greater quantity of specimens would improve the validity of all test results.

Future studies should investigate in detail specific local effects such as mechanical wear in the cladding at the spacer grid as potential failure methods. A study to provide more precise quantification of PCI would allow for a more realistic model to be used in future laboratory tests. This additional work is necessary to accurately characterize the behavior of high burnup fuel during transport after extended storage, which will in turn allow for appropriate transportation risk assessment to be developed.

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