Proceedings of the 18th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 6015

Regulatory Perspective on Transportation of High Burnup Spent Fuel

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Abstract

To successfully certify high burnup (i.e., >45 GWD/MTU) spent fuel (HBF) for transportation, information that demonstrates reasonable assurance in complying with the regulatory requirements of Part 71 in Title 10 of the Code of Federal Regulations (10 CFR Part 71) is required. HBF is susceptible to hydride reorientation which may occur due to elevated cladding temperature during loading, draining, and drying and subsequent cooling during transport. The hydrides reorienting and precipitating from circumferential to radial directions could affect the fuel cladding mechanical properties.

On March 5, 2015, the NRC issued a draft Regulatory Issue Summary (RIS), "Considerations in Licensing High Burnup Spent Fuel in Dry Storage and Transportation." As part of the RIS, potential licensing approaches were provided for certifying the transportation of HBF. These approaches consider certifying transportation packages where fuel is being shipped from a spent fuel pool, from a dry storage cask, or placed in damaged fuel cans prior to shipping. To develop these approaches, the U.S. Nuclear Regulatory Commission (NRC) is working with Oak Ridge National Laboratory and Argonne National Laboratory to obtain data on HBF cladding behavior through vibration tests and bend tests. The NRC staff has also completed the first phase of its research with Oak Ridge National Laboratory that provides data related to the behavior of HBF in transportation. NUREG/CR-7198, "Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications," published in May 2015 (ADAMS Accession No. ML15139A389) provides a benchmarking of the behavior of HBF without hydride reorientation. NUREG/CR-7203, "A Quantitative Impact Assessment of Hypothetical Spent Fuel Reconfiguration in Spent Fuel Storage Casks and Transportation Packages," published in September 2015 (ADAMS Accession No. ML15266A413), provides a conservative consequence analysis assuming a full range of fuel failure. This paper describes the various technical approaches in certifying transportation packages for HBF.

Introduction

This report discusses the formation and effects of radial hydrides on the transportation of high burnup spent nuclear fuel. Nuclear fuel is now regularly irradiated to high-burnup values (> 45 GWd/MTU).

Several phenomena have been identified, such as hydride reorientation [1, 2, 3, and 4], that could affect HBF cladding behaviour under normal and accident conditions of transportation. This paper provides a perspective on the licensing challenges posed by radial hydrides in high burnup spent fuel cladding and possible licensing approaches to address these challenges to meet the requirements in 10 CFR Part 71. These licensing approaches have been developed considering data provided by Oak Ridge National Laboratory and Argonne National Laboratory.

Radial Hydride Formation and Ductile-to-Brittle Transition Temperature

While in the reactor, the spent fuel cladding absorbs hydrogen which precipitates primarily in the circumferential direction. After cooling in the spent fuel pool, and prior to being transported, it is likely that the fuel is removed from the spent fuel pool and stored in dry storage casks meeting the requirements of 10 CFR Part 72 . As part of the preparation for dry storage, the fuel undergoes vacuum drying in temperatures that may reach as high as 400°C. Depending on the fuel cladding type, these temperatures can cause some of the hydrogen to dissolve into the cladding. The amount of circumferential hydrides which go into solution depends on the temperature and increases according to the solubility curve of the material [5, 6, and 7]. As the fuel cools, temperature and stress conditions (hoop stress and end-of-life cladding stress) may result in some of the dissolved hydrogen to re-precipitate in the radial direction.

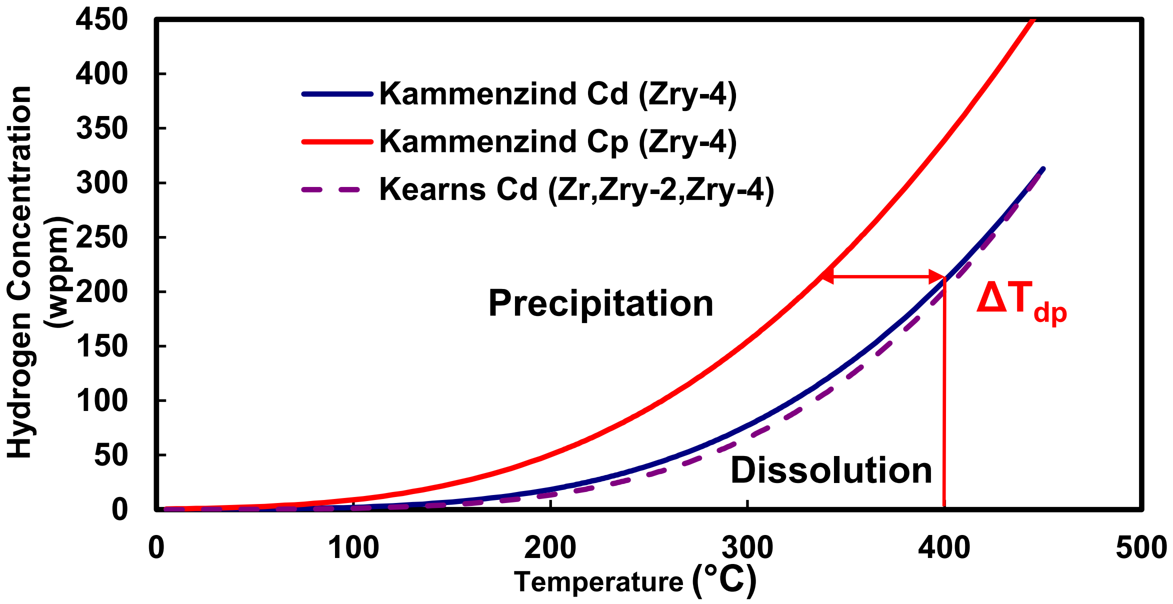

Figure 1. Dissolution and precipitation curves based on the data of Kammenzind et al. [5] for non-irradiated Zry-4. Also shown is the best fit to the dissolution data for Zr, Zry-2, and Zry-4, which includes the Zry-2 and Zry-4 data generated by Kearns [6].

Radial hydride precipitation varies between cladding types, where it is low for Zry-4, moderate for ZIRLO, and high for M5. The extent of precipitation depends on the stress acting on the cladding, the hydrogen content (including the presence of non-dissolved hydrides) in the cladding, and the cooling rate during hydride precipitation. One way to characterize the degree and severity of radial hydride precipitation is to identify the radial hydride continuity factor (RHCF). The RHCF represents the effective radial length of continuous radial-circumferential hydrides normalized to the wall thickness. [8]

The presence of radial hydrides of sufficient length, number density, and axial connectivity (a high RHCF) can degrade the mechanical behaviour of the fuel-rod cladding if the rods are subjected to stresses higher than the fuel's mechanical limit, especially at temperatures below the ductile-to-brittle transition temperature (DBTT). The DBTT also varies between cladding types and is also affected by the hydrogen content. Cladding types with lower hydrogen content have lower ductility as all the hydrides can more readily reorient. Higher hydrogen content may inhibit the reorientation process [8]. Hydride reorientation also results in a shift of the cladding DBTT to a higher value [9].

Regulatory Challenges Associated with Transportation of Spent Fuel with Hydride-Reoriented Cladding

As part of successfully certifying a transportation package, criticality, containment, thermal, and shielding safety evaluations must demonstrate, with reasonable assurance, adherence to the requirements of 10 CFR Part 71. These technical disciplines rely on a successful structural and materials evaluation to determine any potential fuel reconfigurations of fuel assemblies resulting from the inertia loads exerted on the fuel rods during the normal and hypothetical accident conditions of transport. Therefore, knowledge of mechanical properties that account for the effect of radial hydrides, including the extent of radial hydride precipitation and the ductile-to-brittle transition temperature, is required to determine any potential fuel configurations of fuel assemblies.

The effects of hydride reorientation should be considered for compliance with different parts in 10 CFR Part 71 which are related to the state of the package contents. An accurate description of the chemical and physical form of the package contents is one of the enforceable conditions of a Certificate of Compliance and is also required by 10 CFR 71.33(b)(c). There are also several regulations related to the state of the package contents after normal conditions of transportation and hypothetical accident conditions. 10 CFR 71.55(d)(2) specifies that during normal conditions of transport, the geometric form of content cannot be substantially altered. For normal conditions of transport, requirements include vibration testing as specified in 10 CFR 71.71(c)(5) and the 1-ft free drop specified in 10 CFR 71.71(c)(7). 10 CFR 71.55(e)(1) specifies that after hypothetical accident conditions, the package must be subcritical assuming the fissile material is in the most reactive credible configuration. Of the hypothetical accident condition tests, 10 CFR 71.73(c)(1) specifies a 9 m (30 ft.) free drop which is the most bounding when considering any potential change of the fuel configuration for HBF.

NRC-Sponsored Data

NUREG/CR-7198, "Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications [10]"

This testing confirmed the ability of HBF, in an as-irradiated state, to maintain its integrity under normal conditions of transport. To complete this testing, Oak Ridge National Laboratory developed a bending fatigue system (Figure 2, below) which imposed pure bending loads on the HBF fuel rod and measured the resulting curvature during bending. Known as the "Cyclic Integrated Reversible-bending Fatigue Testing (CIRFT)," four static bend tests and sixteen vibration fatigue tests (Figure 3, below) have been completed using PWR Zircaloy-4 cladding with burnups ranging from 63.8 to 66.8 GWd/MTU. The static results demonstrate that the presence of fuel increases the bending stiffness relative to calculations using cladding properties alone. The dynamic results demonstrate that high burnup fuel can experience a large number of cyclic loads without failure. The results from the testing indicate the fuel rod endurance limit of a lateral inertial load equivalent of 15-27 g [15]. For normal conditions of transportation testing, per 10 CFR 71.71(c)(5), vibration test, a vibration amplitude of 0.42 g was considered by a cask vendor for the closure bolt fatigue analysis using the measurement data of NUREG-766510, "Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks." [11]

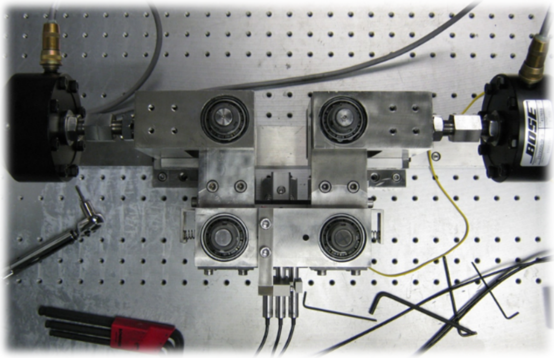

Figure 2 Test device seen from above. The reversible bending is conducted utilizing a U-frame setup with the push-pull force applied at the loading point.

As a future addition to this NUREG, the NRC staff will publish results from the next phase of this testing which has used spent fuel segments taken from different locations on the same rods. For this testing, segments were subjected to a reorientation procedure consisting of 5 cycles, where the fuel was heated to 400°C for 3 hours per cycle at a hoop stress of 140 Mpa. The cooling rate was 0.5-1°C/min. For this phase of testing, two dynamic tests and one static test followed by a dynamic test have been completed. These results are still being analyzed, but it appears that segments that had been subjected to the reorientation procedure exhibited reduced flexural rigidity, and possibly a reduction in the number of cycles to failure, compared to segments in the as-irradiated state. NRC staff are still evaluating the results of this testing, but expect that despite the reduction in the number of cycles to failure, HBF will be able to maintain configuration after normal conditions of transportation and hypothetical accident condition testing.

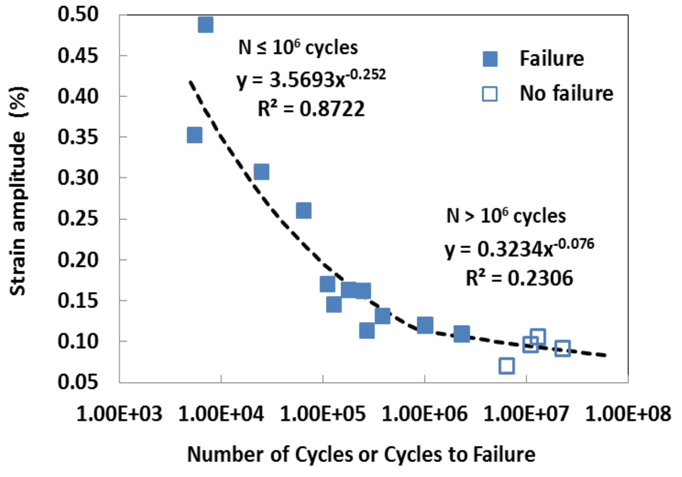

Figure 3 Equivalent strain amplitudes as a function of number of cycles for sixteen vibration fatigue tests. Solid markers represent tests with specimen failure; open markers indicate the tests stopped without failure.

NUREG/CR-7203, "A Quantitative Impact Assessment of Hypothetical Spent Fuel Reconfiguration in Spent Fuel Storage Casks and Transportation Packages [12]"

NUREG/CR-7203 presents a quantitative assessment of the safety impact of unlikely beyond design-basis hypothetical geometric changes of the fuel in spent fuel storage casks and transportation packages using both PWR and BWR fuel. This study analyzed potential changes in system characteristics with respect to criticality, shielding, containment, and thermal safety parameters under a wide range of fuel reconfiguration scenarios. The results of these scenarios are heavily dependent on the modelling assumptions and the results can vary greatly.

Three reconfiguration categories were considered for the study: cladding failure, rod/assembly deformation without cladding failure, and changes in fuel assembly axial alignment without cladding failure. The criticality and shielding analyses were performed using the SCALE code system. The criticality analyses were conservatively assumed to be fully flooded with water. The containment analysis were completed using values derived from NUREG/CR-6487 and the containment acceptance criteria provided in 10 CFR Part 71. The thermal analyses were completed using COBRA-SFS.

Certification Approaches

In 2015, the NRC issued a draft Regulatory Issue Summary (RIS) which provided guidance for some licensing and certification approaches of high burnup fuels for storage and transportation [13]. Figure 4, below, shows a high level diagram of acceptable licensing approaches for transportation of HBF. Figure 4 contains differences from the figure provided in the RIS by removing the need to confirm that the fuel meets the content specified in the Certificate of Compliance prior to and after transport. The applicant may consider and demonstrate other approaches that the staff may also find acceptable upon review.

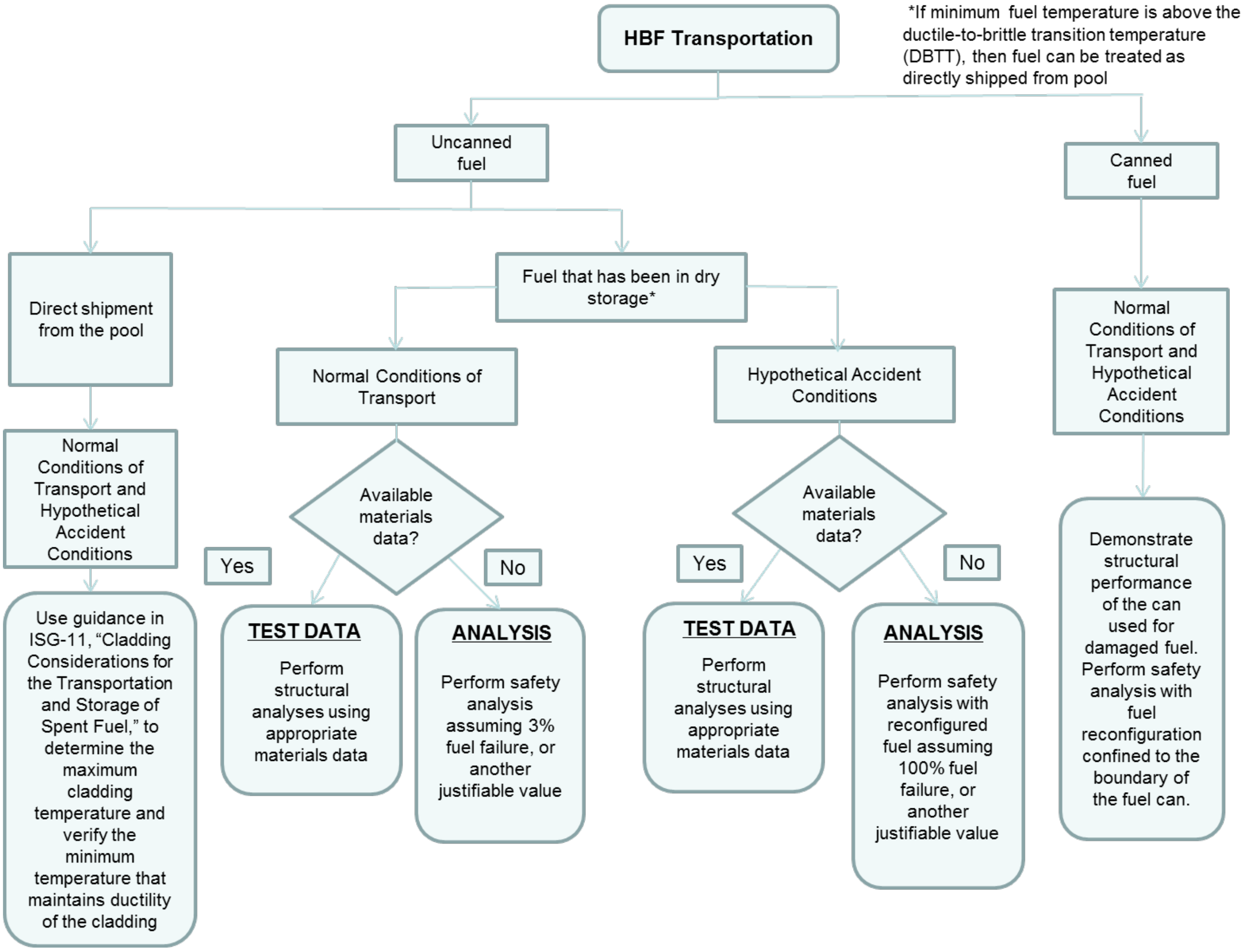

Figure 4 Possible HBF Transportation Licensing Approaches

There are several different options to certify HBF for transportation. One option is to consider placing the fuel in a damaged fuel can [14] thereby ensure the fuel has been "canned." For canned HBF, the applicant may perform bounding safety analyses assuming full reconfiguration inside the fuel can. In this case, however, the structural performance of the fuel can should also be evaluated.

For fuel that has not been placed in a damaged fuel can, the applicant's safety analysis should consider whether the fuel has been in dry storage or is shipped directly from the spent fuel pool.

For the transportation of HBF after dry storage, direct inspection of the fuel may not be necessary. Cladding material properties appropriate to the transportation temperature could be used to model the structural behaviour of the fuel during normal conditions of transport and hypothetical accident conditions. When the cladding temperature is above the DBTT, where the cladding remains more ductile, structural analysis of the fuel should use properties of the cladding with only circumferential hydrides. However, if prior to transport the fuel has been cooled for a substantial period of time, the fuel inside the package may be lower than the DBTT. In this case, the applicant should provide defensible mechanical properties of the HBF cladding with radial hydrides to use in the structural analysis to evaluate fuel failure in the 30 ft. free drop hypothetical accident condition scenario. This data should be representative of the cladding material type, hydrogen content, maximum temperatures, and maximum stresses. In both situations, the applicant should provide data to defend the cited DBTT, and justify that the calculated temperatures for the cladding are conservatively low.

When data for mechanical properties of the HBF cladding with radial hydrides are not available, an acceptable conservative, defense-in-depth approach for performing safety analyses is to assume some percentage of fuel failure for normal conditions of transportation and hypothetical accident conditions. For normal conditions of transportation, safety analyses assuming a 3 percent fuel failure would be considered conservative in evaluating the thermal, containment, criticality, and shielding performance. For hypothetical accident conditions, safety analyses assuming 100 percent fuel failure would be considered conservative for the thermal, containment, criticality, and shielding disciplines. These values, although considered to be conservative, are not mandatory and the applicant can perform the defense-in-depth analyses assuming other justified values of fuel failure percentages. If the applicant is unable to justify the release fractions, the cask should be leaktight, as defined by ANSI N14.5.

For transportation of uncanned HBF loaded directly from the spent fuel pool, an acceptable approach is to use guidance provided in Interim Staff Guidance -11, Revision 3, to determine the maximum cladding temperature, provide a justifiable ductile-to-brittle transition temperature, and to verify the minimum temperature remains above the ductile-to-brittle transition temperature for the entire duration of transportation [5, 6]. If these conditions are met, then the mechanical properties of the cladding material with circumferential hydrides may be used. If sections of the fuel cladding do not remain above the ductile-to-brittle transition temperature, the applicant could follow the approach for canning the fuel or the approach for transportation after dry storage.

Conclusions

Current research indicates that HBF with radial hydrides may experience some reduced flexural rigidity which varies greatly depending on the cladding type, cladding temperatures, and the extent of hydride reorientation. However, the NRC staff is expecting HBF to withstand the loads of normal conditions of transportation and is evaluating the ability of HBF to withstand hypothetical accident condition testing. Currently, the NRC staff expects that any loads resulting from the 30-foot HAC drop not to cause intact or undamaged HBF cladding with 100% RHCF to reconfigure, even if the fuel temperature is below the DBTT. Until this is confirmed, conservative licensing approaches such as considering the effect of the DBTT on the fuel cladding and performing safety analyses assuming failed fuel can be used to obtain certification for transportation.

Acknowledgments

The authors of this paper would like to acknowledge: Michelle Bales, Zhian Li, David Tang, Gordon Bjorkman, Ricardo Torres, Tae Ahn, F.C. (Jimmy) Chang, and Bernard White of the U.S. NRC for working diligently throughout the past few years to consider the effects of HBF in our licensing actions. Additionally, the authors of this paper would also like to thank Mike Billone (Idaho National Laboratory), R.E. (Bob) Einziger (Nuclear Waste Technical Review Board), Bruce Bevard, Yong Yang, Jy-An Wang, Rose Montgomery, and John Scaglione (Oak Ridge National Laboratory) who have provided invaluable input to NRC staff.

References

1. K.J. Geelhood, C.E. Beyer, and W.G. Luscher, “PNNL Stress/Strain Correlation for Zircaloy,” Pacific Northwest National Laboratory (PNNL) -17700, July 2008.
2. J.J. Kearns, “Diffusion Coefficient of Hydrogen in Alpha Zirconium, Zircaloy-2, and Zircaloy-4,” *Journal of Nuclear Materials*, Vol. 43, Issue 3, 1972, p 330-338
3. K. Une and S. Ishimoto, “Dissolution and Precipitation Behavior of Hydrides in Zircaloy-2 and High Fe Zircaloy,” *Journal of Nuclear Materials*, Vol. 322, Issue 1, 2003, p. 66-72.
4. C.F. Magnuson and L.T. Wilson, “Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks,” SAND76-0427, NUREG 766510, Sandia National Laboratories, Albuquerque, New Mexico, 1977
5. B.F. Kammenzind, D.G. Franklin, H.R. Peters, and W.J. Duffin, “Hydrogen Pickup and Redistribution in Alpha-Annealed Zircaloy-4,” *Zirconium in the Nuclear Industry: 11th Intl. Symp.*, ASTM STP 1295, E.R. Bradley and G.P. Sabol, Eds., ASTM, pp. 338–370, 1996.
6. J.J. Kearns, “Terminal Solubility and Partitioning of Hydrogen in the Alpha Phase of Zirconium, Zircaloy-2 and Zircaloy-2,” *Journal of Nuclear Materials,* Vol. 22, 292–303, 1967.

7. A. McMinn, E.C. Darby, and J.S. Schofield, “The Terminal Solid Solubility of Hydrogen in Zirconium Alloys, *Zirconium in the Nuclear Industry: 12th Intl. Symp.*, ASTM STP 1354, G.P. Sabol and G.D. Moan, Eds., ASTM, pp. 173–195, 2000.
8. R. L. Sindelar and M. R. Louthan, Jr. and B. D. Hanson, *"White Paper Summary of 2nd ASTM International Workshop on Hydrides in Zirconium Alloy Cladding June 10-12, 2014 Jackson, WY"* May 29, 2015, FCRD-UFD-2015-000533, SRNL-STI-2015-00256
9. M.C. Billone, T.A. Burtseva, and R.E. Einziger, “Ductile-to-Brittle Transition Temperature for High-Burnup Cladding Alloys Exposed to Simulated Drying-Storage Conditions,” *Journal of Nuclear Materials* 433 (2013) 431–448.
10. Jy-An Wang, Hong Wang, Bruce Bevard and Michelle Flanagan-Bales, *Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications*, NUREG/CR-7198 (ORNL/TM-2014/214), May 2015.
11. C. F. Magnuson and L.T. Wilson, *Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks*, NUREG-766510, June 1977.
12. J.M. Scaglioni, G. Radulescu, W.J. Marshall, and K.R. Robb., *A Quantitative Impact Assessment of Hypothetical Spent Fuel Reconfiguration in Spent Fuel Storage Casks and Transportation Packages*, NUREG/CR-7203 (ORNL/TM-2013/92), September 2015.
13. NRC Draft Regulatory Issue Summary 2015-xx, *Considerations in Licensing High Burnup Spent Fuel in Dry Storage and Transportation*, ML14175A203.
14. Interim Staff Guidance 1 (ISG-1), Revision 2, “Classifying the Condition of Spent Nuclear Fuel for Interim Storage and Transportation Based on Function,” Division of Spent Fuel Storage and Transportation, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, D.C., May 2007.
15. Tang, David, *Engineering Application of Test Data for Determining Behavior of Actual Fuel during Normal Transportation*, U.S. Nuclear Waste Technical Review Board Winter Board Meeting, U.S. Nuclear Waste Technical Review Board, February 2016