THE CASE FOR TRANSPORTATION OF HIGH BURNUP FUEL

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ABSTRACT

Decades of research have been performed examining transportation of high burnup fuel (> 45 GWD/MTU). This research has concluded that when incorporating a risk informed approach, there is not a safety issue with the transportation of high burnup fuel. This holistic approach has not been fully accepted by some regulatory organizations; in the US, for example, transportation of high burnup fuel is to be handled on a case by case basis (ISG-11, Rev. 3). With two independent consolidated interim storage licenses under review in the US, as well as activities in other countries for interim storage, industry needs to be ready for regular shipments of high burnup fuel in large scale casks within the next several years. To ensure these shipments occur in an efficient manner, it is time to resolve once and for all the case for transportation of high burnup fuel. This paper will highlight the inconsistencies between the research conclusions of extremely low risk, and the current regulatory approach. It is hoped the highlighting this disconnect will facilitate action for a more efficient process in addressing transportation of high burnup fuel to support upcoming anticipated needs.

INTRODUCTION

Previous efforts have examined applicable licensing conditions for transportation packages containing discharged “high-burnup” (>45 GWd/MTU) commercial spent nuclear fuel (CSNF) in the context of present and potentially future revisions of regulations. The result of these efforts was to establish a framework for a risk-informed, technically state-of-the-art approach. This work has included: assessment of the probability of a criticality event during transportation [1-2]; options for pursuing moderator exclusion [3]; full burnup credit [4-5]; structural response of cladding to impact loads [6]; and potential impact of fuel reconfiguration on criticality [7-8].

The overall information generated by these projects has not been fully adopted by some regulatory organizations; in the US, for example, transportation of high burnup fuel is still being handled on a case by case basis [9]. With two independent consolidated interim storage licenses under review in the US, as well as activities in other countries for interim storage, industry needs to be ready for regular shipments of high burnup fuel in large scale casks within the next several years. To ensure these shipments occur in an efficient manner, it is time to resolve once and for all the generic case for transportation of high burnup fuel.

In April 2012, the US Nuclear Regulatory Commission (NRC) published NUREG-2150 entitled “A Proposed Risk Management Regulatory Framework” in which they stated that the NRC had “*made progress in its efforts to implement risk-informed and performance-based approaches into its regulation of the various uses of byproduct, source, and special nuclear materials*” and recommended that a Risk Management Regulatory Framework be the next logical step for the NRC [10]. Recognizing that (1) transportation of radioactive materials within the United States is regulated jointly by various Federal, State and local government agencies, and (2) the United States’ endorsement that its domestic transportation regulations should be compatible with

IAEA's transportation regulations to the greatest extent practicable, NUREG-2150 provided three recommendations for transportation of spent fuel, included the following:

"The NRC should explore the value of using risk insights to justify regulations different from the IAEA's for domestic use only, such as regulations dealing with domestic storage and transportation of high burnup fuel. Risk information could be used to develop a more flexible approach toward implementing and making gradual changes to current transportation regulations."

REGULATORY POSITIONS

In the U.S., the present lack of generic regulatory acceptance criteria for licensing transportation packages containing high-burnup fuel is mostly due to staff evaluations related to the analysis of hypothetical transportation accident conditions and the paucity of mechanical property data available for spent fuel irradiated above 45 GWd/MTU. The reactivity of a spent fuel transportation package with re-configured fuel in the presence of water in the package has been of particular concern to regulators. In the context of having applicants performing structural evaluations to determine reconfigured fuel geometries, NRC ISG-19 [11] states:

"The reconfigured fuel geometries would be developed based on the material properties of the spent fuel cladding and the impact loads imposed on the fuel assemblies. It is judged that, at this time, there is insufficient material property information for high burnup fuel to allow this type of evaluation."

This regulatory opinion appears to be the reason for the following statement in ISG – 11, Rev. 3:

"For hypothetical accident conditions, the licensee must assure that there is no significant cladding failure. This is in accordance with the criticality requirements of 10 CFR 71.55 and by the shielding and containment requirements of 10 CFR 71.51."

However, criticality requirements of 10 CFR 71.55 and shielding and containment requirements of 10 CFR 71.51 do not impose cladding performance criteria. Although external radiation dose rate and nuclear reactivity depend on the distribution of the radioactive and fissile content in the transportation package, 10 CFR 71.55(e)(1) simply states it must be assumed that:

"The fissile material is in the most reactive credible configuration consistent with the damaged condition of the package and the chemical and physical form of the contents"

The position stated in ISG – 11, Rev. 3 stipulating assurance that there is no significant cladding failure implies that (1) regulatory requirements are de facto not met when fuel relocation occurs, (2) fuel relocation de facto occurs when significant cladding failure is assumed, and (3) significant fuel failure has to be de facto assumed, due to the paucity of mechanical property data for cladding as a structural element of spent fuel irradiated above 45 GWd/MTU. The end result of the statements highlighted above in ISG -11, Rev. 3 and ISG-19 have resulted in regulatory reviews related to the structural response of fuel *rods* during normal and hypothetical accident conditions that *consider only the cladding and/or moderator exclusion*, yet the fuel pellet provides significant structural capacity as discussed next.

RESULTS FROM SELECTED PREVIOUS INVESTIGATIONS

The contribution of the fuel pellets to the structural response of fuel rods to hypothetical accident conditions was highlighted as early as June 2005 with the publication of an EPRI Report entitled "*Spent Fuel Transportation Applications: Fuel Rod Failure Evaluation under Simulated Cask Side Drop Conditions*" [12] which evaluated a drop accident of a bare cask falling in the horizontal position from a height of nine meters onto a reinforced concrete slab. Structural response of the spent fuel was performed for several initial cladding conditions, including cladding characterized by the presence of both circumferential and radial hydrides in large enough concentrations to conservatively represent high burnup spent fuel after 40 years of dry storage. A pinch load equal to five times the calculated load was reached without the cladding exhibiting failure demonstrating that the fuel pellets contribute the major load-resisting component of the fuel rod. The fuel pellets contribution to the robust behavior of the cladding can be discerned in Figures 1 and 2. The inflexion point in the hoop strain's rate of change in Figure 2 provides a clear illustration of the transfer of load between cladding and cladding-fuel column composite when pellet-cladding contact occurs, the latter being a function of the initial gap between cladding and fuel column. As load increases to its nominal value (1.0) and artificially beyond its nominal value, the cladding hoop strain changes only slowly. Given the small gaps, if any over large fractions of high-burnup rods, this effect is especially beneficial in today's high burnup assemblies. Results from the EPRI work were presented in a number of venues such as Refs. [13-14].

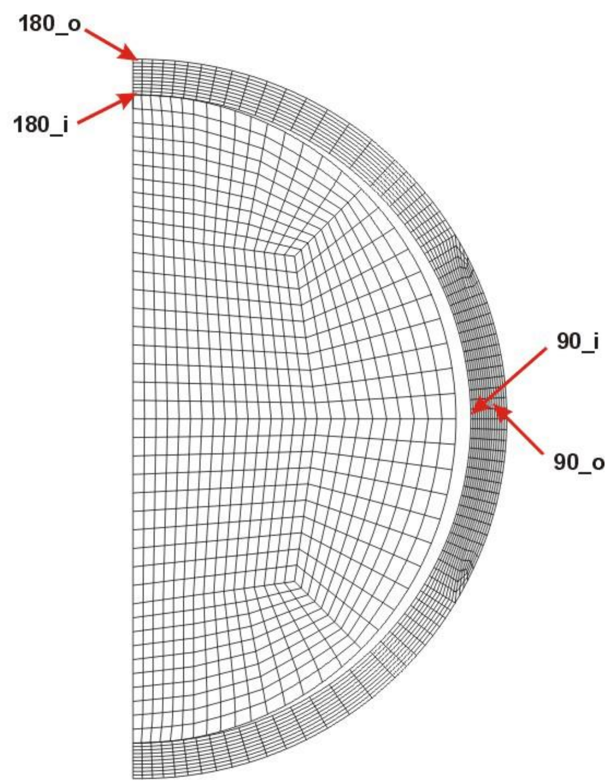

Figure 1. Deformed Finite Element Grid. Arrows point to Grid Locations for Depicting Cladding Strain (Fig. 2) and Stress (Fig. 3) (Fig. 4-1, on page 4-2 of Ref. [12])

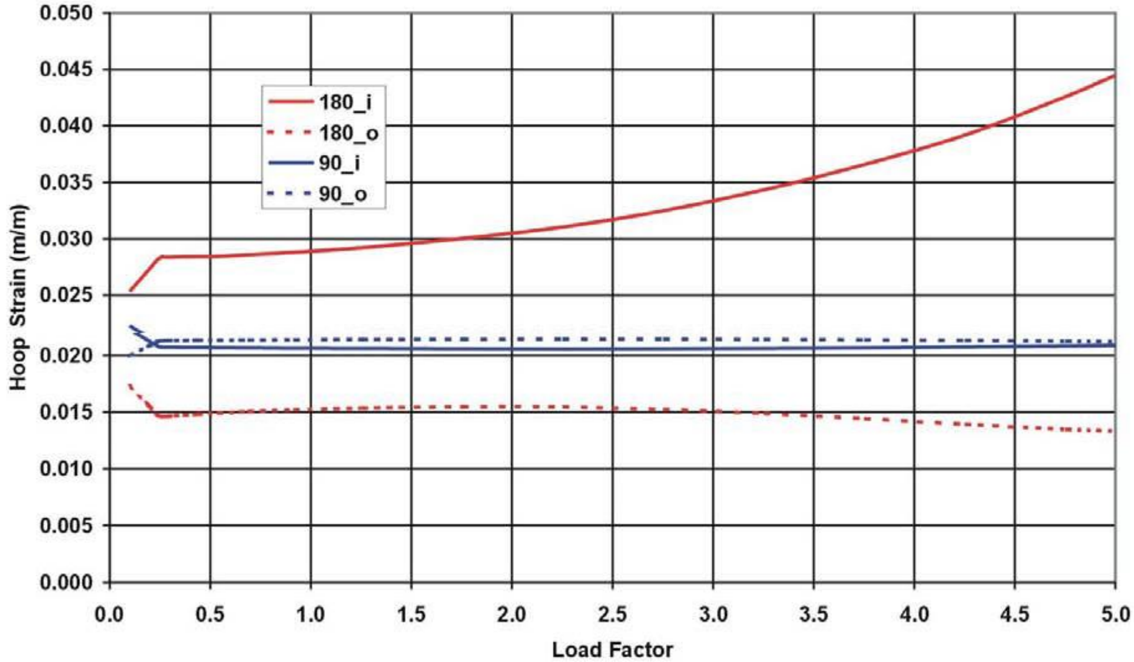

Figure 2. Cladding Hoop Strain versus Pinch Force Load Factor (Fig. 4-24, on page 4-15 of Ref. [12])

Issues related to spent fuel relocation and its impact on nuclear reactivity were also addressed with a focus to provide credible estimates of the probability and maximum reactivity changes resulting from theoretical, “worst-case” fuel reconfiguration scenarios [7]. These scenarios were deconstructed into their physical components so that the reactivity increases (Δk) of a scenario could be expressed as the combination of independent scenarios, based upon physical phenomena. This deconstruction allows the combination of independent physical scenarios to be qualitatively evaluated for probability when the physical scenarios are themselves unlikely, although not impossible. The likelihood of the overall combination of scenarios is the product of the physical scenario probabilities. An example of such a process is shown in Figure 3 for a worst-case expanding PWR fuel rod array scenario. Fuel assemblies are designed to be under-moderated for reactor control purposes, so that a reactivity increase could result if the fuel assembly grids and end fittings were no longer structurally capable to restrain the rod array. This scenario is of concern because of the difficulty of predicting exactly what would happen to a spent fuel assembly in a hypothetical drop accident, which is partly due to the complexity of the various assembly designs, but also partly due to the variable material properties of irradiated materials. Conceptually, the rods of the assembly may bow or splay outward between grids, in a cask nine-meter, end-drop scenario. The scenario may include bowing of only the bottom section of the assembly between the bottom end fitting and the first grid, or it may include several or all sections or the entire assembly.

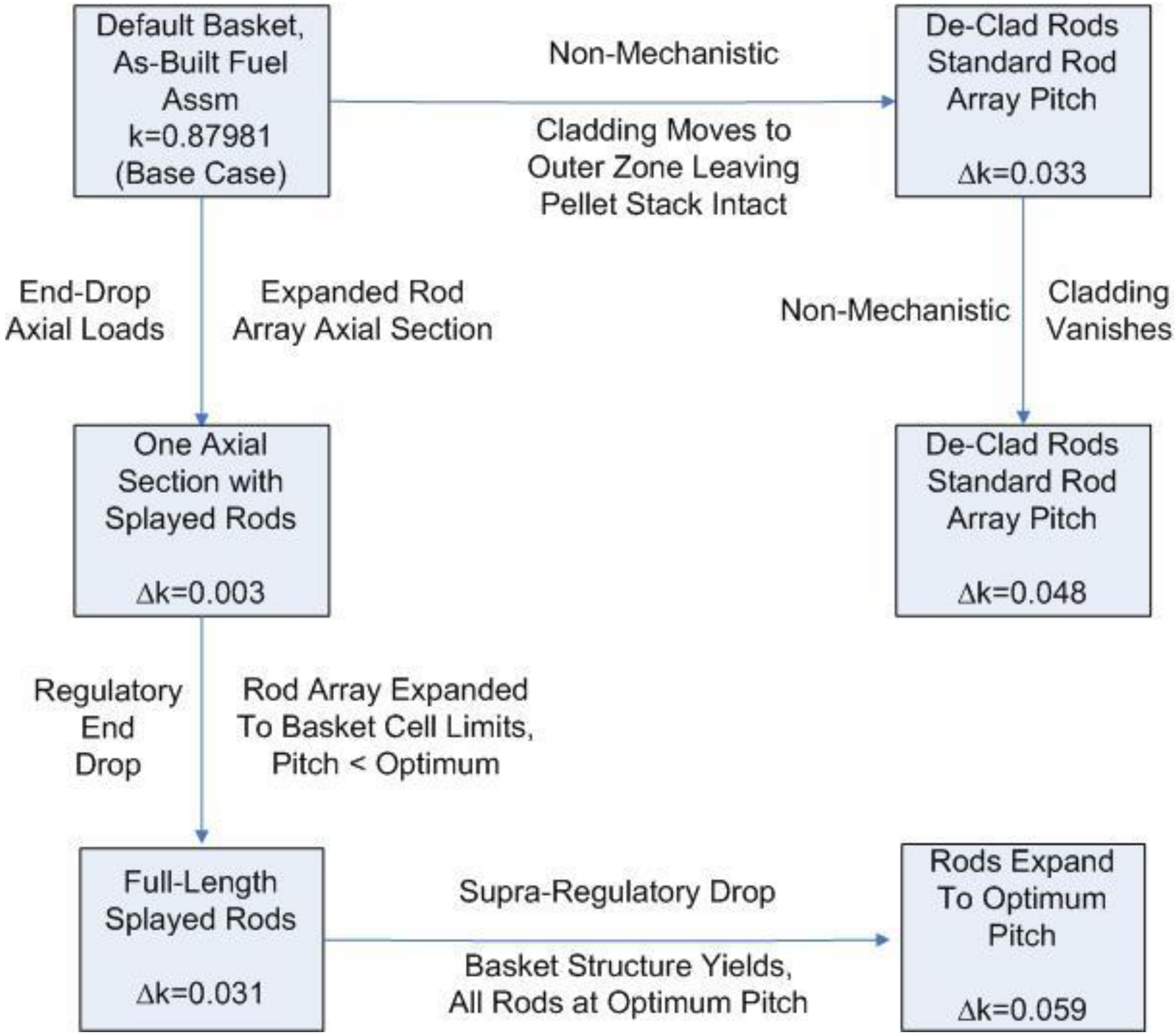

Figure 3. Deconstruction of an expanding fuel rod array scenario [7]

The ANSI/ANS-8.1 "Double Contingency" Principle, which essentially does not require evaluation of the simultaneous occurrence of independent unlikely events, can then be applied when the original "worst-case" scenario is transformed into a group of individually unlikely, but credible, scenarios. Application of the Double Contingency principle to unlikely, but credible, "worst-case" scenarios shows that the maximum reasonable reactivity increase is less than the administrative margin of 0.05 for scenarios involving physical changes to fuel assembly rod arrays. For scenarios involving fuel pellet arrays, a substantial reactivity decrease is actually calculated. Based on these results, criticality is not a credible scenario, conservatively assuming a minimum (administrative) margin of 0.05, for hypothetical accident conditions involving spent PWR assemblies.

LEARNING FROM RISK INFORMATION

Additional insights have also been derived from the extensive NRC-sponsored work on transportation risks starting with NUREG-0170 (1977) [15] followed by the "Modal Study" (1987) [16], NUREG/CR-6672 (2000) [17], and more recently NUREG-2125 (2014) [18].

In the NUREG-2125 Abstract, the following statement is made:

"The improved analysis tools and techniques, improved data availability, and a reduction in uncertainty has made the estimate of accident risk from the release of radioactive material in this study approximately five orders of magnitude less than what was estimated in NUREG-0170."

When the analyses contained in NUREG-2125 were completed, the maximum assembly-average burnup for the spent fuel transported in the analyzed casks was 45 GWd/MTU. Current reactor operations result in higher discharged burnup levels higher. As of 2015, the EPRI database indicates that in the US ~2/3rd of discharged spent PWR assemblies and ~1/2 of discharged BWR bundles now exceeds 45 GWd/MTU.

Section 6.3 in NUREG-2125 provides insights on expected changes resulting from transporting higher burnup spent fuels. In all of the accidents that were assumed to be severe enough to have a release path from the cask, the acceleration level was assumed to be high enough *to fail the cladding of all of the fuel*, whether it was high burnup or not. Because higher burnup fuel has a rim layer with a higher concentration of radionuclides, this could lead to a rod-to-cask release fraction being higher, but would not affect the cask-to-environment release fraction. In addition, the isotopic mixture of the higher burnup fuel contains more transuranic isotopes.

Studies in Germany [19] and Japan [20] have shown that the total amount of fuel material released from a breached rod was not very sensitive to burnup between 19 GWd/MTU to 74 GWd/MTU (<2 g of fuel per guillotine rod fracture). In addition, testing conducted by Pacific Northwest National Laboratory (PNNL) to provide data to determine the fractional release of fuel from a spent fuel rod upon cladding failure (i.e., burst scenario), and to determine the fraction and particle-size distribution (PSD) of oxidized fuel that may become airborne under off-normal scenarios in the surface facilities at the proposed repository at Yucca Mountain came to the following conclusion [21]:

"Based on the releases observed, there is no significant difference in either the release fraction or the PSD between HBU fuels containing HBS and lower burnup fuels"

Therefore, the only significant difference is the isotopics of the fuel. Assuming that the release fractions remain about the same, the effect of the change in radionuclide inventory increases the number of nuclides that need to be considered (A2's) [22] by a factor up to 5.9 according to NUREG-2125 [18]. However, this increase does not alter the conclusions of the NUREG-2125 study.

Regarding the risks of criticality associated with scenarios of fuel relocation, the EPRI studies have shown the negligible probability of a criticality event during transportation [1-2]. The results were presented at a previous PATRAM meeting [23]. The conclusions included the following:

"Within the boundary limits of the analyzed cases, the EPRI-sponsored work shows that there are no credible combinations of accident events, accident locations, and fuel misloading or reconfiguration that would result in a critical configuration during the transportation of spent

nuclear fuel. For most transportation package designs, criticality during hypothetical transportation accidents should be a regulatory non-issue given the extraordinarily low probability of the concomitant occurrence of the conditions required for providing a situation conducive to criticality in the cask. The non-mechanistic criticality evaluation performed in the as-loaded or as-designed configuration can be considered the bounding case for all conditions of transportation because this hypothetical reactivity case bounds all those normal and hypothetical accident cases that can credibly exist for spent fuel transportation packages."

Support for this conclusion was provided by the authors of NUREG-2125 in Ref. [24]:

"Another accident type that is of potential concern is one that leads to a criticality event. This study has shown that the combination of factors necessary to produce such an event is so unlikely that the event is not credible."

As discussed previously, regulatory reviews focus on cladding performance, yet it can be concluded that cladding behavior is largely irrelevant in the context of severe transportation accidents. Instead of focusing on the cladding, the issue, if any, is the behavior of the fuel inside the ruptured cladding. With a risk informed view, the consequence of cladding failure is shown to be of no significance and a criticality event is not credible, so safety is not dependent on the cladding performance.

SUMMARY

This paper has highlighted the existing disconnect between, on one hand, present regulatory treatment of applications for the transportation of high-burnup spent nuclear fuel in the U.S. and, on the other hand, assessments of extremely low transportation risks, assessments which were sponsored by the same regulatory body. Transportation accident risks have been calculated to be orders of magnitude lower than normal transportation risks, which themselves are calculated to be a fraction of the radiological risks from natural background radiation; in such assessments, cladding performance is largely irrelevant. A criticality event during hypothetical transportation accidents was determined to be not credible. These conclusions have been supported by a probabilistic criticality assessment, deconstruction of fuel relocation scenarios, and structural assessments showing the robust behavior of fuel rods subjected to pinch loading. The sequence and timing of the publication of the results of these studies may not have been conducive to the understanding of the importance, or lack of it, of cladding performance. Bounding simulations on non-physical scenarios regarding criticality have also contributed to preventing the development of generic regulatory acceptance criteria consistent with those for dry storage. It is now hoped that highlighting the disconnects in regulatory position (NUREG-2125 vs. ISG-11 and ISG-19) and intent [10] will facilitate action for developing a more efficient process in addressing transportation of high burnup fuel to support upcoming anticipated needs. With two independent consolidated interim storage licenses under review in the U.S., as well as activities in other countries for interim storage, industry needs to be ready for regular shipments of high burnup fuel in large scale casks within the next several years. To ensure these shipments occur in an efficient manner, it is time to resolve once and for all the case for transportation of high burnup fuel.

REFERENCES

1. *Criticality Risks During Transportation of Spent Nuclear Fuel: Revision 1*, EPRI, Palo Alto, CA: 2008. 1016635.

2. A. A. Dykes and A. J. Machiels, *Criticality risks during transportation of spent nuclear fuel*, in Packaging, Transport, Storage & Security of Radioactive Material, Volume 21, No. 1, 2010, pp. 51-61
3. *Options for Pursuing Moderator Exclusion for Application to Spent-fuel Transportation*, EPRI, Palo Alto, CA: 2005. 1011815
4. *Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty— Revision 1*. EPRI, Palo Alto, CA: 2017. 3002010613.
5. Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation – Revision 1. EPRI, Palo Alto, CA: 2018. 3002010614.
6. *Spent Fuel Transportation Applications – Assessment of Cladding Performance: A Synthesis Report.* EPRI, Palo Alto, CA: 2007. 1015048.
7. *Fuel Relocation Effects for Transportation Packages.* EPRI, Palo Alto, CA: 2007. 1015050.
8. A.H. Wells and A.J. Machiels, *Effects of Fuel Relocation for Transport Casks* – Nuclear Technology, Vol. 179, pp. 180-188 (August 2012)
9. Interim Staff Guidance - 11, Revision 3, *Cladding Considerations for the Transportation and Storage of Spent Fuel*, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office (2013)
10. *A Proposed Risk Management Regulatory Framework,* Report to NRC Chairman Gregory B. Jaczko from the Risk Management Task Force headed by Commissioner George Apostolakis, NUREG-2150 (April 2012)
11. Interim Staff Guidance - 19, *Moderator Exclusion under Hypothetical Accident Conditions and Demonstrating Subcriticality of Spent Fuel under the Requirements of 10 CFR 71.55(e),* U.S. Nuclear Regulatory Commission, Spent Fuel Project Office (2013)
12. *Spent Fuel Transportation Applications: Fuel Rod Failure Evaluation under Simulated Cask Side Drop Conditions,* EPRI. Palo Alto, CA: 2005. 1009929
13. A. Machiels, *Storage & Transportation – EPRI Program Overview*, Dry Storage Information Forum 2006, Key Biscayne, FL, May 9-11, 2006
14. J. Rashid and A. Machiels*, Threat of Hydride Re-orientation to Spent Fuel Integrity During Transportation Accidents: Myth or Reality?* Proceedings of the 2007 International LWR Fuel Performance Meeting. San Francisco, California, September 30 – October 3, 2007
15. NUREG-0170, *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes,"* US NRC, December 1977
16. NUREG/CR-4829, *Shipping Container Response to Severe Highway and Railway Accident Conditions,* US NRC, 1987
17. NUREG/CR-6672 *"Reexamination of Spent Fuel Shipment Risk Estimates,* US NRC, March 2000
18. NUREG-2125: *Spent Fuel Transportation Risk Assessment*, US NRC, 2012
19. Rondinella, V.V., Wiss, T., Papaioannou, D., Nasyrow, R., Studies on nuclear fuel evolution during storage and testing of used fuel response to impact loadings, PSAM11-ESREL 2012, June 25-29, 2012, Helsinki; Vol. 1, 3171-3179, IAPSAM & ESRA, ISBN: 978-1-62276-436-5, (2012)
20. Hirose, T., Ozawa, M., Miura, H., Baba, T., Kamimura, K., *Dynamic Load Impact Tests on High Burnup Spent Fuel Rods of BWR and PWR*, NuMat 2012: the Nuclear Materials conference, Osaka, Japan, 22—25 October, (2012)

21. B. D. Hanson, W. Wu, R. C. Daniel, P. J. MacFarlan, A. M. Casella, R. W. Shimskey, and R. S. Wittman, *Fuel-In-Air FY07 Summary*, U.S. Department of Energy, PNNL-17275, Rev. 1 (2008)
22. U.S. Code of Federal Regulations Title 10, Part 71, Table A-2, "Exempt Material Activity Concentrations and Exempt Consignment Activity Limits for Radionuclides."
23. Machiels, A.J. and J.H. Kessler, *Multi-facet approach for evaluating criticality risks during transportation of commercial spent nuclear fuel*, PATRAM 2010
24. R. Meiner and D. Ammerman, *Spent fuel transportation risk assessment: transportation accident analysis,* Packaging, Transport, Storage and Security of Radioactive Material, Volume 24, 2013 - Issue 3, pp. 121-127