Regulatory Perspective on Potential Fuel Reconfiguration and Its Implication to High Burnup Spent Fuel Storage and Transportation - 13042

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ABSTRACT

The recent experiments conducted by Argonne National Laboratory on high burnup fuel cladding material property show that the ductile to brittle transition temperature of high burnup fuel cladding is dependent on: (1) cladding material, (2) irradiation conditions, and (3) drying-storage histories (stress at maximum temperature) [1]. The experiment results also show that the ductile to brittle temperature increases as the fuel burnup increases. These results indicate that the current knowledge in cladding material property is insufficient to determine the structural performance of the cladding of high burnup fuel after it has been stored in a dry cask storage system for some time. The uncertainties in material property and the elevated ductile to brittle transition temperature impose a challenge to the storage cask and transportation packaging designs because the cask designs may not be able to rely on the structural integrity of the fuel assembly for control of fissile material, radiation source, and decay heat source distributions. The fuel may reconfigure during further storage and/or the subsequent transportation conditions. In addition, the fraction of radioactive materials available for release from spent fuel under normal condition of storage and transport may also change. The spent fuel storage and/or transportation packaging vendors, spent fuel shippers, and the regulator may need to consider this possible fuel reconfiguration and its impact on the packages' ability to meet the safety requirements of Part 72 and Part 71 of Title 10 of the Code of Federal Regulations.

The United States Nuclear Regulatory Commission (NRC) is working with the scientists at Oak Ridge National Laboratory (ORNL) to assess the impact of fuel reconfiguration on the safety of the dry storage systems and transportation packages. The NRC Division of Spent Fuel Storage and Transportation has formed a task force to work on the safety and regulatory concerns in relevance to high burnup fuel storage and transportation. This paper discusses the staff's preliminary considerations on the safety implication of fuel reconfiguration with respect to nuclear safety (subcriticality control), radiation shielding, containment, the performance of the thermal functions of the packages, and the retrieveability of the contents from regulatory perspective.

INTRODUCTION

Part 72 of Title 10 of Code of Federal Regulations (CFR) prescribes the safety requirements for spent fuel storage systems. 10 CFR Part 71 prescribes the safety requirements for packaging of radioactive material for transportation. In addition to the safety requirements, 10 CFR 72.122 (l) requires that the storage systems be designed to allow readily retrieval of the spent fuel and other contents and 10 CFR 71.89 requires that the package designer must provide the carrier with any special instructions needed to safely open the package, including retrieval of the content upon arrival.

The fundamental concerns of the 10 CFR Part 72 and Part 71 regulations are safety. To safely store and subsequently transport high burnup spent fuel, the spent fuel dry storage systems and transportation packages must meet their respective regulatory requirements. Traditionally, spent fuel storage and transportation package designs assume that the fuel will retain its structural integrity under storage and normal transport conditions with recognition that fuel may experience some plastic deformation under hypothetical accident conditions depending upon the outcome of the structural analysis with given cladding and spacer grid material properties [2, 3, 4, 5]. The important assumption in these analyses was that the cladding would remain ductile during storage and transportation. However, this assumption may no longer be assured for high burnup fuel because of lack of experimental data. In order to gain a better understanding of the cladding material property of high burnup fuel, the NRC has supported research projects at Argonne National Laboratory (ANL) and ORNL to test the performance of cladding of high burnup fuel. Based on the initial results of the ANL study, the ductile to brittle transition temperature (DBTT) is dependent on: cladding material, irradiation conditions, and drying-storage histories (stress at maximum temperature). The cladding of high-burnup ZIRLO™ fuel exhibited higher susceptibility to radial-hydride formation and embrittlement than that of high-burnup Zry-4 fuel [1]. The ANL research results further indicate that the DBTT increases as burnup increases. This means that the cladding of high burnup fuel may become brittle as the fuel cools down over time and there exists a possibility that the high burnup fuel in dry storage may reconfigure under design basis accident or even normal storage conditions. Similarly, the fuel may not be able to withstand the impacts of the transportation conditions as prescribed in 10 CFR 71.71 and 71.72.

To assess the safety implication of fuel reconfiguration, the Electric Power Research Institute (EPRI) and ORNL performed independent studies on fuel reconfiguration and its impact on the criticality safety of transportation packages [5, 6, 7, 8]. EPRI has also established a research program to study issues related to spent fuel and high-level waste management. Although these studies may not be all inclusive, they do provide new information valuable to addressing the issues facing high burnup fuel storage and transportation. The NRC is working with the scientists at ORNL to assess the impact of fuel reconfiguration on package safety. The NRC Division of Spent Fuel Storage and Transportation has formed a task force to work on the safety and regulatory implication in relevance to high burnup fuel storage and transportation. Presented below is a summary of the staff's preliminary considerations on the safety implication of spent fuel and the necessary demonstration for package safety from the regulatory perspective.

POSSIBLE SCENARIOS OF FUEL RECONFIGURATIONS

With undetermined cladding material properties, it is difficult to predict the exact behaviors of the fuel assemblies in a package under normal storage and transport modes. From the regulatory perspective, the fundamental determination is whether the high burnup fuel storage systems and transportation packages can meet the safety requirements of the regulations. Based on published literatures [5, 6, 7, 8], the following scenarios have been considered in various studies:

- removal of single rod or multiple rods from a fuel assembly
- partial loss of cladding material because of cladding thinning
- complete loss of cladding
- loss of fuel geometry:
    1. change of rod pitch due to end impact and side impact
    2. change of rod pitch with uniform lattice expansion bounded by fuel cell
    3. change of rod pitch with bird-cage like lattice deformation
- axial misalignments of the fuel in the casks

- homogeneous rubble stays within poison plate region
- homogeneous rubble shift outside of the poison plate region

The NRC staff is working with scientists at ORNL to examine other potential fuel reconfiguration scenarios together with those that are identified in publications and to assess the safety impact on the current storage and transportation casks.

POTENTIAL FUEL RECONFIGURATION AND ITS IMAPCT ON PACKAGE SAFETY

Reconfigured fuel will change the geometry of the contents and hence the neutronics characteristics, radiation and thermal source distributions and available release fraction of gaseous and fine particles of the contents. Consequently, fuel reconfiguration may impose challenges to the criticality, shielding, containment, and thermal safety of the high burnup fuel storage systems and transportation packages. Table 1 provides a cross reference between fuel reconfiguration scenarios and the corresponding safety considerations.

Table 1. Fuel Reconfiguration Scenarios and Potential Impact on Satisfying Regulatory Requirements

	Criticality (Applicable Regulations)	**Shielding (Applicable Regulations)**	**Containment (Applicable Regulations)**	**Thermal (Applicable Regulations)**	**Operational Needs**
Lattice Deformation (no breakage of fuel rods)	**Yes** Both Part 71 and Part 72	**Potential** Both Part 71 and Part 72 (Depend on assumptions in shielding analysis)	**None**	**Potential** 71.43 (Elevated local package surface temperature)	**Yes** Both Part 71 and Part 72 (Retrievability special equipment, facility)
Rod or assembly slide out (no breakage of fuel rods)	**Yes** Both Part 71 and Part 72	**Yes** Both Part 71 and Part 72 (source relocation)	**None**	**Yes** 71.43 (Elevated local package surface temperature)	**Yes** Both Part 71 and Part 72 (Retrievability special equipment, facility)
Rod break/ Loss of assembly structure integrity	**Yes** Both Part 71 and Part 72	**Yes** Both Part 71 and Part 72 (source relocation)	**Yes** Both Part 71 and Part 72 (Higher release fraction)	**Yes** 71.43 (Elevated local package surface temperature)	**Yes** Both Part 71 and Part 72 (Retrievability special equipment, facility)

It is important to note that the fuel reconfiguration scenarios presented in Table 1 are all based on the assumption that the fuel was loaded as intact and there is only a potential for fuel to reconfigure. If the fuel is damaged before loading or there is a reasonable expectation the fuel will deform, it must be treated as damaged for packaging.

IMPACT ON PACKAGE CRITICALITY SAFETY

The impact of fuel reconfiguration on criticality safety is particularly important. It is particularly complicated for spent fuel transportation packages seeking burnup credit. To get the maximum credit for fuel burnup, applicants typically use burnup profile(s) to account for the uneven burnup distribution. Because of the uneven distributions of the fissile materials along the axial direction of the spent fuel assemblies, fuel reconfiguration in such a type of casks will result in a more complicated fissile material distribution that may affect the package's criticality safety. Fuel reconfiguration may necessitate separate considerations of fuel geometry and material composition at different axial sections of the assembly. Lattice expansion of low burnup section may become more reactive because power-reactor fuel assemblies are typically under-moderated before being irradiated in the reactors. However, lattice compression of the high burnup section of the fuel may make this part more reactive because depletion of fissile materials may have made the high burnup section over-moderated. The criticality safety evaluation for the burnup-credit package designs may need to consider the potential of fuel reconfiguration. The criticality safety analyses taking burnup credit may be particularly difficult for high burnup fuels for which the performance of the cladding property is uncertain.

IMPACT ON PACKAGE RADIATION SHIELDING

Typically, shielding analyses of spent fuel storage casks and transportation packages assume homogenized material composition in fuel cell and burnup-profile-adjusted source distribution along the axial direction of the fuel assembly. Although the fuel content was assumed smeared in the fuel cell compartments in these calculations, the implicit assumption is that the assembly will retain its geometric shape along the axial direction. The source terms are distributed following fuel burnup profile. As such, fuel reconfiguration may affect the radiation shielding analysis because reconfiguration of the fuel assembly may result in redistribution of the source toward one end of the package when it is at a vertical position or the side of the package when it is at a horizontal position. Since the source terms in a vertical cask are constrained with a different geometric boundary than that of a horizontal cask, shielding safety for these two cask positions may need to be analyzed separately.

IMPACT ON PACKAGE CONTAINMENT

Fuel reconfiguration may affect containment analyses for the storage system and transportation package because the release fractions may change for fuel fines, volatile and gaseous isotopes that are released from a fuel rod in the event of a cladding breach. For intact fuel, NUREG-1536 [9] and NUREG-1617 [10] provide typical values of release fractions and specific activities for the contributors to the releasable source term for storage and transportation packages for intact fuel. For fuel reconfiguration scenarios that involve change only in fuel geometry without rod breach, no additional analysis is necessary for compliance with the regulations because there is no additional release of radioactive sources. For scenarios that involve additional breakage of cladding, the containment analysis with additional available release source may be necessary. In addition, the results of the containment analyses may affect the shielding and radiation protection analyses because the external contamination level will be different.

IMPACT ON PACKAGE THERMAL PERFORMANCE

There is no specific regulatory requirement on the cask internal or external temperature for spent fuel storage casks. For transportation package design, however, 10 CFR 71.43(g) requires: "A package must be designed, constructed, and prepared for transport so that in still air at 38°C (100°F) and in the shade, no accessible surface of a package would have a temperature exceeding 50°C (122°F) in a nonexclusive use shipment, or 85°C (185°F) in an exclusive use shipment." The thermal analyses of the spent fuel transportation packages typically assume that the decay heat source distribution follows the fuel assembly burnup profile. When fuel reconfigures, the decay heat source redistributes. The thermal analyses of a spent fuel package with potential fuel reconfiguration must address the effect of the decay redistribution to the package external temperature to ensure the package meets the regulatory requirements. Since the decay heat source in a vertical cask is constrained by the fuel basket in a different geometric boundary than that of a horizontal package, different source relocation and source distribution scenarios may need to be analyzed.

In addition, relocation of the heat source toward the top end of the cask may increase the temperature near the cask seal. A prolonged high temperature of the seal may impair the performance of the seal and eventually lead to loss of containment boundary, leading to release of radioactive materials from the cask. This crosscutting issue may require attention of both thermal design and containment safety analyses.

PRACTICAL OPERATION and RETRIEVABILITY CONSIDERATION

In addition to the safety requirements, 10 CFR 72.122 (l) requires the storage systems be designed to allow readily retrieval of the spent fuel. 10 CFR 71.89 requires: "Before delivery of a package to a carrier for transport, the licensee shall ensure that any special instructions needed to safely open the package have been sent to, or otherwise made available to, the consignee for the consignee's use in accordance with 10 CFR 20.1906(e)."

For storage of high burnup fuel, the cask design may need to consider the possibility of fuel reconfiguration after the fuel has been stored for some time at which the fuel temperature has decreased substantially. The cask design may also need to consider providing specific requirements and/or instructions to the users for preserving the integrity of the fuel in the casks so that the eventual shippers of the fuel would not have to deal with rubbished fuel.

For transportation of high burnup fuel, for which the material properties of the cladding and assembly structure cannot be determined, the packaging designer may need to consider: (1) assuring the integrity of the fuel at the time of loading to demonstrate that the package meets the criticality safety requirement of 10 CFR 71.55(b) and (2) demonstrating that the package meets the requirement of 10 CFR 71.55(d), with the assumption that the fuel in the package will reconfigure under normal conditions of transport. Since the fuel in the package may reconfigure during transportation, adequate tools, facilities, and operating procedures must be developed for handling the reconfigured fuel in accordance with 10 CFR 71.89 and assure the package meets the regulatory requirements of 10 CFR 71.55(b) during unloading.

In order to demonstrate that the package satisfies the requirement of 10 CFR 71.89 and to facilitate the unloading operation, the packaging designer may need to develop appropriate operating procedures of the package and required facilities to assure that detailed loading and unloading procedures are in place to: (1) determine if the fuel has stayed substantially intact and (2) handle the reconfigured fuel, if necessary. These procedures and required tools for unloading reconfigured fuel may also be essential to assure that the package meets the criticality safety requirements of 10 CFR 71.55(b).

With consideration of potential fuel reconfiguration, the package design might be able to transport undamaged high burnup fuel as intact with consideration of the possibility that fuel may reconfigure under both normal conditions of transport and hypothetical accident conditions and address the safety requirements and practical operational needs by:

1. analyzing the worst case scenario fuel geometry that is bounding to all four safety related areas: criticality, shielding, thermal, and containment,
2. developing and implementing Aging Management Programs [11] for the ISFSI to make every effort to preserve the integrity of fuel cladding and the canister so that the fuel can be handled with normal mean under normal conditions of transport, and
3. developing facility and equipment that is capable of handling the fuel that was loaded as intact and had failed during normal transportation.

The underlying logic of this thinking is to explore a risk-informed and defense in-depth licensing philosophy for high burnup fuel storage and transportation. The key idea is that the licensee is expected to make every effort to preserve the integrity of cladding so that there is a reasonable assurance that the fuel will remain intact and can be handled as intact fuel during storage beyond the initial license and subsequent transportation. With the defense in-depth analyses for fuel reconfiguration, the carriers are informed for the potential risk and provide with procedures to handle reconfigured fuel. In case there is an indication that the fuel has reconfigured during storage and transportation, adequate facility and equipment are available to the receivers to handle the casks with reconfigured fuel.

SUMAMRY

Although high burnup fuel may reconfigure during further storage and subsequent transportation, it is not damaged when they are loaded in the casks. If the licensees make good effort to preserve the integrity of cladding so that there is a reasonable assurance that the fuel will remain intact, the cask designs may be able to treat high burnup fuel as intact during storage beyond the initial license and subsequent transportation. However, recognizing that the there is a potential that high burnup fuel may reconfigure during storage beyond the initial license and subsequent transportation, the cask designers may need to analyze the safety impact of fuel reconfiguration. The worst-case scenario analyses provide a defense-in-depth safety evaluation for the casks so that criticality, radiation, thermal, and containment safety of the casks are assured. With the defense in-depth analyses for fuel reconfiguration, the users are informed for the potential risk and provided with procedures to handle casks with reconfigured fuel. The NRC staff is currently evaluating the feasibility of this risk-informed and defense-in-depth licensing approach. Further studies may provide more information to help gain better understanding of high burnup fuel storage and transportation issues and develop effective regulations.

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