Requirements for the Transportation of Spent Nuclear Fuel (SNF) in Terms of Fuel Integrity and Data Needed According to

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1. Introduction

It would be desirable to delineate the requirements for the transportation of SNF in terms of fuel integrity, out of which the data needed to assure the satisfaction with the requirements could be enlisted and pursued according to, i.e. impact toughness, DBTT etc.(hydride behavior).

To meet the transportation regulations as well as to be able to predict confidently how SNF will behave during transportation and when handled after transportation to a repository or a processing facility also, we need to know the materials' properties and behavior.

Especially for the high burnup fuels, the higher the burnup level of the fuel increases beyond 45 GWd/MTU, the more vulnerable it should become. The thickness of the oxide layer on the exterior of Zircaloy cladding increases at a faster rate than at lower burnup levels possibly causing localized degradation of the cladding material. Additionally, as burnup levels increase, the cladding absorbs more hydrogen which affects the rate of material deformation and, depending on the environmental conditions of the cladding, can affect the mode of ultimate cladding failure. Hydride re-orientation and the increase of DBTT out of it could be a factor of its failure resulting from the cyclic vibration and impact encountered during transportation. Those factors should be evaluated in detail especially for the high burnup SNF. To have a look at the requirements in terms of fuel integrity and to draw a research plan for getting necessary data should be valuable to prepare SNF transportation near future.

2. Requirements in transportation of SNF in terms of fuel integrity

Regardless of the length of storage, used fuel eventually will have to be moved from the reactor sites either to off-site interim storage facilities or to used-fuel processing facilities for recycling or for waste management. Transportation regulations are largely focused on the integrity of the transportation casks, which contain the used fuel, and maintaining sub-criticality of the fuel. The primary goal is to ensure that the cask does not fail in the event of a transportation accident, with the potential for release of radioactive materials. The regulations require that under both normal and accident conditions, the transportation cask and its contents are capable of meeting stringent performance specifications that include maintaining geometric configuration of the fuel to certain limits largely for criticality and to address concerns about external radiation levels [1].

The most important technical issue should be whether the cladding could maintain its integrity against the impact encountered during transportation, despite that there shall be some degradation factor resulted from the extended storage period. The regulations regarding to the fuel integrity in transportation are as follows:

Fuel-Specific Regulations:

A fuel-specific regulation means a characteristic or performance requirement of the fuel specifically named in the applicable Code of Federal Regulations (CFR). These are regulations that specify capabilities that the SNF must have. For transportations:

- 10 CFR 71.55(d) states, in part: "A package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in 10 CFR 71.71 ('Normal conditions of transport')
  (1) The contents would be subcritical.
  (2) The geometric form of the package contents would not be substantially altered."
- Interim Staff Guidance-11, Revision 3, 'Cladding Considerations for the Transportation and Storage of Spent Fuel': "For hypothetical accident conditions, the licensee must assure that there is no significant cladding failure"[2].

System-Related Regulations:

A transportation and storage system must satisfy all applicable regulations in 10 CFR Parts 71 or 72. A system-related regulation is a performance requirement placed on the fuel for the system (i.e., transportation or storage cask) to meet a regulation that does not specifically require performance capabilities of the SNF. Examples include:

- 10 CFR 71.55(d): Requiring the system to remain subcritical and unchanged during normal transport, must be met. If gross breaches occurred on cladding, the SNF would be classified as damaged for transport because the requirements of 10 CFR 71.55(d) might not be met.
- 10 CFR 71.55(e) states in part: "A package used for the shipment of fissile material must be so designed and constructed and its contents so limited that under the tests specified in 10 CFR 71.73 ('Hypothetical accident conditions'), the package would be subcritical."

This regulation does not place a specific requirement on the SNF. However, if the package requires the SNF to maintain its geometric configuration to ensure sub-criticality, then a function is imposed on the SNF [3].

•NUREG-1617: For the containment review, fractions of rods that develop cladding breaches were assumed 3 % for normal condition of transport, 100 % for hypothetical accident conditions, respectively. Although these bounding values are for the evaluation of transportation system itself and have been developed from reasoned argument and experimental data, it does not mean the fraction of fuel breach is allowed to that value. The SAR should justify release fractions and specific activities, as appropriate.

3. Fuel Integrity during Transportation

Verification of the predicted mechanical performance of fuel after extended dry storage during cask and container handling and normal transportation operations shall be considered in the process of licensing. As the regulations describe the requirements for SNF integrity above, the integrity of SNF shall be maintained for normal operation and there should be no significant cladding failure for hypothetical conditions during transportation as well.

This is to ensure that the transported fuel assemblies will be retrievable at every type of facility they may be shipped to and that the other regulations will be met [1].

However it is not possible to design a transportation system which is able to maintain the SNF intact in perfect condition throughout whole transportation process. Then here comes a question, 'What fraction of fuel rods could be allowed to fail during transportation?'

The answer to this question would be that those failure percentages assumed in evaluating transport system are only guidance and an applicant would be able to come in with fuel values that are greater or less than those percentages as long as they demonstrate compliances to the other regulations. [Private correspondence with NRC staff]

4. Needed Data for evaluating of the Integrity of Cladding

Then, what kinds of material properties of cladding should we look at to evaluate the integrity of fuel rod in terms of failure rate?

The most significant potential degradation mechanisms affecting the fuel cladding during extended storage and transportation are expected to be those related to hydriding, creep, stress corrosion cracking and delayed hydride cracking, affecting its ductility, strength, and fracture toughness. Cladding can become brittle at low temperatures than DBTT. As the burnup goes higher, the pellet-cladding gap decreases, which would increase the cladding stresses and might lead to creep and SCC of cladding in extended storage. Pellet also acts as a resistance of cladding to the pinch mode stress.

Upon reaching the repository site, or other processing facility, the SNF will have to be handled, and that's why the integrity of it should be verified prior to transportation. If the fuel degrades during extended storage, it could be susceptible to damage from the vibration and shocks encountered during transportation. Here are two main players considered to be affecting cladding integrity mostly during transportation. 1) Hydride Re-orientation during dry storage is perceived to be of critical importance. 2) Ductile-Brittle transition Temperature (DBTT)

Radial hydrides can represent an additional embrittlement mechanism that could potentially result in cladding failure if the cladding temperature decreases below a DBTT and the rods are subjected to stresses higher than the fuel's mechanical limit. Recent research indicates that the hydride reorientation results in a shift of the DBTT of the cladding to a higher value.

To be able to evaluate cladding integrity during transportation, we need to model hydrogen content and hydride profile, hydride re-orientation, and 3-phase metal/hydride mixture in cladding, and also to implement a few of mechanical tests, i.e. bending and fatigue tests. Radial hydride continuity factor and critical strain energy density could be calculated out of those models and with which we can predict what fraction of fuel cladding would be intact or failed by analyzing of pinch loads to the cladding during transportation. This failure fraction should be incorporated in reviewing the transportation system for licensing. The most important thing as a foundation for the modeling of them would be that knowing the exact condition of microstructure of cladding and loaded condition with pellets in fuel rod. The difference between the condition of real SNF and the simulated experiment could misguide the conclusion to the wrong side, especially for the high burnup fuels. Currently, reviews of the transportation of high burnup SNF will be handled on a case-by-case basis due to lack of confirming data until further guidance is developed [4].

5. Summary

For the safe transportation of SNF and licensing, the integrity of SNF should be evaluated carefully. Researches to obtain the data for SNF cladding properties, i.e. impact toughness, DBTT (hydride behavior) when evaluating transportation of SNF, shall be precisely implemented by simulating the condition of real SNF to the hilt, accordingly.

REFERENCES

[1] US NWTRB, 'Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel' (2010).

[2] NRC Interim Staff Guidance-11, Revision 3.

[3] NRC Interim Staff Guidance-1, Revision 2.

[4] NRC RIS 2015-XX, 'Considerations in licensing HBF in dry storage and transportation'.