Criticality Safety of Spent Fuel Casks Considering Water Inleakage

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1. Abstract

A fundamental safety design parameter for all fissile material packages is that a single package must be critically safe even if water leaks into the containment system. In addition, criticality safety must be assured for arrays of packages under normal conditions of transport (undamaged packages) and under hypothetical accident conditions (damaged packages). The U.S. Nuclear Regulatory Commission staff has revised the review protocol for demonstrating criticality safety for spent fuel casks. Previous review guidance specified that water inleakage be considered under accident conditions. This practice was based on the fact that the leak tightness of spent fuel casks is typically demonstrated by use of structural analysis and not by physical testing. In addition, since a single package was shown to be safe with water inleakage, it was concluded that this analysis was also applicable to an array of damaged packages, since the heavy shield walls in spent fuel casks neutronically isolate each cask in the array. Inherent in this conclusion is that the fuel assembly geometry does not change significantly, even under drop test conditions. Requests for shipping fuel with burnup exceeding 40 GWd/MTU, including very high burnups exceeding 60 GWD/MTU, caused a reassessment of this assumption. Fuel cladding structural strength and ductility were not clearly predictable for these higher burnups. Therefore the single package analysis for an undamaged package may not be applicable for the damaged package. NRC staff developed a new practice for review of spent fuel casks under accident conditions. The practice presents two methods for approval that would allow an assessment of potential reconfiguration of the fuel assembly under accident conditions, or, alternatively, a demonstration of the water-exclusion boundary through physical testing.

2. NRC Regulations for Fissile Material Packages

In the U.S., the Nuclear Regulatory Commission approves designs for fissile material packages. The regulations that pertain to criticality safety of fissile material packages are contained in the U.S. Code of Federal Regulations, Title 10, Part 71 [1], sections 71.55 and 71.59. The provisions of 71.55 specify the primary requirements. The derivation of the criticality safety index and the criticality safety requirements for package arrays are contained in 71.59.

Section 71.55 specifically addresses how the criticality evaluation of the package must be performed with respect to water inleakage into the containment system for a single package in isolation. For the single package evaluation, 71.55(b) states that a package must be subcritical if water were to leak into the containment system, assuming that the fissile material is in the most reactive credible configuration consistent with the chemical and physical form of the material, and with moderation by water to the most reactive credible extent. This is considered to be a “non-mechanistic” approach to ensure criticality safety in transport, that is, the assumption of water inleakage is not necessarily dependent upon the condition of the package under the normal and accident conditions tests typically used to evaluate package performance. The regulation in 71.55(c) allows the NRC to approve exceptions to 71.55(b) under certain circumstances.

Section 71.55(d) specifies that a single package subjected to the normal conditions tests must remain subcritical. In addition it requires that the package must be designed to prevent water inleakage into the containment system under the normal conditions tests, unless the criticality evaluation for package arrays assumes moderation to the most reactive extent.

Section 71.55(e) specifies that the single package must remain subcritical if subjected to the hypothetical accident tests (damaged package), including the free drop, fire and immersion sequence, as well as the 15-meter water immersion test.

In addition to the single package evaluation, 71.59 specifies that criticality safety must be ensured for arrays of undamaged and damaged packages, and includes the derivation of the criticality safety index.

3. Past Review Practice

The Spent Fuel Project Office of the NRC has reviewed and certified a large number of fissile material package designs. In addition, NRC staff has published a number of guidance documents that describe methods that are acceptable to the staff with respect to criticality evaluations and the consideration of water inleakage. NUREG-1609 [2] and NUREG-1617 [3] are the NRC guidance documents that describe staff review procedures for transportation package applications. These are the Standard Review Plans for transportation packages for spent fuel and other radioactive materials. These documents indicate that the single package and damaged packages should be evaluated with water inleakage to the most reactive extent. For the single package analysis and for arrays of damaged packages, excluding packages of uranium hexafluoride, NRC-certified designs have been evaluated with water inleakage into the containment system. Uranium hexafluoride has been recognized as a unique commodity, and separate regulatory requirements have been established for its shipment.

Thus, for design approvals, the criticality safety of NRC-approved fissile material packages does not rely on the package excluding water moderation. This has provided a high degree of defense in depth with respect to prevention of accidental criticality in transport. Because of this high degree of defense in depth, accident criticality has not been considered in the risk studies associated with the transport of radioactive materials in the U.S.

For the criticality safety assessment for spent fuel packages, it was recognized that analyses used to satisfy the requirements of 71.55(b), the "non-mechanistic" water inleakage, and 71.55(e), water inleakage under accident conditions, were essentially the same. This was because under 71.55(b) water was always assumed to leak into the containment system, which represents the most reactive condition with respect to criticality. Because 71.55(b) requires a criticality analysis assuming water inleakage, this analysis was typically used to represent the single damaged package as well. In addition, although regulations allowed the Commission to authorize exceptions, it was recognized that approval of package designs should continue to comply with 71.55(b). Based on structural analyses of fuel rod cladding and physical testing performed, it was concluded that credible fuel reconfiguration under accident conditions would not result in a more reactive fuel system. Although there could be some changes in the packaging as a result of the accident conditions tests that could affect system reactivity, for example, loss or damage of a neutron shield, the undamaged fuel configuration would be the most reactive credible condition.

4. Reevaluation of Review Practices

The reevaluation of the practice associated with water inleakage into fissile material packages was initiated as a result of the problems associated with the structural integrity of highly irradiated nuclear fuel, primarily in storage casks. Due to the effects of irradiation, the cladding of spent fuel, and particularly high burnup fuel (i.e., fuel with a burnup greater than 45,000 MWD/MTU) may become brittle. If excessively brittle, the cladding could fracture under impact loads associated with the hypothetical accident free drop test conditions. The criticality safety of the reconfigured fuel assembly was not clearly bounded by the undamaged fuel geometry. For example, it was postulated that the cladding on some rods could shear circumferentially and result in the removal of large sections of fuel rods from the lattice. This removal of rods could result in a more reactive fuel system than the undamaged fuel configuration.

It was recognized that the reevaluation of the review practices for spent fuel packages involved multiple technical disciplines associated with the package review. A working group of senior staff was assembled to reevaluate the practices. The working group included technical staff expert in criticality safety, structural evaluations, and materials reviews, as well as transportation project managers. The working group process included a technical evaluation for any proposed changes to the review practice.

5. Considerations of the Working Group

The working group first defined the scope of its work based on preliminary deliberations. Recognizing that the provisions of 71.55(b) required the "non-mechanistic" evaluation of water inleakage, the working group limited its scope to the evaluations under 71.55(e), criticality safety of a single package under accident conditions. The working group did not consider changes in the regulatory requirements of 71.55(b) nor a generic exemption to the requirements of 71.55(b) as a practical near-term path forward.

To address the primary concerns, the working group limited its deliberations to transportation packages for spent fuel. This was done for a number of reasons. First, it was recognized that the most immediate need was in the nuclear power industry for the licensing of dual purpose cask systems that were designed for both interim storage then transport of high burnup fuel. Second, spent fuel casks are always heavily shielded structures that are neutronically isolated. That is, with respect to criticality safety, a single spent fuel cask is essentially the same as a large array of casks, since the fuel in each cask does not communicate neutronically with its neighbors. Third, spent fuel casks are typically shipped singly. This makes the evaluation of arrays of damaged packages conservative when considering actual shipping configurations. Fourth, the NRC has published several guidance documents that address the design and manufacture of spent fuel casks. Much of the guidance is based on nationally and internationally recognized codes and standards, such as the American Society of Mechanical Engineers Boiler and Pressure Vessel Code. The working group agreed that other fissile material packages should continue to consider water inleakage under both 71.55(b) and 71.55(e) for criticality safety. The working group also limited its deliberations to intact (undamaged) spent fuel.

6. Revised Review Guidance

The Spent Fuel Project Office periodically issues Interim Staff Guidance documents (ISGs). The ISGs are intended to address emergent issues and are considered to be supplements to the applicable Standard Review Plan. An ISG is issued to document staff practice with respect to certain technical aspects of a package review. The working group developed ISG 19 [4] to document acceptable practices with respect to assumptions regarding water inleakage into spent fuel transportation casks. ISG 19 was issued in May 2003. As with other ISGs, it is available on the NRC website to provide information to the public and to applicants for package approvals (http://www.nrc.gov/reading-rm/doc-collections/isg/). ISG 19 outlines two approval pathways to demonstrate compliance with 71.55(e). These pathways are: (1) approvals based on an evaluation of reconfigured fuel assuming water inleakage, and (2) approvals based on moderator exclusion under accident conditions. The tables below are extracted from the ISG and outline the fundamental elements of the two approaches.

7. Conclusion

The Spent Fuel Project Office has revised its review practices with respect to criticality evaluations for spent fuel transportation packages. The review practice recognizes two approaches that can be used to adequately demonstrate criticality safety under accident conditions. The applicant can show that that the fuel, assumed to be damaged and reconfigured, remains subcritical even if water leaks into the containment system, or the applicant can show, by a combination of physical tests and analyses, that the containment system will not leak water. The review guidance includes a description of the type of information that should be provided by an applicant using the chosen approach.

APPROVALS BASED ON RECONFIGURED FUEL		
Approach	**Characteristics**	**Objective**
Criticality Assessment of Limiting Reconfigured Fuel Geometries Assuming Water Inleakage	1. Postulate limiting configurations for criticality. 2. Find limiting configurations with respect to criticality safety. A generic approach may be practical. 3. Limited reliance on material properties of high burnup fuel cladding and failure criteria. 4. Criticality analyses of reconfigured fuel.	Demonstrate subcriticality of defined set of bounding fuel configurations with water inleakage.
Criticality Assessment of Credible Reconfigured Fuel Geometries Assuming Water Inleakage	1. Need material properties of high burnup fuel cladding and failure criteria. 2. Requires nonlinear finite element analysis of fuel assemblies and fuel rods under drop impact conditions. 3. Failure modes and fuel rod failure distributions to be addressed (probabilistic approach to the distribution of material properties among fuel rods). 4. Credible fuel reconfiguration geometries. 5. Criticality analyses of reconfigured fuel.	Demonstrate subcriticality of credible fuel configurations with water inleakage. This requires extensive data for irradiated hydrided cladding material properties for high burnup fuels. These data are currently not available. Therefore it is judged that this approach is currently not practical.

APPROVALS BASED ON MODERATOR EXCLUSION		
Approach	**Characteristics**	**Objective**
Criticality Assessment of Reconfigured Fuel Assuming Moderator Exclusion	1. Demonstrate water-tight barrier under hypothetical accident conditions. 2. Bolted closures must meet NUREG/CR-6007 [5]. 3. Drop test of cask or inner canister (see below).	Bolted closures should meet NUREG/CR-6007, including fatigue evaluation and program for testing for counterfeit bolts.
For Welded Canister-Based Systems: Canister Drop Test as Part of Impact Limiter Testing	1. Scale model of canister and contents included in transport cask impact limiter 30-foot drop tests. 2. Perform relative leak rate testing (before and after drops). 3. Demonstrate leakage rate to prevent water inleakage.	Physical test of canister to provide added assurance of moderator exclusion under accident conditions.
For Canister-Based Cask Systems and Direct-Loaded Casks: Bolt Closure System Test as Part of Impact Limiter Testing	1. Include transport cask bolt closure system in scale model drop tests of impact limiter. 2. Perform relative leak rate testing (before and after drops). 3. Demonstrate leakage rate to prevent water inleakage.	Physical test of bolt closure system to provide added assurance of moderator exclusion under accident conditions.

8. References

[1] United States Code of Federal Regulations, Title 10, Part 71.

[2] U.S. Nuclear Regulatory Commission, “Standard Review Plan for Transportation Packages for Radioactive Material,” NUREG-1609, May 1999.

[3] U.S. Nuclear Regulatory Commission, “Standard Review Plan for Transportation Packages for Spent Nuclear Fuel,” NUREG-1617, March 2000.

[4] U.S. Nuclear Regulatory Commission, Staff Interim Guidance Document No. 19, “Moderator Exclusion under Hypothetical Accident Conditions and Demonstrating Subcriticality of Spent Fuel under the Requirements of 10 CFR 71.55(e), Rev. 0, May 2003.

[5] U.S. Nuclear Regulatory Commission, “Stress Analysis of Closure Bolts for Shipping Casks,” NUREG/CR-6007, January 1993.