Spent Fuel Project Office
Interim Staff Guidance - 11, Revision 2

Issue: Cladding Considerations for the Transportation and Storage of Spent Fuel

The staff has reevaluated the technical basis for the storage of spent fuel including assemblies with average assembly burnups exceeding 45 GWd/MTU. This revision to Interim Staff Guidance No. 11 (ISG-11) addresses the technical review aspects and specifies the acceptance criteria for limiting spent fuel reconfiguration in storage casks. It modifies the previous revision of the ISG by: removing the definitions for intact and potentially damaged high burnup fuel which were based on the cladding oxide thickness; removing the confinement and containment analysis criteria which required applicants to assume (for analytical purposes) a percentage of leaky high burnup fuel rods under normal conditions of storage; removing the 1 percent creep strain limit; and adding criteria to limit hydride reorientation in the cladding.

The staff is currently reevaluating the technical basis for the transportation of spent fuel including assemblies with average assembly burnups exceeding 45 GWd/MTU. The staff is reviewing data and technical reports to further understand the mechanical and fracture toughness properties of spent fuel cladding in relation to the transportation of high burnup fuel under 10 CFR 71.55. Therefore, until further guidance is developed, the transportation of high burnup commercial spent fuel will be handled on a case-by-case basis using the criteria given in 10 CFR 71.55.

This ISG focuses on the acceptance criteria needed to provide reasonable assurance that commercial spent fuel is maintained in the configuration that is analyzed in storage Safety Analysis Reports (SARs). Further, these criteria are applicable to all intact spent fuel independent of the burnup level.

Regulatory Basis

The regulations for storage in 10 CFR Part 72 and for transportation in 10 CFR Part 71 have the following common safety objectives: (1) ensure that the doses are less than the limits prescribed in the regulations; (2) maintain subcriticality under all credible conditions of storage and transportation; and (3) ensure there is adequate confinement and containment of the spent fuel under all credible conditions of storage and transportation. Additionally, 10 CFR Part 72 regulations require that the spent fuel be readily retrieved from the storage systems. The regulations that underpin these objectives will continue to be the foundation from which safety is ensured for the storage and transportation of spent fuel at all burnup levels. The following Part 72 and Part 71 regulations pertain to the configuration control of spent fuel under the various storage or transportation conditions.

The requirements of 10 CFR 72.122 (h)(1) seek to ensure safe fuel storage and handling and to minimize post-operational safety problems with respect to the removal of the fuel from storage. In accordance with this regulation, the spent fuel cladding must be protected during storage against degradation that leads to gross ruptures, or the fuel and must be otherwise confined such that degradation of the fuel during storage will not pose operational problems with respect to its removal from storage. Additionally, 10 CFR 72.122(l) and 72.236(m) require that the storage system be designed to allow ready retrieval of the spent fuel from the storage system for further processing or disposal.

In accordance with 10 CFR Part 71, the geometric form of the spent fuel should not become substantially altered under normal conditions of transport as analyzed and specified in the SAR. Additionally, for normal conditions of transport, the licensee must assure that there will be no loss or dispersal of spent fuel, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the spent fuel package as required by 10 CFR 71.43(f). For hypothetical, credible, accident conditions, the licensee must assure that any damage to the cladding does not lead to a failure to meet the criticality requirements of 10 CFR 71.55 and the shielding and containment requirements of 10 CFR 71.51. Full reliance on cladding integrity during hypothetical, credible accident conditions of transport will require further information on the impact properties of high burnup cladding material. Therefore, until further guidance is developed, reviews of the transportation of high burnup commercial and noncommercial spent fuels will be handled on a case-by-case basis.

Applicability

This guidance applies to reviews of dry cask storage systems and radioactive material transportation packages conducted in accordance with NUREG-1536, “Standard Review Plan for Dry Cask Storage Systems” (January 1997); NUREG-1567, “Standard Review Plan for Spent Fuel Dry Storage Facilities” (March 2000); and NUREG-1617, “Standard Review Plan for Transportation Packages for Spent Nuclear Fuel” (March 2000).

Because this ISG includes acceptance criteria related to multiple review disciplines, it supercedes, in their entirety, ISG-11, Revision 1, and the guidance on high burnup fuel that is contained in Section X.5.4. of ISG-15.

Technical Review Guidance

The staff has reevaluated the basis for developing the acceptance criteria contained in ISG-11, Revision 1, and ISG-15, Revision 0, and believes there is a technical basis for revising the guidance. The Appendix provides detailed guidance to the reviewers of spent fuel storage cask applications and amendments.

The acceptance criteria and review procedures provide reasonable assurance that the spent fuel is maintained in the configuration that is analyzed in the storage SARs. The guidance and criteria are applicable to all commercial spent fuel burnup levels and cladding materials. Therefore, the staff believes that the guidance will allow all commercial spent fuel that is currently licensed by the NRC for commercial power plant operations to be stored in accordance with the regulations contained in Part 72. However, cask vendors' requests for the storage of spent fuel with burnup levels in excess of those levels licensed by the Office of Nuclear Reactor Regulation (NRR), or for cladding materials not licensed by NRR, may require additional justifications by the applicant.

The acceptance criteria and staff guidance for the classification of damaged fuel assemblies can be found in Interim Staff Guidance-1, “Damaged Fuel." Additionally, the acceptance criteria for assuring retrievability of commercial spent fuel from storage casks and facilities are contained in ISG-2, “Retrievability.”

Recommendation

The staff proposes that NUREG-1536, NUREG-1567, and NUREG-1617 be modified to add the acceptance criteria and staff review guidance contained in the Appendix. This ISG will result in modifications to the materials and containment or confinement chapters of these SRPs.

Approved:_______***/RA/*** *(Original Signed by M. Wayne Hodges for:)*___07/30/02______
E. William Brach, Director Date
Spent Fuel Project Office

APPENDIX
Review Guidance for ISG-11, Revision 2

Materials Reviewers

Spent fuel storage casks and systems must be designed to meet four safety objectives: (1) ensure that doses from the spent fuel in the casks and systems are less than limits prescribed in the regulations, (2) maintain subcriticality under all credible conditions, (3) ensure that there is adequate confinement and containment of the spent fuel under all credible conditions of storage, and (4) allow the ready retrieval of the spent fuel from the storage systems. In general, the materials reviewer should coordinate with the structural reviewer to assure that the spent fuel is maintained in the configuration that is analyzed in the Safety Analysis Reports (SARs) in order to meet the objectives described above. Requests for the storage of commercial spent fuel with burnup levels in excess of those levels licensed by the Office of Nuclear Reactor Regulation (NRR), or for cladding materials not licensed by NRR, may require additional justifications by the applicant. Staff should conduct these reviews on a case-by-case basis. Additionally, reviews of the transportation of commercial and noncommercial spent fuel will be handled on a case-by-case basis. The staff is reviewing data on the mechanical properties and fracture toughness properties of commercial spent fuel cladding in order to develop further guidance to assist the applicant in meeting the requirements of 10 CFR 71.55 for transportation.

The following review guidance and acceptance criteria should be used by the staff when reviewing SAR analyses of the potential for fuel reconfiguration during storage operations. The spent fuel cladding is the primary structural component that is used to ensure that the spent fuel is contained in a known geometric configuration. Accordingly, the guidance and acceptance criteria address cladding considerations to provide reasonable assurance that commercial spent fuel is maintained in the configuration that is analyzed in storage SARs.

Creep is the dominant mechanism for cladding deformation under normal conditions of storage. The relatively high temperatures, differential pressures, and corresponding hoop stress on the cladding will result in permanent creep deformation of the cladding over time. Several laboratory programs have demonstrated that spent fuel has significant creep capacity even after 15 years of dry cask storage. Einziger, et al. (2002) reported that irradiated Surry-2 PWR fuel rods (35.7 GWd/MTU) that were stored for 15 years at an initial temperature of 350 °C (with temperatures reaching as high as 415 °C for up to 72 hours) experienced thermal creep which was estimated to be less than 0.1 percent. Post-storage creep tests were conducted to assess the residual creep capacity of the Surry-2 fuel rods. One rod segment experienced a creep strain of 0.92 percent without rupture at 380 °C and 220 MPa in 1820 hours (75.8 days). A different rod segment was tested at 400 °C and 190 MPa for1873 hours (78 days) followed by 693 hours (28.9 days) at 400 °C and 250 MPa and experienced a creep strain of more than 5 percent without failure (Tsai, 2002). Profilometry measurements on that fuel rod indicated that the creep deformation was uniform around the circumference of the cladding with no signs of localized bulging, which can be a precursor for rupture. A recent report of the literature (Beyer, 2001) also indicates that spent fuel cladding can accommodate creep strains of 2.8-7.5 percent at temperatures between 390 and 420 °C and hoop stresses between 225 and 390 MPa. Other significant contributions to the understanding of the effects of creep on spent fuel cladding can be found in several references (Johnson and Gilbert, 1983; Rashid, et al., 2000; Hendricks, 2001; Rashid and Dunham, 2001; Machiels, 2002). In general, these data and analyses support the conclusions that: (1) deformation caused by creep will proceed slowly over time and will decrease the rod pressure; (2) the decreasing cladding temperature also decreases the hoop stress, and this too will slow the creep rate so that during later stages of dry storage, further creep deformation will become exceedingly small; and (3) in the unlikely event that breaching of the cladding due to creep occurs, it will not result in gross rupture.

Based on these conclusions, the staff has reasonable assurance that creep under normal conditions of storage will not cause gross rupture of the cladding and that the geometric configuration of the spent fuel will be preserved provided that the maximum cladding temperature does not exceed 400 °C. Accordingly, the materials reviewer should coordinate with the thermal reviewer to assure that the maximum calculated temperatures for normal conditions of storage, and for short-term operations including cask drying and backfilling, do not exceed 400 °C (752 °F). As discussed below, this temperature limit will also limit the amount of radially oriented hydrides that may form, as temperatures decreases over time.

The effects of normal conditions of storage (i.e., the decaying temperature and hoop stress on the cladding with time) can affect the metallurgical condition of spent fuel cladding containing significant amounts of hydrogen (e.g., spent fuel with high burnup levels). As the burnup level of the fuel increases beyond 45 GWd/MTU during reactor operation, the thickness of the oxide layer on the cladding increases. With increasing oxidation during reactor operation, the cladding absorbs more hydrogen. As discussed in Garde, et al. (1996), Chung and Kassner (1997), and Newman (1986), high burnup fuels tend to have relatively higher concentrations of hydrogen in the cladding. The hydrogen is present in the cladding predominantly as zirconium hydride precipitates, or particles. After the fuel is removed from the reactor, the zirconium hydrides are generally elongated and oriented circumferentially. At elevated temperatures, a percentage of the zirconium hydrides will dissolve, and under decreasing temperatures, zirconium hydrides will precipitate, or re-form.

The materials phenomenon of hydride reorientation in zirconium-based alloys usually involves the dissolution of circumferential hydrides and the formation of zirconium-hydrides oriented perpendicular to the hoop stress (also referred to as radially oriented or radial hydrides) (Chung, 2000). This occurs under sufficiently high hoop stresses along with the decrease in solubility of hydrogen that accompanies decreasing temperatures. The extent of the formation of radially oriented hydrides is a function of many parameters including the solubility of hydrogen in irradiated cladding material, cladding temperature, hoop stress, cooling rate, hydrogen concentration, thermal cycling, and materials characteristics. A temperature limit of 400 °C for normal conditions of storage and for short-term storage operations will limit cladding hoop stresses and limit the amount of soluble hydrogen available to form radial hydrides.

It should be noted that, in any one storage cask, there will be a distribution of cladding temperatures less than 400 °C resulting in distributions in the rod internal pressures and the cladding hoop stresses. It is expected that due to these distributions a small fraction of the rods will experience the temperature and stress conditions that could lead to the formation of radial hydrides.

The general effects of irradiation on the mechanical properties and fracture toughness of spent fuel cladding are well understood for cladding temperatures that are likely to be encountered under normal conditions of storage and short-term operations. However, the effects of high hydrogen concentrations (such as in high burnup fuel) combined with high strain rate loading conditions (such as under accident conditions) on the mechanical properties and fracture toughness are not as well understood. Depending on the concentration of hydrogen in the cladding and the size, distribution, orientation, and location of zirconium hydrides, the spent fuel cladding could become less ductile with decreasing storage temperatures such that the stresses on the cladding when applied at high strain rates could cause fracture of the cladding under accident conditions. To limit the decrease in ductility and fracture toughness that may be associated with hydride reorientation, the materials reviewer should coordinate with the thermal reviewer to assure that: (1) the peak cladding temperatures for normal conditions of storage and short-term operations are limited to a temperature less than 400 °C, and (2) repeated thermal cycling of the cladding during fuel loading operations is minimized. Thermal cycling of the cladding with temperature differences greater than 65 °C should not be permitted.

The 400 °C temperature limit is regarded to be applicable to all spent fuel types and should be applied as the maximum allowable temperature until the effects of reorientation are better understood.

It should be noted that, historically, applicants had to calculate the cladding hoop stress at the peak cladding temperature. The temperatures of the fuel and the fuel rod internal pressures (which correspond to the cladding hoop stresses) were input parameters used to calculate the maximum allowable cladding temperature that prevented creep rupture from occurring under normal conditions of storage. Recognizing that the cladding temperature and the hoop stress (or, more correctly, the rod internal pressure) are related, the 400 °C limit also corresponds to a limit on the hoop stress, which is a function of the internal pressure and design of the fuel rod. Accordingly, the applicant does not need to calculate, and the reviewer does not need to verify the applicant's calculation of the cladding hoop stress. However, high burnup fuel (i.e., fuel with burnups generally exceeding 45 GWd/MTU) may have wall thinning from increased oxidation or the formation of a layer of zirconium hydride. The applicant should estimate and specify the maximum cladding oxide thickness, and thickness of the hydride layer (or rim) used in evaluations of fuel rod structural integrity, such as the buckling analysis, under hypothetical, credible, accident conditions. The reviewer should verify that the applicant has used a value of cladding oxide thickness that is justified by using oxide thickness measurements, computer codes validated to experimentally measured oxide thickness data, or other means that the staff finds appropriate. Note that oxidation may not be of a uniform thickness along the axial length of the fuel rods.

Regarding accidents involving a fire or off-normal thermal transients, the dominant cladding failure mechanism is expected to be rupture of the cladding due to excessive creep. To limit the amount of spent fuel that could be released from the cladding under off-normal thermal transients or accidents, the materials reviewer should coordinate with the thermal review to verify that the maximum calculated cladding temperatures during an accident involving a fire are maintained below 570 °C (1058 °F). The basis for using 570 °C is established by the creep tests conducted on irradiated Zircaloy-4 rods (Johnson, et al., 1983). The results from these experiments indicated that for two spent fuel rods no cladding ruptures were observed for test times of 30 and 73 days.

Confinement Reviewers

The reviewer should verify that all of the criteria outlined in ISG-5 are met.

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