Spent Fuel Project Office
Interim Staff Guidance - 11, Revision 3

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

The staff has broadened the technical basis for the storage of spent fuel including assemblies with average burnups exceeding 45 GWd/MTU. This revision to Interim Staff Guidance No. 11 (ISG-11) addresses the technical review aspects of and specifies the acceptance criteria for limiting spent fuel reconfiguration in storage casks. It modifies the previous revision of the ISG in three ways: (1) by clarifying the meaning of some of the acceptance criteria contained in Revision 2, (2) adding acceptance criteria to allow higher cladding temperature limits for certain conditions of storage, and (3) providing justification for allowing licensees to continue to use the 570°C cladding temperature limit for short-term fuel loading operations of previously certified dry cask storage systems licensed to store low burnup (less than 45 GWd/MTU) spent fuel only.

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, 10 CFR 71.43(f), and 10 CFR 71.51.

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 the Safety Analysis Reports (SARs) for spent fuel storage. Further, this guidance is applicable to all intact commercial spent fuel, independent of the burnup level, unless otherwise noted.

Regulatory Basis

The regulations for storage, as given in 10 CFR Part 72, and those for transportation, as given 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 retrievable 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 various conditions of storage or transportation.

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 rupture of 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. Additionally, for normal conditions of transport, 10 CFR 71.43(f), requires that 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. 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.

For high burnup cladding material, cladding performance during hypothetical accident conditions of transport will require further information on the impact properties. Data is not currently available. 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).

This ISG supercedes, in its entirety, ISG-11, Revision 2 and the guidance on cladding integrity contained in Section X.4.4 and X.5.4 of ISG-15.

Technical Review Guidance

Materials Reviewers

The following acceptance criteria and review procedures are designed to provide reasonable assurance that the spent fuel is maintained in the configuration that is analyzed in the storage SARs. These criteria are applicable to all commercial spent fuel burnup levels and cladding materials.

In order to assure integrity of the cladding material, the following criteria should be met:

1. For all fuel burnups (low and high), the maximum calculated fuel cladding temperature should not exceed 400°C (752°F) for normal conditions of storage and short-term loading operations (e.g., drying, backfilling with inert gas, and transfer of the cask to the storage pad).

   However, for low burnup fuel, a higher short-term temperature limit may be used, if the applicant can show by calculation that the best estimate cladding hoop stress is equal to or less than 90 MPa (13,053 psi) for the temperature limit proposed.

2. During loading operations, repeated thermal cycling (repeated heatup/cooldown cycles) may occur but should be limited to less than 10 cycles, with cladding temperature variations that are less than 65°C (117°F) each.

3. For off-normal and accident conditions, the maximum cladding temperature should not exceed 570°C (1058°F).

High burnup fuel (i.e., fuel with burnups generally exceeding 45 GWd/MTU) may have cladding walls that have become relatively thin from in-reactor formation of oxides or zirconium hydride. For design basis accidents, where the structural integrity of the cladding is evaluated, the applicant should specify the maximum cladding oxide thickness and the expected thickness of the hydride layer (or rim). Cladding stress calculations should use an effective cladding thickness that is reduced by those amounts. The reviewer should verify that the applicant has used a value of cladding oxide thickness that is justified by the use of oxide thickness measurements, computer codes validated using 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.

Prior to issuance of ISG-11, Rev. 2, the short-term cladding temperature limit applicable to fuel loading operations was 570°C. All storage casks were certified using this limit. With the issuance of ISG-11, Rev. 2, the need to maintain cladding temperatures less than 400°C during fuel loading operations put into question whether the licensees who use certified storage casks (certified for fuel having average assembly burnups less than 45 GWd/MTU) would have to change their loading procedures and Technical Specifications to comply with this new temperature limit. Based on staff's evaluation, it is expected that fuel assemblies with burnups less than 45 GWd/MTU are not likely to have a significant amount of hydride reorientation due to limited hydride content. Further, most of the low burnup fuel has hoop stresses below 90 MPa. Even if hydride reorientation occurred during storage, the network of reoriented hydrides is not expected to be extensive enough in low burnup fuel to cause fuel rod failures.

Given the conservatism used in calculating peak clad temperatures for low burnup fuel, the staff has reasonable assurance that storage cask systems which use the 570°C temperature limit for low burnup fuel loading operations will continue to perform as expected when the casks were originally certified. Therefore, there is no need to require the licensees of storage-only or dual-purpose cask systems to repackage spent fuel that was loaded using the 570°C temperature limit. Nevertheless, the 400°C limit is intended, with exceptions as stated above, to be generally applicable to all future loadings. Therefore, licensees are not required to modify their Technical Specifications or fuel loading procedures (i.e., vacuum drying) to meet the new 400°C limit for loading low burnup fuel into storage casks previously certified with the 570°C limit. Note that for future amendments to certified designs, the applicants may be required to comply with the 400°C temperature limit as discussed above.

The staff believes that this guidance will allow all commercial spent fuel that is currently licensed by the Nuclear Regulatory Commission (NRC) for commercial power plant operations to be stored in accordance with the regulations contained in 10 CFR 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 background for this guidance and criteria can be found in Appendix A.

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.”

Confinement Reviewers

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

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 Appendix A. This ISG will result in modifications to the materials and containment or confinement chapters of these SRPs.

Approved: /RA/ original signed by L. W. Camper acting for 11/17/03
E. William Brach, Director Date
Spent Fuel Project Office

APPENDIX A
Background for Review Guidance for ISG-11, Revision 3

Dry Cask Storage

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 justification by the applicant. Staff should conduct these reviews on a case-by-case basis.

The following review guidance and acceptance criteria should be used by the staff when reviewing SAR analyses of potential 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., (2003) 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 for 1873 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 report of the literature (Beyer, 2001) also indicates that some 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 (Einziger, et al., 1982; 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 a breach of the cladding due to creep occurs, it is believed that this 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 (752°F). As discussed below, this temperature will also limit the amount of radially oriented hydrides that may form under normal conditions of storage.

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 and are predominantly present in the outer rim of the cladding. 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 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. Among these parameters, the formation of radial hydrides is highly dependent on the hoop stress in the cladding. Data obtained from irradiated cladding (Einziger and Kohli, 1984; Cappelaere, et al., 2001; and, Goll, et al., 2001) indicate that stresses greater than 120 MPa (17.4 ksi) are required to initiate the formation of radial hydrides. Other data obtained from unirradiated zirconium-based cladding materials (Kese, 1998) indicate that radial hydrides can form at stresses as low as 90 MPa. Therefore, until the effects of reorientation are better understood, the hoop stress on the cladding should be controlled to preclude the formation of radially oriented hydrides.

In general, a temperature limit of 400°C that is specified for normal conditions of storage and for short-term fuel loading and Part 72 storage operations (which includes drying, backfilling with inert gas, and transfer of the cask to the storage pad) will limit cladding hoop stresses and limit the amount of soluble hydrogen available to form radial hydrides. The use of a 400°C temperature limit for normal conditions of storage and for short-term fuel loading and storage operations will simplify the calculations in SARs while assuring that hydride reorientation will be minimized. For low burnup fuel, a higher temperature limit may be used for short-term fuel loading and storage operations only, as long as the applicant can demonstrate that the best estimate cladding hoop stresses are equal to or less than 90 MPa for the temperature limit that is justified. For example, if the calculated best estimate hoop stress is equal to 90 MPa at 540°C, then 540°C is the maximum allowable temperature for loading operations. In this example, 570°C is not the maximum allowable temperature limit. If the applicant can show that the best estimate hoop stress is less than or equal to 90 MPa at 570°C, then 570°C is the maximum allowable temperature. For some fuel types, short-term fuel loading and storage operation temperature limits as high as 570°C (1058°F) should be justified by the applicant.

The materials reviewer should coordinate with the thermal reviewer to assure that either of the following criteria are used: (1) for low and high burnup fuel, the maximum calculated temperatures for normal conditions of storage and for fuel loading operations do not exceed 400°C, or (2) for low burnup fuel, a higher temperature limit may be used for loading and transfer operations, if the best estimate cladding hoop stress is less than 90 MPa for the temperature specified by the applicant. If the applicants use the latter approach, the materials reviewer should verify that the cladding hoop stresses are less than 90 MPa for each fuel assembly type (e.g., 14x14, 17x17, 9x9, etc.) proposed for storage. Since the hoop stress is dependent on the rod internal pressure, cladding geometry, and the temperature of the gases inside the rod, the materials reviewer should coordinate with the thermal reviewer to verify that the applicant has calculated the best estimate hoop stress corresponding to the rod internal pressure of the highest burnup fuel assemblies of the specific type of assembly.

It should be noted that during normal conditions of storage there will be a range of cladding temperatures that are less than the maximum allowable cladding temperature of 400°C, and this leads to a range of the internal rod pressures and the cladding hoop stresses, in any one storage cask. In general, the maximum allowable temperature will be 400°C or the maximum allowable temperature specified and supported (as discussed above) by the applicant. The maximum allowable temperature should be based upon the **peak** rod temperature, not the average rod temperature. By employing the peak rod temperature, only a small fraction of the rods will experience the temperature and stress conditions that could lead to the formation of radial hydrides during normal conditions of storage.

It also has been observed and reported that thermal cycling (repeated heatup/cooldown cycles) can enhance the amount of hydrogen that eventually re-precipitates in the form of radial hydrides (Kammenzind, et al., 2000). The extent of the formation of radial hydrides is dependent on many factors including the maximum temperature, change in temperature, number of thermal cycles, applied stress, hydrogen concentration, and solubility of hydrogen in the material. Kammenzind, et al., 2000, indicates that the formation of radial hydrides in spent fuel cladding can be minimized by restricting the change in cladding temperatures to less than 65°C and minimizing the number of cycles to less than 10. The 65°C temperature limit is based upon the temperature drop required to obtain the degree of supersaturation required for the precipitation of hydrides in a short thermal cycle.

The materials reviewer should also assure that thermal cycling of cladding temperatures with differences greater than 65°C are not an inherent part of the drying, backfilling and cask transferring procedures. Additionally, the reviewer should assure that the number of thermal cycles that the cladding experience is less than 10 to minimize hydride reorientation. As reported in the literature (Kammenzind, et al., 2000), a minimum of 10 cycles were required before an enhancement in hydride reorientation was observed. The intent of the thermal cycling acceptance criteria is to prevent licensees from applying cask drying, loading and transfer operations that could inadvertently enhance an undesirable hydride reorientation to form radial hydrides. Accordingly, these criteria pertain only to periods of fuel loading and transfer operations of the casks to the storage pads.

For short-term accidents and short-term off-normal conditions that lead to an increase in temperature of the cladding, the dominant cladding failure mechanism is expected to be creep (stress rupture) of the cladding. To limit the amount of spent fuel that could be released from the cladding under off-normal conditions or accidents, the materials reviewer should coordinate with the thermal reviewer to verify that the maximum calculated cladding temperatures 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 (Einziger, et al., 1982). The results from these experiments indicated that no cladding ruptures were observed for test times of 30 and 73 days.

Transportation

Reviews of the transportation of commercial and noncommercial spent fuel will be handled on a case-by-case basis. Depending on the concentration of hydrogen in the cladding; and the size, distribution, orientation, and location of zirconium hydrides, the spent fuel cladding with decreasing storage temperatures loses fracture toughness such that the stresses on the cladding when applied at high strain rates could cause fracture of the cladding. Therefore, the staff is continuing to review the data on the mechanical 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, 10 CFR 71.43(f), and 10 CFR 71.51 for transportation.

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November 17, 2003

MEMORANDUM TO: SFPO Staff Members

FROM: E. William Brach, Director /RA/ orig signed by LWC for
Spent Fuel Project Office
Office of Nuclear Material Safety
and Safeguards

SUBJECT: APPROVAL OF INTERIM STAFF GUIDANCE MEMORANDUM NO. 11, CLADDING CONSIDERATIONS FOR THE TRANSPORTATION AND STORAGE OF SPENT FUEL, REVISION 3

Attached is Revision 3 of the Spent Fuel Project Office (SFPO) Director's Interim Staff Guidance Document -11 (ISG) entitled "Cladding Considerations for the Transportation and Storage of Spent Fuel" for your use when conducting reviews of spent fuel storage cask applications and amendments. This revision modifies Revision 2 of ISG-11 by (1) clarifying the meaning of some of the acceptance criteria contained in Revision 2 and (2) adding acceptance criteria to allow higher cladding temperature limits for certain conditions of storage. It also provides the justification for NOT requiring a backfit (changing TSs and operating procedures) for previously certified casks containing low burnup fuel using the pre-ISG-11, Rev. 2, 570°C fuel loading temperature.

Attachment: ISG No. 11, Rev. 3

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