REVIEW GUIDANCE FOR THE SAFE TRANSPORT AND DRY STORAGE OF HIGH BURNUP SPENT NUCLEAR FUEL

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Abstract

The performance of spent nuclear fuel (SNF) cladding during transportation and dry storage is an important consideration for demonstrating compliance with the safety-based requirements for transportation and dry storage in the United States. The structural performance of the cladding ensures that the fuel performance remains as analyzed for the transport duration or approved dry storage period. Historically, the U.S. Nuclear Regulatory Commission (NRC) has discussed considerations for ensuring adequate cladding performance through safety review guidance. This guidance has defined adequate fuel conditions, including peak cladding temperatures during short-term loading operations to prevent and mitigate degradation of the cladding. The U.S. NRC has recently supplemented the technical basis in support of the existing guidance on cladding performance by issuance of two draft reports for public comment, NUREG-2224, "Dry Storage and Transportation of High Burnup SNF" and NUREG-2214, "Managing Aging Processes in Storage Report". This paper will discuss the technical conclusions in these documents and their implications to the regulatory framework for the safety review of high burnup SNF (i.e., SNF with burnups exceeding 45 gigawatt-days/metric ton of uranium). NUREG-2224 addresses the technical issue of hydride reorientation, a process in which the orientation of hydrides precipitated in high burnup SNF cladding during reactor operation changes from the circumferential-axial to the radial-axial direction. NUREG-2224 provides a technical assessment of results from NRC-sponsored research on the effects of hydride reorientation on high burnup SNF cladding performance. NUREG-2224 also provides example approaches for licensing and certification of high burnup SNF for dry storage and transportation, which aim to clarify NRC's expectations for supporting data on high burnup SNF performance for the evaluation of design-basis drop accidents and vibration normally incident to transport. These approaches recognize the increased flexural rigidity imparted by the fuel pellets on the cladding's mechanical performance. NUREG-2214 provides a generic evaluation of the age-related mechanisms that have the potential to challenge the ability of SNF cladding to support important-to-safety functions of dry storage systems for periods up to 60 years. These mechanisms consider that time-dependent changes to the cladding are primarily driven by the fuel's temperature, internal pressure-induced cladding hoop stresses, and the environment during storage or transport operations. Both NUREG-2224 and NUREG-2214 clarify the technical position of the NRC on high burnup SNF performance, which will help improve the effectiveness and efficiency of the review process for applications for dry storage and transportation.

Key Words: spent nuclear fuel, high burnup, cladding, aging, hydride reorientation

1. INTRODUCTION

The performance of spent nuclear fuel (SNF) cladding during dry storage and transportation is an essential consideration for demonstrating compliance with the safety-based regulatory requirements per Title 10 of the United States Code of Federal Regulations [1]. In dry storage, the SNF cladding is to be protected against degradation that leads to gross ruptures, or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage. In transportation, the geometric form of the contents of the transportation package is evaluated to not be substantially altered under the tests for normal conditions of transport and the package is to be designed and constructed so its contents remain subcritical and comply with other performance requirements under the tests for hypothetical accident conditions. To comply with these requirements, the fuel cladding generally serves a design function in both dry storage systems (DSSs) and transportation packages for ensuring that the configuration of undamaged and intact fuel remains within the bounds of the reviewed and approved safety analyses.

Time-dependent (i.e., age-related, not event-related) mechanisms resulting in changes to the fuel cladding performance are all primarily driven by the fuel's temperature, rod internal pressure (and corresponding pressure-induced cladding hoop stresses), and the environment during dry storage or transport operations. Contrary to the hoop stresses experienced by the fuel cladding during reactor operation, which are generally compressive because of the high reactor coolant pressure, the hoop stresses during drying-transfer, dry storage, and transport operations are tensile because of the low pressure external to the cladding. For instance, the pressure of the environment surrounding the fuel in the reactor can be 16 megapascal (MPa) while the environment surrounding the fuel inside the cask/canister may be as low as 400 pascal (Pa) at the end of vacuum drying and 0.5 MPa during dry storage. The magnitude of the cladding hoop stresses will depend on the differential pressure across the cladding wall and thus the rod internal pressure at a given time. Various factors determine the rod internal pressure, including the fuel's fabrication and irradiation conditions (i.e., fabrication gas fill pressure, cladding thickness, presence of burnable absorbers, burnup) and the average gas temperature within the fuel rods. The average gas temperature within the fuel rods has a first-order effect on the hoop stress in the cladding and thus cladding performance, and therefore it is critical to controlling the peak cladding temperature (PCT) of the fuel rods during vacuum drying and storage/transport operations to temperatures demonstrated to preserve cladding integrity.

To assist the safety review of potential degradation mechanisms, the U.S. Nuclear Regulatory Commission (NRC) has historically issued guidance on acceptable storage and transport conditions that limit SNF degradation during operations and provide reasonable assurance that the reviewed safety analyses remain valid. Historically, guidance has been issued as Interim Staff Guidance (ISG)-11, "Cladding Considerations for the Transportation and Storage of Spent Fuel," which has been revised multiple times to incorporate new data and lessons learned from the NRC's review experience.

The latest revision, ISG-11, Revision 3 [2], defines a generic 400 degrees Celsius (°C) PCT limit applicable to modern zirconium-based cladding SNF designs during normal conditions of storage and transportation, as well as short-term loading operations (e.g., drying, backfilling with inert gas, and on-site transfer of the DSS cask or canister to the storage pad). ISG-11, Revision 3, also defines a higher short-term temperature limit of 570 °C applicable to low burnup SNF[1] if the applicant demonstrates by calculation that the cladding hoop stress would not exceed 90 MPa for the proposed temperature limit. The guidance also defines a generic PCT limit of 570 °C for off-normal and accident conditions applicable to all burnups.

The technical basis and references in ISG-11, Revision 3, support the NRC's conclusions that (1) cladding deformation caused by thermal creep will proceed slowly over time and will decrease the fuel rod internal pressure, (2) the decreasing cladding temperature will decrease the cladding hoop stresses, 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, this will not result in gross rupture. Based on these conclusions, the staff has reasonable assurance that, by meeting the generic 400 °C PCT applicable to normal conditions of storage and transportation, thermal creep will not cause gross ruptures of the cladding and that the geometric configuration of the SNF will be preserved.

In addition to creep, ISG-11, Revision 3, considered the effects of hydride reorientation on cladding performance of high burnup SNF[2]. At the time of its issuance, the technical basis discussed in ISG-11, Revision 3, supported the NRC's conclusion that hydride reorientation, a process in which cladding hydrides reorient from the circumferential-axial to the radial-axial direction, would be minimized by complying with the aforementioned PCT criteria and restricting repeated thermal cycling (i.e., repeated heatup/cooldown cycles) during drying-transfer operations with the change in cladding temperatures being less than 65 °C in each cycle. This temperature change limit was based on the temperature drop required to obtain the degree of supersaturation required for the precipitation of radial hydrides in a short thermal cycle.

Research results obtained since the ISG-11, Revision 3, have shown that hydride reorientation can still occur below the generic PCT limit [3-6]. To better understand hydride reorientation, the NRC sponsored an independent test program to evaluate the performance of high burnup SNF cladding with reoriented hydrides to determine if the guidance in ISG-11, Revision 3, ought to be revised. These results are summarized in NUREG-2224, "Dry Storage and Transportation of High Burnup Spent Nuclear Fuel" [7], which also provides an

[1] NRC defines low burnup SNF to be assembly average burnups generally less than 45 GWd/MTU.
[2] NRC defines high burnup SNF to be assembly average burnups generally exceeding 45 GWd/MTU.

engineering assessment of the results and its consequences on high burnup SNF performance during design-basis drop accidents and vibration normally incident to transport. NUREG-2224 also provides example approaches for licensing and certification of high burnup SNF for dry storage and transportation, which aim to clarify NRC's expectations per the test results. These approaches recognize the increased flexural rigidity imparted by the fuel pellets on the cladding's mechanical performance. A summary of the discussions in NUREG-2224 is provided in this paper.

In addition to the work on hydride reorientation, the NRC has also published a report to supplement the guidance in ISG-11, Revision 3, on the potential for other age-related phenomena to impact SNF performance during dry storage up to 60 years. NUREG-2214, the "Managing Aging Processes in Storage Report" [8], provides discussions on the impact of aging mechanisms on the performance of zirconium-based SNF cladding and assembly hardware. A summary of the aging mechanisms considered in NUREG-2214 is provided in this paper.

2. NUREG-2224, DRY STORAGE AND TRANSPORTATION OF HIGH BURNUP SNF

During reactor irradiation, hydrogen is generated due to water-coolant corrosion of the cladding, which diffuses into the zirconium-based material. As the solubility limit of hydrogen in the cladding is exceeded, hydrides precipitate in either circumferential-axial or radial-axial directions (Fig. 1), the former being more prevalent due to texture of cladding developed during the manufacturing process. The number density of these circumferential hydrides varies across the cladding wall due to the temperature drop from the fuel side (hotter) to the coolant side (cooler) of the cladding. Migration and precipitation of dissolved hydrogen into the coolant side of the cladding can result in the formation of a rather dense hydride rim just below the outer cladding oxide layer. At temperature and stress conditions experienced during vacuum drying and storage/transport operations, some of these hydrides may dissolve and subsequently precipitate as new hydrides. During this process, the orientation of precipitated circumferential-axial hydrides may change into the radial-axial direction (Fig. 1).

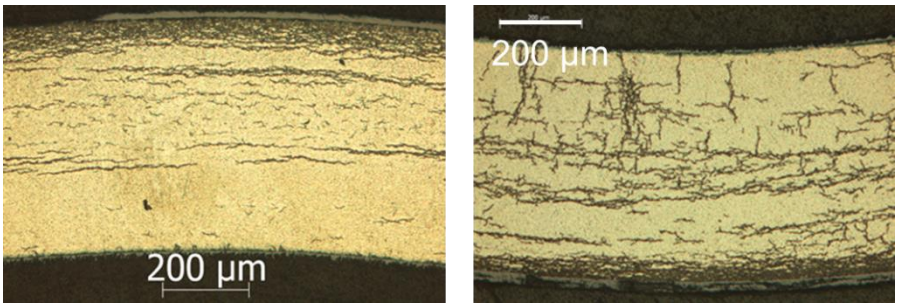

FIG. 1. Hydride content and distribution (530 ± 70 parts-per-million by weight, average) in high burnup SNF cladding (ZIRLOTM, 68 GWD/MTU) before and after hydride reorientation [4].

The NRC has sponsored an independent test program to assess the effects of hydride reorientation on the mechanical behavior of the cladding, considering that the structural safety evaluation of the SNF assembly generally assumes as-irradiated cladding mechanical properties (i.e., properties not accounting for hydride reorientation). In addition, the NRC wanted to understand the contribution of the fuel pellets to increasing the flexural rigidity of high burnup SNF rods that were subjected to a hydride reorientation treatment. This would allow the NRC to evaluate the mechanical response of the composite cladding-fuel system during bending representative of normal conditions of transport and drop accidents scenarios characteristic of transportation and dry storage transfer operations.

2.1. Flexural rigidity and fatigue life of high burnup SNF under bending loads

In 2009, the NRC tasked Oak Ridge National Laboratory (ORNL) with investigating the flexural rigidity and fatigue life of high burnup SNF [9]. Testing proceeded in two phases. Phase I involved testing high burnup SNF in the as-irradiated state, where cladding hydrides were predominantly in the circumferential-axial orientation. Phase II involved testing high burnup SNF segments subjected to a treatment designed to reorient

cladding hydrides to be predominantly in the radial-axial orientation. All testing was conducted at room temperature, which is expected to result in the most limiting cladding ductility.

In 2013, a testing system was installed in a hot cell at ORNL's Irradiated Fuels Examination Laboratory and formally named the "cyclic integrated reversible-bending fatigue tester" (CIRFT). After tuning of the test system and performance of benchmark testing in September 2013, Phase I testing began on HBU SNF rod segments with intact Zircaloy-4 cladding irradiated in the H.B. Robinson Steam Electric Plant (HBR). ORNL completed four static tests under displacement control at the rate of 0.1 mm/s to a maximum displacement of 12.0 mm, and 16 dynamic (cyclic bending) loading tests were completed. Load ranges applied to the CIRFT varied, to produce bending moments in the rod, from ±5.08 to ±35.56 N·m. Twelve dynamic tests resulted in rod fracture and four tests without rod fracture. One of the cyclic tests reached 1.3×10^7 cycles with no rod fracture. The test was terminated as higher cycles would not be expected during actual transport.

Phase II testing began in 2016, again using HBR high burnup SNF rods with intact Zircaloy-4 cladding, which had been subjected to an aggressive hydride reorientation treatment. ORNL completed testing on four specimens in the CIRFT following an aggressive hydride reorientation treatment (HRT): one in static loading and three in dynamic loading. The fatigue lifetime and flexural rigidity of these samples were compared to the results obtained in Phase I for as-irradiated samples.

2.2. Application of Results

2.2.1. Static Bending

The NRC reviewed the results from the static bending of high burnup SNF rods to assess the impact to the drop orientations evaluated in drop accident scenarios (i.e., side and end drop orientations). In the side drop, lateral inertia loads are applied to the fuel rods, and bending dominates the structural response. For a side drop event, the CIRFT static bending test results discussed in NUREG-2224 were directly applied to quantify the fuel rod structural response of a representative SNF assembly. In the end drop, axial compression and the associated buckling of the fuel rod dominates the structural response. For the end drop, the presence of axial compression in the fuel rod represents a force component that was not present in the CIRFT static bending tests. However, the NRC does not consider this to pose a problem since the CIRFT static test results can be used to conservatively quantify the effect of the fuel pellets on increasing the flexural rigidity of the rods to resist buckling.

In NUREG-2224, the NRC developed a simple methodology that uses the CIRFT static bending results for fully-fueled composite SNF rodlets to calculate the SNF rod cladding stresses and strains during accident scenarios. The methodology is based on a set of assumptions based on the integrated average response of the fully-fueled composite SNF rodlet along its gauge length. The NRC compared the measured flexural rigidity from the CIRFT static test results to the calculated flexural rigidity values using the validated cladding-only mechanical property models developed by Pacific Northwest National Laboratory (PNNL) [10]. This allowed the NRC to assess the effect of fuel pellets on the fuel rod's flexural rigidity and cladding strain.

The NRC reviewed the applied moment vs. curvature CIRFT response for fully-fueled composite SNF rodlets in both the as-irradiated and hydride-reoriented cladding condition, which were compared to the calculated cladding-only mechanical response (Fig. 2). The comparison shows that hydride reorientation does not impact the fuel's flexural rigidity for expected bending moments due to drop accidents (e.g., NUREG-2224 provides a calculation for a prototypical PWR 15 × 15 SNF assembly which shows that 100-g load corresponds to an applied moment of 34 N·m). This comparison supports the pretest expectation that, because the bending tensile stress in the cladding is parallel to the plane of both the radial and circumferential hydrides, the presence of radial hydrides would not significantly alter the flexural response from the case where only circumferential hydrides are present.

In addition, the hydride-reoriented rodlets showed markedly higher bending moment resistance compared to the calculated cladding-only response, which confirmed that the use of cladding-only mechanical properties is adequate for the evaluation of drop accident scenarios. The comparison, as discussed in NUREG-2224, allowed the NRC to also propose a new approach for crediting the flexural rigidity imparted by the pellet in the drop accident safety analyses.

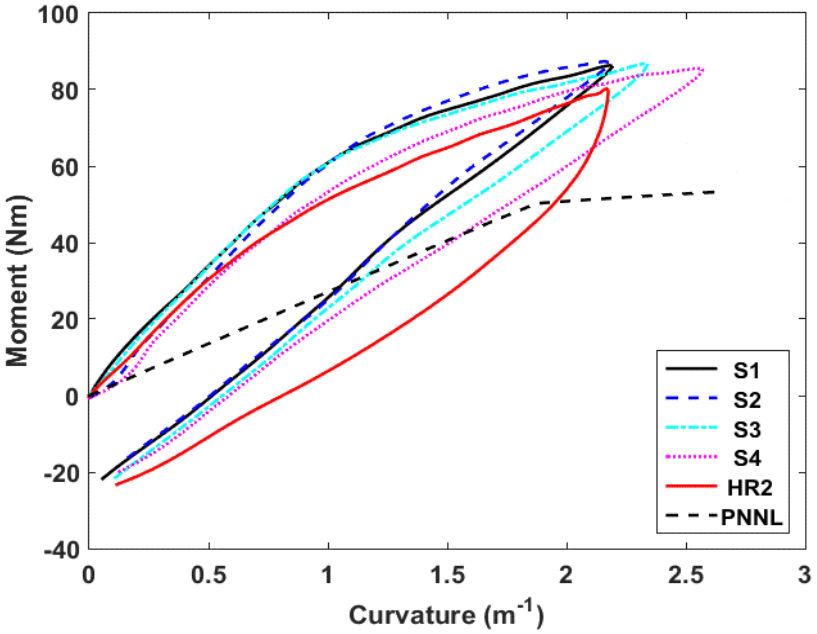

FIG. 2. Comparison of CIRFT Static Bending Results with Calculated PNNL Moment Curvature (Flexural Rigidity) Derived from Cladding-Only Stress-Strain Curve (Reproduction of Figure 22 from NUREG/CR-7198, Revision 1 [9]. S1, S2, S3, and S4 Represent the Experimental Results for HBR high burnup SNF As-Irradiated Specimens, HR2 Represents the Experimental Results for HBR HBU SNF Hydride-Reoriented Specimen, and PNNL Represents the Results Calculated Using the Validated Cladding-Only Mechanical Property Models Developed by PNNL [10].

2.2.2. Dynamic Bending

Fatigue strength data are commonly presented in the form of an S-N curve, where S is a strength parameter, such as stress or strain, and N denotes the number of cycles to failure at a specific value of the strength parameter. The NRC evaluated the CIRFT dynamic (cyclic) bending test results for HBR Zircaloy-4 high burnup rods tested in both the as-irradiated and hydride-reoriented cladding condition. The NRC has described and demonstrated a process for developing a lower bound fatigue S-N curve, that envelopes the CIRFT fatigue data.

In NUREG-2224, the NRC describes a cumulative fatigue damage model to express how damage from vibration normally incident to transport can be evaluated. The model recognizes that fuel rod vibration during normal conditions of transportation is expected to have a series of many cycles encompassing a range of strain amplitudes and with each cycle, damage to the fuel rod cladding is continuously accumulating. The NRC has proposed the use of a linear damage rule, such as that developed by Miner [11], to provide a simple and reasonably reliable prediction of fatigue behavior under random loadings, and therefore, that can be used to evaluate fatigue damage accumulation during transport of high burnup SNF. This simple linear damage rule assumes that the load history can be reduced to a series of different strain levels for a number of cycles associated with each strain level. To account for uncertainty in using a simple linear damage rule to describe the accumulated fatigue damage in high burnup SNF, the NRC incorporated an approximate lower bound for the uncertainty in Miner's damage model (Hashin, 1979).

3. NUREG-2214, MANAGING AGING PROCESSES IN STORAGE REPORT

NUREG-2214, the Managing Aging Processes in Storage (MAPS) report is a technical basis document that provides guidance to NRC staff to improve the effectiveness and efficiency of the review of applications for dry storage of SNF up to 60 years. The MAPS report provides a generic evaluation of the aging mechanisms that have the potential to challenge the ability of DSSs important-to-safety functions, including the SNF assemblies since the safety analyses for DSSs may rely on the assemblies remaining in the analysed configuration. The SNF assembly components evaluated in the MAPS report include the zirconium-based cladding and fuel assembly hardware that provide structural support to ensure that the SNF is maintained in a known geometric configuration.

The MAPS assessment of the condition of the SNF assembly at loading considered changes to the fuel pellets and the zirconium-based cladding during reactor service, including hydrogen absorption by the cladding, swelling of the fuel pellets, increased rod pressurization due to helium and fission gas release, and pellet-cladding interactions. The dry storage environment considered was helium or an alternative cover gas in high radiation and temperature. Consistent with the guidance in NUREG-1536, "Standard Review Plan for Dry Cask Storage Systems, Revision 1" [12], a minimal amount of water (about 0.43 gram-mole) was also considered to be retained inside the cask/canister. This moisture content is based on a design-basis drying process that evacuates the cask/canister to less than or equal to 400 Pa and maintains a constant pressure for 30 minutes before closure.

The aging mechanisms considered for high burnup zirconium-based cladding included hydride reorientation, delayed hydride cracking, thermal and athermal (low-temperature) creep, localized mechanical overload, radiation embrittlement, fatigue, oxidation, pitting corrosion, galvanic corrosion, and stress corrosion cracking (SCC). TABLE I provides a summary of the aging mechanisms considered in the MAPS assessment based on their potential to adversely affect an DSS important-to-safety function in the 60-year timeframe.

TABLE 1. NUREG-2214 CONCLUSIONS PER EVALUATIONS OF SNF ASSEMBLY AGING MECHANISMS.

Material	Aging Mechanism
Cladding: Zirconium-based Alloys	Hydride reorientation
	Delayed hydride cracking
	Thermal creep
	Low-temperature creep
	Mechanical overload
	Oxidation
	Pitting corrosion
	Galvanic corrosion
	SCC
	Radiation embrittlement
	Fatigue

The technical basis in the MAPS report concludes that hydride reorientation and thermal creep are both active aging mechanisms during dry storage up to 60 years. However, separate-effects test results documented in ISG-11, Revision 3, and NUREG-2214 support the NRC's conclusion that these aging mechanisms are not expected to result in cladding failures and reconfiguration of the fuel, if the DSS design basis is consistent with the acceptance criteria in ISG-11, Revision 3. The NRC also recognizes that the experimental evidence used in support of the NRC's conclusion is based on short-term testing (i.e., laboratory scale testing up to a few months). Therefore, the NRC considers it prudent that evidence from high burnup SNF in dry storage beyond 20 years be gathered in the field and reviewed. In support of this expectation, the MAPS report provided an example Aging Management Program (AMP) for high burnup SNF monitoring and assessment.

This example AMP is a licensee program that monitors and assesses data and other information regarding the performance of uncanned (undamaged or intact cladding) high burnup SNF to confirm that the assumed configuration in the DSS safety analyses is maintained during dry storage periods exceeding 20 years. This example AMP relies on a surrogate demonstration program to provide data on HBU fuel performance, consistent with the NRC guidance in Appendix D of NUREG–1927, Revision 1 [13]. The U.S. Department of Energy (DOE) is currently sponsoring a research program at the North Anna Independent Spent Fuel Storage Installation (Louisa County, Virginia), which is expected to gather experimental confirmatory data consistent with the example AMP in the MAPS report [14].

4. LICENSING AND CERTIFICATION OF HIGH BURNUP SNF

The results discussed in NUREG-2224 on the static bend testing of aggressively hydride-reoriented Zircaloy-4 high burnup SNF rods supports the NRC's conclusion that the use of best-estimate cladding mechanical properties that do not account for the flexural rigidity imparted by the fuel pellet continue to be adequate for assessing the structural performance of high burnup SNF rods during drop accident scenarios for transportation and dry storage transfer operations. These include the hypothetical 9-m drop accident scenario and the 0.3-m drop scenario considered for normal conditions of transport, as well as the postulated drop and cask tip-over accident scenarios during dry storage transfer operations. The NRC does not consider that the orientation of the hydrides is a critical consideration when evaluating the adequacy of cladding-only mechanical properties. Therefore, the use of mechanical properties for cladding in either the as-irradiated or hydride-reoriented condition is considered acceptable for the evaluation of drop accident scenarios. If an applicant is unable to demonstrate satisfactory performance of high burnup SNF by assuming cladding-only mechanical properties, the NRC has proposed an alternative approach for using the results from CIRFT static bend testing to account for the increased flexural rigidity imparted by the fuel pellet.

The results discussed in NUREG-2224 on the fatigue (dynamic bend) testing of aggressively hydride-reoriented Zircaloy-4 HBU SNF rods have provided an adequate technical basis for establishing a reasonable lower-bound fatigue curve and endurance limit for tensile axial-bending loads experienced during vibration normally incident to transport. The NRC considers that applicants can use a cumulative damage approach to assess vibration-induced damage to the cladding. The applicant is expected to provide fatigue test data for the cladding alloy types to be transported and develop the respective lower-bound fatigue curve and endurance limit.

The technical basis discussed in NUREG-2214 (the MAPS report) further support the NRC's conclusion that aging mechanisms during dry storage periods between 20 and 60 years are not expected to result in degradation of HBU SNF that would lead to an unanalyzed configuration. Short- term testing and scientific analyses examining the performance of high burnup SNF have provided a foundation for the technical basis that dry storage of high burnup SNF can continue safely and in compliance with applicable regulations. A licensee may implement an AMP to monitor and assess data and other information regarding high burnup SNF performance in support of this expectation.

If an applicant chooses not to propose the implementation of an AMP, both NUREG-2214 and NUREG-2224 present an alternative approach for demonstrating compliance with the pertinent regulatory requirements by assuming hypothetical reconfiguration of the design basis SNF. This example approach considers lessons learned from an NRC-sponsored generic consequence assessment for transportation packages, as discussed in NUREG/CR-7203, "A Quantitative Impact Assessment of Hypothetical Spent Fuel Reconfiguration in Spent Fuel Storage Casks and Transportation Packages" [15].

5. CONCLUSIONS

The NRC has developed two technical reports in support of the safe management of high burnup SNF in transportation and dry storage. NUREG-2224 expands the technical basis in support of current safety review guidance, as it pertains to hydride reorientation in high burnup SNF cladding. NUREG-2214 expands the technical basis in support of dry storage periods up to 60 years by considering potential aging mechanisms for high burnup SNF cladding and assembly hardware. These reports clarify the technical position of the NRC on high burnup SNF performance, which will help improve the effectiveness and efficiency of the review process for applications for dry storage and transportation.

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DISCLAIMER

The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

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