Damage in Spent Nuclear Fuel Defined by Properties, & Requirements

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Abstract. The United States Nuclear Regulatory Commission's (USNRC) Spent Fuel Program Office (SFPO) has provided guidance in defining damaged fuel in Interim Staff Guidance (ISG) - 1. This guidance is similar to that developed by the American National Standards Institute (ANSI). Neither of these documents provides the logic behind the definition of damaged fuel. Title 10 (Energy) of the U.S. Code of Federal Regulations Parts 72 and 71 establish requirements for spent fuel in storage and transportation, respectively. In particular, Part 72 requires spent fuel to be stored in a manner such that the fuel is retrievable and protected from gross cladding breaches. Part 71 requires that the fuel be transported in a manner such that normal conditions of transportation do not result in substantial alterations of the geometric form of the fuel. To facilitate meeting the regulations in Parts 72 and 71, cask designers may need to place additional requirements on the behavior of the fuel during storage or transportation. In-service irradiation alters the structural and material properties of light water reactor (LWR) fuel rods and assemblies. In some cases, the alterations render the fuel unsuitable for placement into storage or transportation casks without special handling. Spent fuel that has been altered in a manner that prevents it from satisfying its required safety functions without special handling should be regarded as damaged. Since the requirements placed on the fuel may vary during phases of the fuel cycle, the potential exists for independent definitions to co-exist for interim dry storage, and transport. This paper discusses the requirements placed on spent fuel for dry interim storage and transportation and the ways in which service requirements drive the definition of damage for spent fuel. Examples will be given to illustrating the methodology, which focuses on defining damaged fuel based on the properties the fuel must exhibit to meet the requirements of storage and/or transportation.

1. Introduction

Both the U.S. Nuclear Regulatory Commission, via Interim Staff Guidance (ISG)-1 [1], and the American National Standards Institute (ANSI) in N14.33 [2] have definitions of damage for spent fuel. While these definitions have been linked to regulations, explanations are not provided on why the fuel, under these definitions, should be considered damaged. This paper provides explanations for definitions of damaged spent fuel. In each case, the rationale is based on the ability of the fuel to meet a regulatory requirement for a particular phase of the nuclear fuel cycle. Due to the variety of regulatory requirements at various stages of the nuclear fuel cycle, the meaning of damage varies with the requirements for each stage in either the reactor life or the post-reactor period. Thus, the potential exists for independent definitions to co-exist for interim storage, and transport. During each stage in the life of the fuel, the definition of damage is related to the requirements of the fuel that are specific to that stage.

Fuel rods and assemblies undergo many changes from the time they are manufactured until they are removed from the reactor, and these changes can alter their mechanical properties. Numerous factors affect the changes: radiation damage, cladding oxidation and thinning, creepdown of the cladding, and the presence of hydrides formed as byproducts of the oxidation process. Physical properties and characteristics of the rods are also affected by reactor service: (1) the effective thermal conductivity is decreased by a coating of CRUD that forms on the rod surface during irradiation, creep-down, and by the release of the fission products and gas into the plenum region; (2) the rods and assemblies elongate and the assemblies bow; (3) the effective localized thickness of the cladding decreases by abrasion from debris floating in the reactor coolant and by vibrations that lead to rod fretting against the grid spacers; and (4) inside the rods, the fuel pellets crack into numerous pieces. Any of these

alterations of the mechanical and physical properties could be considered to represent damage to a fuel rod. Fuel rods are considered damaged only if they can not function as required for post-reactor conditions and operations. Fuel that is considered damaged for any other part of the fuel cycle may or may not be considered damaged for post-reactor operations, as the expectations of the fuel performance may be different. The term "damaged" can be defined by the ability of the fuel to perform its intended function in a given phase of the nuclear fuel cycle.

2. USNRC Regulations for Spent Fuel Storage and Transportation

The U.S. Federal regulations [3, 4] contain requirements relating directly to the condition of spent fuel during storage and transportation. The regulations for spent fuel storage[1] stipulate that the fuel must be: retrievable, protected against gross ruptures, and compatible with the rest of the system. While gross ruptures are not defined in the regulations, the objective might be related to the prevention of the escape of fuel fragments from the rod into the cask and to assurance that retrievability in the form of a rod was maintained. The regulations for spent fuel transportation[2] require the spent fuel not to substantially rearrange during normal conditions of transportation. When the properties of spent fuel rods and assemblies do not meet the properties required by the approved conditions for storage and transport, the regulatory performance requirements are not met by the fuel, and the fuel should be classified as damaged.

In addition to those regulations that specifically address the state of the spent fuel during storage and transportation, there are a number of regulatory requirements pertaining to criticality, shielding, thermal, containment or confinement, structural, and materials issues that may indirectly impose performance requirements on the fuel rods and fuel assembly. When an applicant requests NRC approval for a cask design, the applicant specifies the system, the materials to be used, the range and condition of the fuel (type, burnup, cooling time, etc.) to be stored, and the conditions of storage such as temperature, atmosphere, and length of storage. The system is analyzed to ensure and demonstrate that all pertinent regulations are met. When this is done, any fuel assembly or fuel rod in the specified range that prevents the system from meeting these indirect regulations should be considered damaged.

3. Existing Guidance on the Definition of Damaged Fuel

An applicant is required to meet the storage and transportation regulations given in 10 CFR Parts 71 and 72, and is free to define damaged fuel in any manner provided that the definition allows the regulations to be met. The NRC Spent Fuel Project Office (SFPO) staff has evaluated mechanisms that could affect the behavior of spent fuel and spent fuel assemblies, and proposed a definition of damaged fuel in interim staff guidance (ISG) - 1, "Damaged Fuel." ANSI has written a standard that defines damaged spent fuel with respect to storage and transportation. Neither document gives a basis for the definition nor how they satisfy the requirements of 10 CFR 71 and 72. Both documents provide guidance for other information such as records, quality assurance, and examination techniques useful for determining fuel rod condition. The pertinent parts, those related to the definition of damage, are compared in Table 1. Both are very similar and appear to be related to the function of the fuel rods or assemblies.

4. Condition of Fuel, Definitions, and Mechanisms of Degradation

4.1 Typical Spent Fuel

The condition of the SNF as it comes out of the reactor is the baseline for determining the behavior of fuel in storage and transportation. The typical condition of the fuel and the associated range of uncertainty is typically determined by poolside non-destructive and hot cell destructive examinations on representative numbers of assemblies, and by reviewing reactor records to determine when and

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[1] 10CFR72.122(l) addresses spent fuel retrievability, 10CFR72.122(h)(1) addresses gross ruptures of spent fuel cladding, and 10CFR72.236(h) addresses compatibility.

[2] 10CFR71.55(d)(2) addresses spent fuel configuration during normal conditions of transportation.

how many cladding breaches have occurred. It is common practice in the industry to extensively examine breached rods. Usually, the typical fuel rod has no through-cladding penetrations and the fission gas release from the pellets, cladding creep down, cladding hydrogen impurities, oxide thickness, and distortion of the assemblies due to bow, all fall within an established set of limits.

Table 1 - Comparison of ISG-1 and ANSI definitions of Damaged Fuel

	ISG-1 Rev1	ANSI
Fuel Rod Breach	1) The fuel contains known or suspected cladding defects greater than a pinhole leak or hairline crack that have the potential for release of significant amounts of fuel particles into the cask.	**Cladding Damage, Level I.** Cladding defects greater than pinholes or hairline cracks but the fuel assembly still remains intact as a fuel assembly
Debris	3) The fuel is no longer in the form of an intact fuel bundle and consists of, or contains, debris such as loose fuel pellets, rod segments, etc	**Cladding Damage, Level II.** Fuel that is no longer in the form of a fuel assembly and consists of debris, loose pellets and particles, rod segments, etc.
Structural	2) The fuel assembly: a) Is damaged in such a manner as to impair its structural integrity; b) Has missing or displaced structural components such as grid spacers; c) Is missing fuel pins which have not been replaced by dummy rods which displace a volume equal to or greater than the original fuel rod; d) Cannot be handled using normal (i.e., crane and grapple) handling methods 4) The fuel assembly structural hardware or cladding material properties are in a degraded condition such that its ability to withstand the normal and design basis events of storage (for storage-only casks), or the normal and hypothetical accident	**Fuel Assembly Damage.** Fuel assemblies that have structural damage such that they can not be handled by normal methods.

4.2 What Is a Pinhole or Tight Crack, or Gross Breach?

In early studies, the most prevalent breach mechanism was stress corrosion cracking (SCC). SCC caused cladding penetrations large enough to only release gases. With this size breach the cladding still can satisfy the requirements to confine the fuel in the rods for operational safety and retrievability purposes. As a result, both ISG-1 and ANSI describe damaged fuel in terms of pinhole leaks and tight (hairline) cracks. Generally speaking, pinhole leaks and hairline cracks are breaches in the fuel cladding that do not allow the escape of fuel particulate material. The guidance in ISG-1 allows fuel to be classified as intact if only pinhole leaks and hairline cracks are present. From a retrievability perspective, a gross breach might be considered to be any cladding penetration that allows fuel to escape from the rod, i.e. any breach that compromises the confinement capability of the cladding. During irradiation, a pellet cracks into 10 to 30 pieces, excluding of a small amount of fines at the pellet-pellet interface. Although the fragments tend to be wedge-shaped, a fractured, 10 g pellet could be approximated by 30, individual 3-mm-diameter fragments, which would not be able to escape from a 1-mm breach. One might possibly define a tight (hairline) crack as any crack that doesn't visually expose fuel.

4.3 The Fuel Pellet Oxidation Process and Cladding Splitting

Irradiated uranium dioxide exposed to an oxidizing atmosphere will eventually oxidize to U_3O_8. The oxidation time is exponentially related to temperature, according to the Arrhenius Law. Initially, the pellet grain boundaries are oxidized to U_4O_9, resulting in a slight matrix shrinkage and further opening of the structure [5]. The oxidation then proceeds into the grain until there is complete transformation of the grains to U_4O_9. A plateau in the process occurs at this time, until the fuel resumes oxidizing to the U_3O_8 state. The transformation to U_3O_8 occurs with ~33 % lattice expansion that tears the ceramic fragment structure into grain sized particles. When the UO_2 pellets are encased in cladding to form a fuel rod, the swelling of the fuel pellets due to oxidation to U_3O_8, places a stress on the cladding. The cladding may experience strains of up to 6% before any initial defect starts to propagate axially along the rod [6].

During the oxidation process, the fuel pellet fragments are reduced to a grain-sized powder that can easily escape from the damaged rod [7]. The extent of oxidation and cladding splitting in any particular rod will depend on the number of rods with cladding breaches, the free volume in the cask, and the temperature. The rate at which the cladding splitting occurs has been experimentally measured and modeled, but there are a number of variables that can affect the rate, such as fuel burnup, moisture content of the air, cladding material, and type of initial defect. Depending on the temperature, over a 20 -year storage period, anywhere from 10 to 750 cm of the fuel column could oxidize and split the cladding [8].

4.4 Cladding Hydride Reorientation

From the time SNF is removed from the spent-fuel pool until it reaches the repository, it is subject to numerous mechanical forces (e.g. vibration) and a variety of thermal cycles. These forces and cycles can degrade the fuel and alter its ability to meet the requirements for criticality and retrievability. Of particular concern is the possibility of hydride reorientation during storage and subsequent reduction of the cladding mechanical strength during transport. During short-term cask loading operations (including drying, backfilling with inert gas, and transfer of the cask to the storage pad), the fuel is subject to elevated temperatures, and hydrogen goes into solution in the cladding up to the saturation concentration of the solvus. As the spent fuel later cools, the hydrogen will re-precipitate. The orientation of the re-precipitated hydrides depends strongly on the hoop stress inside the fuel rod vis-à-vis the critical stress needed for reorientation (σ_H^{cr}).

Studies at Argonne National Laboratory are currently underway to determine this critical stress for hydride reorientation as a function of cladding type, fuel cooling rate, temperature and other parameters. In addition, work is planned to determine the effects of the reorientation on the mechanical properties of the cladding as a function of cladding type, hydride concentration, and temperature. Until these studies have been completed, the degree of cladding damage due to hydride reorientation cannot be completely assessed. Due to this uncertainty, NRC staff guidelines currently suggest that the cladding hoop stress be kept below the best available estimate for the value of σ_H^{cr}, which is 90 MPa at 400°C.

5. Examples[3]

Following are a number of examples where the definition of damaged fuel rods or damaged assemblies is driven by either the direct regulations which specifically reference the condition of spent fuel (e.g., regulations addressing retrievability or gross breaches in storage) or those regulations that indirectly relate to the state of the spent fuel (e.g., regulations addressing criticality control). These examples demonstrate why it is important to consider function-based definitions of damaged fuel.

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[3] These examples are not to be taken as the NRC position or guidance but rather as illustrative of the concept of "damage defined by function".

5.1. Retrievability

5.1.1. Fuel Damage

This example discusses the dependence of fuel classification on temperature and atmosphere, two of the parameters that may be controlled by the design of the storage system. Base on an extensive evaluation of potential degradation mechanisms (creep and hydride reorientation for example) for cladding in storage, an upper fuel cladding temperature limit for storage of 400°C was recommended by the NRC staff in ISG-11, revision 3 [9]. At this temperature, an inert atmosphere must be maintained to prevent small breaches (pinhole breaches and hairline cracks) in the cladding from deteriorating into gross ruptures due to fuel oxidation. If an inert atmosphere is not used, or the temperature is not sufficiently lowered, small breaches may split open to form gross breaches; thus, spent fuel that was classified as intact[4] at the time of loading in the storage cask should have been classified as "damaged" due to its potential to not meet the regulatory requirements while in storage. This poses retrievability and ALARA concerns when it comes time to remove the spent fuel from the storage cask; gross breaches may lead to the formation of fuel debris that is not contained in a manner that allows for retrieval by normal means. This example demonstrates how the cask designer's informed choice of both the maximum allowable temperature and atmosphere in the storage cask can prevent fuel that is stored as intact from becoming damaged during the duration of storage. If an oxidizing atmosphere is used and the temperature is not appropriately controlled, fuel rods with any cladding breaches may have to be classified as damaged and stored as such, even if they do not meet the criteria of damaged fuel at the time of loading, to ensure that the fuel is retrievable later in the fuel cycle.

In addition to the environment of the storage cask itself, it is important to pay attention to the environment present in cask loading operations. For example, if air is used to blow down loaded casks prior to lid welding and to possibly completely void the cask of water, it is possible that some of the uncovered rods or parts of rods might be exposed to air at elevated temperatures for extended periods of time. Under these circumstances, small breaches in rods defined as "intact" could become gross ruptures which can release fuel particulates to the cask interior. The regulatory requirement that the rods do not have gross breaches mandates that either the time-temperature history of the rods or the potential for rod breaches be considered in the definition of damaged fuel if an oxidizing atmosphere is used in cask blow-down operations.

5.1.2. Assembly Damage

The assembly hardware is a vehicle for transferring the fuel. Fuel assemblies in storage, possibly excepting those in dual-purpose (storage and transport) casks, will eventually have to be removed from the storage cask either to be placed into a transportation cask or to be transferred to a disposal cask. All relevant past and current experience should indicate that a fuel assembly can be handled and moved using normal methods in order to be classified as undamaged.

If a fuel assembly has been altered such that it may not be handled and moved by normal means, then it does not fulfill its purpose and should be classified as damaged. Alterations to or removal of the fuel rods, grid spacers, grid straps, or other structural components or hardware may impact the way a fuel assembly must be handled.

A fuel assembly otherwise classified as damaged may be analyzed against storage or transportation requirements to determine if it may be considered as undamaged intact fuel. For example, an assembly missing part of a grid strap may be classified as undamaged if analysis shows that the damaged strap does not hinder meeting all of the transport requirements. This approach could avoid the requirement for using damaged fuel cans, in some cases. Such analyses would have to demonstrate

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[4] Based on the guidance in NRC ISG-1, revision 1

with reasonable assurance that the assembly can withstand the conditions of storage or transportation and still meet retrievability requirements.

Assemblies with modified or repaired top bails, etc., may be classified as undamaged from a retrievability perspective since they readily permit the transfer of fuel. However, before classifying such an assembly, the repair method must be evaluated. The evaluation must reasonably demonstrate that the repair will not degrade after either exposure to the high temperatures of dry storage or transportation (relative to spent fuel pool temperatures) or being subject to other design conditions such as the hypothetical drop accident of transportation. Fuel assemblies that are properly reconstituted and complete, and that contain undamaged components of original type or equivalent, and are of original geometry should not be considered damaged since they fulfill their intended retrievability function.

5.2. Radiation Dose Rate, Containment and Criticality Control in Transport

5.2.1. Fuel Damage

Transportation regulations in 10 CFR 71.51 limit radioactive releases from a package and limit dose rate increases under normal and accident conditions. The configuration of the fuel and the ability of the cladding to retain fuel particulate and fines are parameters that are used when evaluating these requirements. The permitted degree of fuel damage is therefore a design basis assumption used to demonstrate that a package design meets the performance requirements of Part 71. 10 CFR 71.55 requires that, during transportation, the fuel does not rearrange under normal or hypothetical regulatory accident conditions so that if a moderator floods the package a criticality will not occur. Any fuel assemblies not meeting these specifications may need to be classified as damaged.

5.2.2. Assembly Damage

The fuel must not assume a configuration, during either normal or hypothetical accidents, such that criticality could occur. The structural analysis of the assemblies during an event usually assumes specified components of the assembly, such as grids, flow mixers, tie rods, etc, are in place and the components have the properties associated with the given material, material state, irradiation level, and transportation temperature.

If a fuel assembly is missing components, has damaged components, or has been modified, it might still be classified as intact if it can be shown that the assembly in the defined configuration still meets the regulatory requirements. Should the structural integrity of the assembly be adversely affected under the design basis storage and/or transportation conditions then the assembly might not fulfill the requirement to maintain configuration and should be considered damaged. The cask designer has the freedom to design a system that mitigates the forces transmitted to the assembly and fuel rods. If the storage cask or transportation package design prevents or mitigates forces transmitted to its contents such that structural integrity is not significantly compromised, the assemblies need not be classified as damaged, assuming other factors (temperature, inert atmosphere, etc.) have been adequately addressed. This example illustrates how the design of the system can change the requirements that define an assembly as either damaged or intact.

5.3. Stress Driven Damage

If the hoop stress on the cladding exceeds the stress threshold due to in-reactor temperature excursions or CRUD buildup, for example, over a large number of rods or length of rod, then hydride reorientation might occur. Should it be determined that hydride reorientation degrades the properties of the high burnup SNF to the degree where it can not maintain an acceptable configuration (e.g. a potentially critical geometry is not prevented) during normal and hypothetical accident conditions of transportation, then SNF with stresses exceeding the threshold might be considered damaged. This is a case where damage is not an intrinsic property of the fuel but depends on the design assumptions. If

the applicant can demonstrate that even if the fuel reconfigures, and the cladding does not retain fuel particulate, that the regulatory requirements for containment and subcriticality are met, then reconfiguration is not an issue and stress no longer becomes a measure of damage. Until concerns regarding stress thresholds, effects of reorientation on cladding mechanical properties, and responses of rods with altered mechanical properties are resolved, the use of stress as a determinate of damage can not be definitively addressed. These concerns and examples illustrate that a nexus exits among the requirements on a fuel rod, the conditions of service, the properties of a fuel rod, and the definition of damage.

6. Summary

Currently the SFPO and ANSI have similar definitions of damaged spent fuel. Both allow fuel rods that have pinholes or tight cracks to be considered undamaged. This is based on storage in an inert atmosphere and the need to retain fuel retrievability. Air atmospheres might allow fuel oxidation that promotes gross breaches. Damaged fuel assemblies have also been defined so that fuel can be retrieved from storage and so that fuel maintains its non-critical configuration during transportation Should hydride reorientation significantly reduce the ductility and axial strength of the fuel cladding to the point where the cladding can no longer meet the transportation requirements, the cladding stress might need to be considered a characteristic of fuel rod damage. This will depend on whether the requirements on the cladding are mitigated by the use of burnup credit, moderator exclusion, or other means.

Damage is not an intrinsic property of the fuel. A new definition, classifying a rod as damaged depends on the system, storage and/or transportation conditions, and requirements on the fuel performance is proposed. U.S. Federal regulations (10 CFR Parts 71 and 72) put minimal direct requirements on the fuel itself. During storage, the fuel must not degrade beyond the transportation package design requirements. During normal storage or transport the fuel can not reconfigure. The cask designer can impose indirect requirements and the definition of damaged fuel may change in order to meet the system requirements for containment, confinement, criticality, structural, and thermal behavior. Together, these requirements establish the purpose of the performance of the spent fuel. Fuel that can not fulfill its defined requirements in the designed storage or transportation atmosphere (temperature range and fill gas) should be considered damaged. Damage is defined by the requirements of the system and those of the regulations, and fuel may be considered damaged under one scenario but undamaged under another.

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