Measures for the Failure Evaluation of SNF Cladding During the Transportation

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1. Introduction

In order to evaluate the SNF cladding integrity during the transportation, knowing the loads at first, then the responses from the fuel itself is essential. First of all, it would be the priority to know whether the cladding fails or not, which requires the failure criteria to which the loads and the responses need to be referred. This paper presents a few of failure measures used to determine the possibility of cladding failure during the transportation. Also proposition for appropriate failure measures which would be used as failure criteria for the SNF cladding during the transportation with quantification is presented.

2. Examples of failure measures applied to cladding integrity evaluation

2.1 Strain and K_{IC} for the failure determination of cladding due to impact [1]

The release of rod contents under normal transport or regulatory accident conditions is postulated for two types of failure: material rupture as a result of strains exceeding the ductility limit, and fracture as a result of excessive stress on an existing crack in the material. Three modes of failure are described by these two failure mechanisms: (1) transverse tearing initiated by material rupture, (2) rod breakage caused by crack propagation, and (3) longitudinal tearing initiated by material fracture in Fig. 1. The failure criteria used to determine these failure modes are the strain, ε_f (material rupture) and fracture toughness, K_{IC} (material fracture) failure mechanisms.

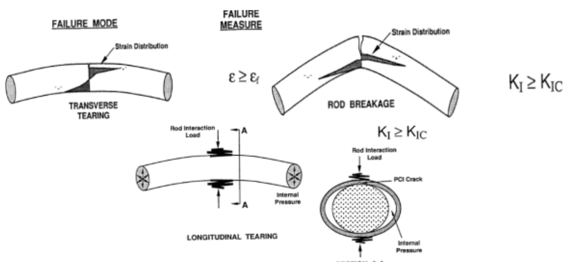

Fig. 1. Fuel rod failure mode [1].

2.2 Uniform Elongation and Fatigue Strength under NCT(Normal Conditions of Transportation) [2]

The potential failure modes under NCT where criteria could be established are classified as follows:

• Classic failure due to excessive stress or strain: This type of failure could be caused by a large shock load on the fuel rods due to a normal event such as road bump and rail car coupling. For this activity, the uniform elongation (plastic strain at maximum load) was used to assess damage fraction as well as failure rate under those events.

• Fatigue failure: Failure of the rods due to excessive strain cycling at low amplitude. The mechanism causing this strain cycling would be vibrations normal to the axial direction of the fuel rods as they are transported by rail or road. This is the most likely failure mechanism for UNF under NCT. The fatigue-design curve for the cladding was used to assess failure under vibrational loading.

2.3 CSED(Critical Strain Energy Density) in terms of Total Elongation and Uniform Elongation

These were developed first as a Hydrogen-Enhanced PCMI Cladding Failure Criteria during Reactivity-Initiated Accident (RIA) and then applied to the cladding of SNF. The clad ductility is measured in terms of strain energy density (SED). Clad failure is assumed to occur when the strain energy density in the material reaches and exceeds a critical strain energy density (CSED), which is determined from mechanical property tests.

The PCMI cladding failure thresholds proposed in the EPRI report are based on total elongation data (i.e., CSED (TE)). However, in response to staff concerns, the EPRI report also includes CSEDs based on uniform elongation data, which showed a significant reduction in CSED as expected. Cladding hydrogen content and hydride distribution and orientation are also likely to influence this relationship.

2.4 Hoop plastic strain

A strain-based criterion for clad tube failure under RIAs is proposed by Sweden researchers.[3] The criterion is intended for prediction of clad tube failures caused by pellet-clad mechanical interaction during the early heat-up phase of RIAs.

The mechanisms responsible for fuel rod failure under RIAs was delineated first, based on an evaluation of RIA simulation tests performed on pre-irradiated fuel rods in pulse reactors. The ability of the clad tube to expand radially by plastic deformation is found to be crucial for fuel rod survival under RIAs. From an experimental database of more than 200 out-of-pile mechanical property tests, a correlation for clad hoop plastic strain at failure with respect to clad temperature, irradiation damage, strain rate and hydrogen content was formulated. Cladding tube failure is assumed to take place when the clad hoop plastic strain exceeds the ductility limit defined by this correlation.

2.5 Yield Stress

The failure criteria assumed for the determination of the structural integrity of irradiated fuel rod cladding under axial loads from hypothetical transportation accident was that axial stresses in the cladding reach the yielding stress of the irradiated. Due to the inertial load on end drop, fuel rod buckles and, then, failure criterion (yielding) could be reached.

3. Discussions of failure measures

There could not be one generic failure criterion which can cover the all kinds of failure modes in claddings. Each has its own pros and cons. Different loads are subjected to cladding during transportation should be examined accordingly to their orientations and cladding microstructures.

Stress based failure criteria do not appear to be suitable for the evaluation of materials which would experience elastic-plastic strain, because of far more incremental strain with less increase of stress, and especially for the anisotropic materials. Strain could be one of candidate criteria for its simple measurability.

Strain based failure criteria for the cladding subjected to shock loads appears to be a simple measure to determine the cladding integrity during NCT. However, applying the test sample data to actual cladding in complicated stress environments needs a lot of experiments to be justified, especially a series of criteria for the various types of cladding alloy, burnup history, and hydride morphology, etc. are needed. A failure criterion based on strain alone could not cover the whole failure modes, of course, especially for the accident conditions.

The energy based criteria, i.e. **K_{IC}/CSED** would be appropriate better for the impact loads encountered during accident conditions than the other measures.

CSED was first proposed to evaluate the cladding integrity for the RIA events as a failure measure. And then, EPRI applied it to the evaluation of high burnup SNF cladding during hypothesized accident condition of transportation, which requires the assessments of the shock and impact loads for the cladding, while strain and K_{IC} were used as failure measures to evaluate the impact loads for cladding in SAND90-2406. However, it is not easy to deduce the K_{IC} without knowing the crack size in material. Furthermore, the SAND90-2406 methodology is of general applicability independently of burnup level, its quantitative results are not directly transferable to high-burnup fuel because of significant changes in mechanical and failure properties with burnup and the potential effects of dry storage on modifying the cladding hydride morphology. One of the critical areas in which the SAND90-2406 methodology needs to be updated is in the choice of failure criteria to replace the low burnup criteria, which were based on the cladding rupture strain and fracture toughness. To this end, the CSED, which combines the states of stresses and strains, has been proposed as a failure measure most suited for cladding with hydride-morphology-dependent failure mechanisms as can potentially exist in high-burnup spent fuel subjected to several decades of dry storage. Because the direction dependence of fracture toughness is more pronounced at high hydride concentrations, this limitation on K_{IC} data has a larger impact on high-burnup cladding. Further, radial hydrides have virtually no effect on Mode-I and –II failures, because the dominant stress acts in a direction parallel to the hydrides, unlike Mode-III failure where the highest stress is normal to the plane of the hydrides. That is, another important factor in the choice of CSED as a cladding failure measure is its ability to capture the behavior of radial hydrides.

For the vibration loads, the **fatigue-design curve** for cladding would be used to assess failure due to excessive strain cycling at low amplitude under vibrational loading.

Anyhow, it is important to determine an appropriate failure criterion for a certain failure mode selectively because no one measure can cover the whole set of failure modes fully. A lot of experiment with various types of cladding conditions, especially hydride morphologies, should be implemented to evaluate the appropriateness of a certain failure criterion for a specific failure mode.

4. Summary

It is important to set up a reasonable failure criterion for cladding, because being able to determine the cladding integrity during transportation is essential for the evaluation of SNF transportation system.

There are a few of measures which can be used as a failure criterion for cladding subjected to its specific failure mode. Therefore, to select and to use appropriate failure criterion measures, i.e. strain(UE), K_{IC}, and CSED would be a key in evaluating the cladding integrity during transportation with every aspects. In order to justify and quantify that criterion properly, various experiments for the mechanical properties of the claddings with different conditions shall be implemented, which data will enable to justify the failure criteria proposed.

ACKNOWLEDGEMENT

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REFERENCES

[1] Sandia Report SAND90-2406, ‘A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements’.

[2] Used Nuclear Fuel Loading and Structural Performance Under NCT, FCRD-UFD-2013-000325.

[3] A strain-based clad failure criterion for RIA in light water reactors, Sweden TR 03-008, 2004.