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Review of Current Criteria of Spent Fuel Rod Integrity during Dry Storage

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1. Introduction

A PWR spent fuel has been stored in a wet storage pool in Korea. However, the amount of spent fuel is expected to exceed the capacity of a wet storage pool within 10~15 years. From the early 1970's, a research on the PWR spent fuel dry storage started because the dry storage system has been economical compared with the wet storage system. The dry storage technology for Zircaloy-clad fuel was assessed and licensed in many countries such as USA, Canada, FRG and Switzerland.

In the dry storage system, a clad temperature may be higher than in the wet storage system and can reach up to 400℃. A higher clad temperature can cause cladding failures during the period of dry storage, and thus a dry storage related research has essentially dealt with the prevention of clad degradation. It is temperature and rod internal pressure that cause cladding failures through the mechanisms such as clad creep rupture, hydride re-orientation, and stress-corrosion cracking etc.[1].

In this paper, the current licensing criteria are summarized for the PWR spent fuel dry storage system, especially on spent fuel rod integrity. And it is investigated that an application propriety of existing criteria to Korea spent fuel dry storage system.

2. Principal clad degradation mechanism

A spent fuel rod in a dry storage system generates decay heat and experiences a higher rod internal pressure than the atmospheric pressure due to the fission gas. In addition, cladding material has partly lost its integrity because clad surface oxide and dissolved hydrogen can reduce the cladding integrity during the reactor operation.

Main degradation mechanisms of the spent fuel cladding can be classified into creep, stress corrosion cracking(SCC) and delayed hydride cracking(DHC).

In the dry storage environment, the spent fuel cladding is placed in high temperature and hoop stress conditions. Creep rate can be expressed as the following equation.

$$\varepsilon = K\sigma^{n}\exp(-Q/RT) \qquad (1)$$

ε : creep rate
σ : hoop stress of the spent fuel cladding
Q : activation energy
R : gas constant
T : absolute temperature of the cladding
K : proportional constant
n : stress exponent

The above equation suggests that the temperature and hoop stress of the spent fuel cladding are main driving forces for the creep deformation. Accordingly, it is crucial to limit the maximum temperature of the stored fuel cladding and the maximum hoop stress - fuel rod internal pressure - in order to maintain the mechanical integrity of the fuel rod during dry storage.

Stress corrosion cracking (SCC) of the spent fuel cladding may be also a degradation mechanism of fuel cladding. Iodine released from fuel pellets can play a chemically detrimental role in the vicinity of cracks on cladding inner surface. Combined with the iodine, mechanical stress due to pellet cladding interaction or rod internal pressure is exerted on the cladding. Iodine concentration, stress and initial crack size on inner surface have a critical effect on the initiation of SCC.

Delayed hydride cracking (DHC) mechanism may be also a cause of fuel rod integrity degradation. Hydride precipitates are distributed circumferentially in the matrix. If a crack initiates at hydride precipitates, the hydrogen tends to diffuse and precipitate at crack tip by a driving force of stress gradient. Therefore, the crack tip becomes so brittle that the crack propagation leads to the cladding rupture when the crack size is larger than the threshold size.

3. Fuel rod integrity criteria and operating experience of dry storage system

In 1980, the U.S. NRC specified in 10CFR, "Licensing Requirements for the Storage of Spent Fuel in an Independent Spent Fuel Storage Installation (ISFSI)"[2]. After the some modifications in 1987, the 10CFR72 demanded to license applicants that stored fuel in dry storage cask must be protected from the degradation that leads to gross ruptures. The PNNL has performed many experimental tests in order to establish the fuel rod integrity criteria for dry storage system. The results have suggested a set of criteria consisting of maximum allowable cladding temperature and rod hoop stress; 400℃ and 90Mpa [3]. These criteria are also limited within rod average burnup (< 45,000MWD/MTU), clad material (Zircaloy) and storage period (<20 years). Table 1 shows that the currently operating dry storage system for PWR spent fuel in the world [1].

As can be seen in table 1, the stored fuel average burnup is lower than the assessed range (< 40MWd/kgU) and maximum clad temperature is much lower than the suggested temperature by PNNL.

Table 1. Current PWR spent fuel dry storage system

Gas	Burnup (MWd/kgU)	Max. Clad Temp (℃)	Cooling Time (yr)
He	27	278	2-4
He	27	145	3-4
He	27	233	3-4
He	40	340	8-10
He	27	168	3-4
He	35	370	5

4. Technical limitation of current dry storage system

The established criteria of dry storage system can be applied only for the limited range. In case of new fuel design or storing condition change such as array variation, burnup increase, new material usage and storage period extension, the NRC demands that new proper criteria and safety analysis results must be shown [4]. A spent fuel discharge burnup has been increased gradually up to 60MWd/kgU. The impact of high burnup fuel on dry storage system can be summarized as follows:

- Higher oxide thickness and hydrogen concentration
- Higher rod internal pressure
- Higher decay heat generation
- Longer storing period
- Advanced Zirconium alloy

First of all, current high burnup cladding toughness is lower than low burnup fuel due to the higher oxide thickness and hydrogen pick up. In PNNL's tests, a peak cladding oxide thickness is around 50μm but current high burnup fuel cladding oxide thickness is nearly doubled (> 100μm)[5]. This situation necessarily requires a new, extended experimental tests on high burnup cladding.

Secondly, an increased rod internal pressure raises a serious concern about the integrity of spent fuel rod. As mentioned in chapter 3, the current criteria restrict the maximum clad hoop stress to prevent clad gross rupture.

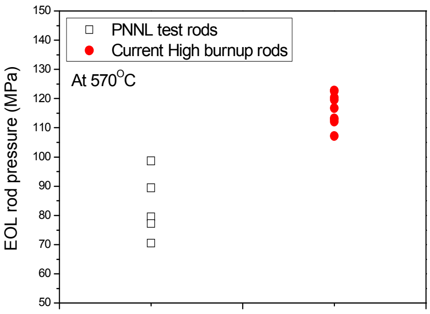

Figure 1. EOL rod internal pressure of low and high fuel

A preliminary estimation shows that the hoop stress of a high burnup fuel rod can easily exceed the suggested limitation (90MPa) during dry storage. Finally, the storage period extension beyond the currently assessed period (~20 yr) can cause the unanticipated rod failure due to the high burnup fuel decay heat is larger than low burnp (figure 2)[6].

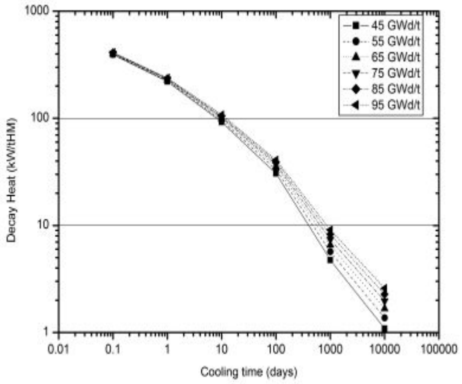

Figure 2. Decay heat generation as a function of discharged burnup

5. Summary

The spent PWR fuel dry storage system has many advantages. The currently licensed criteria of dry storage system is restricted to low burnup, Zircaloy cladding and 20 year storage period in order to secure spent fuel rod integrity. Experimental database was established only for the above range. As the spent fuel discharge burnup becomes higher, fuel failure probability becomes larger during dry storage due to higher oxide thickness, higher hydrogen concentration, higher decay heat and increased rod internal pressure. Therefore, for the dry storage of high burnup fuel, the fuel integrity degradation mechanism must be reviewed and integrity tests have to be performed to confirm the existing licensed criteria.

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