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High Burnup Issues of Zr-based Nuclear Fuel Cladding

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1. Introduction

As the fuel burn-up increases, corrosion, hydrogen absorption, and neutron irradiation become pronounced, resulting in degradation of cladding mechanical properties. The thermal shock resistance of the high burn-up fuel during the accident has been a great concern for the safety of LWRs. In the safety analysis of a postulated loss-of-coolant accident(LOCA) in a light water reactor(LWR), the fuel cladding is subjected to high-temperature steam exposure for several minutes until the emergency core cooling system(ECCS) quenches the fuel assembly[1]. High-burnup nuclear fuel cladding does not pose significant issues due to embrittlement during normal operation. However, under Design Basis Accident(DBA) conditions such as Loss of Coolant Accident(LOCA) and Reactivity Initiated Accident(RIA), severe material embrittlement can lead to cladding failure. As a result, the safety margin of nuclear fuel is reduced, and existing safety criteria are being reinforced[2,3]. Therefore, understanding the embrittlement phenomenon of nuclear fuel cladding is essential for evaluating the failure conditions and characteristics of the cladding under accident scenarios. Accordingly, this study aims to examine the behavior of high-burnup nuclear fuel cladding during accident conditions, focusing on the main embrittlement mechanisms such as namely, neutron irradiation, coolant oxidation, and hydrogenation.

2. Degradation Mechanism of High Burnup Fuel Cladding

In As the burnup increases in a reactor, the nuclear fuel cladding undergoes various physical and chemical changes. Unlike the initial as-received condition when first installed in the reactor, the cladding at high burnup exhibits completely different characteristics. These changes significantly impact the material properties, safety, and mechanical performance of the cladding. The changes in nuclear fuel cladding can be explained by three main mechanisms:

2.1 Damage caused by fast neutrons

Fast neutrons generated within the reactor collide with the cladding material, creating point defects, dislocations, pores, and other forms of damage. As burnup increases, these defects accumulate, significantly affecting the microstructure of the cladding. This results in a deterioration of the material's mechanical properties, particularly a reduction in ductility and an increase in brittleness. Damage from fast neutrons notably decreases the cladding's durability, and at high burnup, the embrittlement caused by this damage becomes more pronounced. Since the cladding plays a critical role in maintaining reactor function, this embrittlement can severely impact the cladding's reliability and safety.

2.2 Oxidation by coolant leading to the formation of a ZrO2 oxide layer

The nuclear fuel cladding is in continuous contact with high-temperature coolant in the reactor, leading to oxidation of the cladding surface. This oxidation results in the formation of a ZrO_2 oxide layer, which thickens as the burnup increases. While the oxide layer helps protect the cladding from corrosion, it also negatively affects the mechanical properties of the cladding. Specifically, as the oxide layer thickens, the cladding's ductility decreases, and its brittleness increases, reducing the safety margin during accidents, such as Loss of Coolant Accidents (LOCA). This can have significant consequences for reactor safety, especially in design-basis accidents (DBAs).

2.3 Hydride precipitation

Hydrogen ions generated during oxidation by the coolant are absorbed into the cladding surface and penetrate into the material. When hydrogen accumulates to a certain concentration, hydride precipitates form within the cladding material. As burnup increases, the amount of hydride precipitates continues to increase, which significantly affects the cladding's brittleness. Hydride precipitation is a major cause of embrittlement, particularly in high-burnup cladding. These hydrides adversely affect the mechanical properties of the cladding, making it more vulnerable to failure. The impact of hydride precipitation on embrittlement is much more significant than that of the oxide layer, and it poses an even greater threat to reactor safety.

Thus, as burnup increases, the nuclear fuel cladding undergoes changes due to fast neutrons, oxidation by coolant, and hydrogenation reactions. These changes significantly affect the cladding's mechanical properties, safety, and durability. Therefore, it is crucial to consider these changes in reactor design and operation to ensure the reliability and safety of the nuclear fuel cladding.

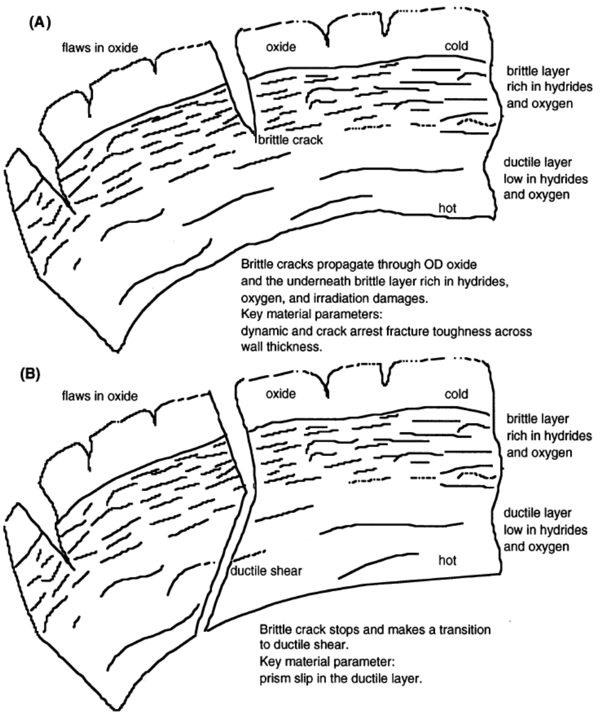

Fig. 1. Hydride distribution of high burnup nuclear fuel cladding [4].

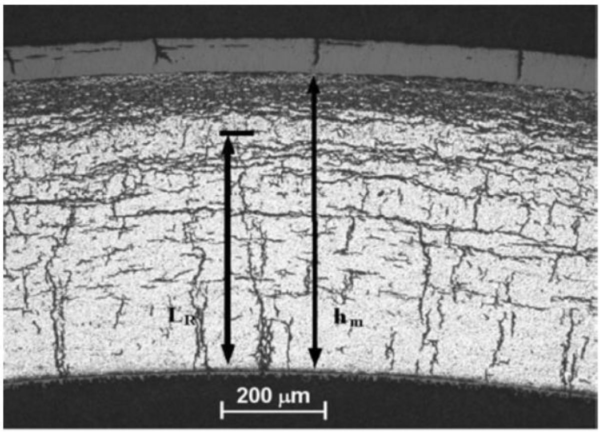

Fig. 2. Hydride morphology in HBU ZIRLO™ cladding [5].

3. Conclusions

This study investigates the characteristics and key degradation mechanisms of high burnup nuclear fuel cladding. As the burnup of nuclear fuel increases, various types of damage occur. First, point defects, dislocations, and pores are generated by high-energy neutrons, leading to embrittlement of the cladding. Second, oxidation due to coolant interaction results in the formation of a ZrO2 oxide layer, and as its thickness increases, the mechanical properties change, causing further embrittlement. Third, hydride precipitation due to the hydrogenation reaction exacerbates the embrittlement of the cladding. All of these factors contribute to the embrittlement of high burnup nuclear fuel cladding. In conclusion, the degradation characteristics of high burnup nuclear fuel cladding are critical not only during normal reactor operation but also in accident scenarios such as LOCA, where they can significantly impact fracture time and fracture conditions.

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