Research status and modeling development of FFRD

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1. Introduction

Extensive research has been conducted on the Fuel Fragmentation, Relocation and Dispersal (FFRD) that occur during Loss-Of-Coolant Accidents (LOCAs) [1-5]. And these FFRD phenomena have been found critical for especially high burnup fuels. Recently, the U.S. Nuclear Regulatory Commission (NRC)' Office of Nuclear Regulatory Research (RES) summarized the research findings on the FFRD phenomena as Research Information Letter(RIL)[6] and they defined several conservative and empirical thresholds as follows.

1. Fine fragmentation(pulverization) : the onset at a pellet average burnup of approximately 55 GWd/MTU
2. Relocation : Restriction in regions with less than 3% cladding strain
3. Dispersal : It is related to fragment size and strain threshold.
4. Transient fission gas release(tFGR) : Signification FGR during LOCA can impact ballooning and burst behavior in high burnup fuel.
5. Packing fraction : It is typically range from 70%~85%, depending on burnup and fragment size.

The threshold values presented in RIL[6] are mainly based on the observed relationship between the FFRD phenomena and burnup. However, the FFRD phenomena are influenced not only by burnup but also by properties that vary with the operating history, such as the fuel microstructure, temperature, porosity and stresses within the fuel pellet.

For this reasons, an operation history based High Burnup Structure(HBS) model is being developed to improve the FFRD model. Since it has been reported that HBS is associated with fine fragmentation, it is expected that the extent of fine fragmentation can be calculated by predicting HBS formation.

Under these circumstances, in the present study, a sensitivity analysis was performed on the QT model (the FFRD model implemented in FRAPTRAN 2.0 Patch 1)by applying the conservative threshold parameters proposed by RES[6]. Additionally an operation history-based HBS model, which is currently under development, is introduced.

2. Sensitivity analysis of FFRD model

The Quantum Technologies (QT) model was proposed and implemented in FRAPTRAN 2.0P1 to simulate the FFRD phenomena. In this chapter, the influence of the QT model is investigated by applying conservative threshold parameters, namely pulverized particle size, strain threshold and packing fraction, as proposed by RES for the onset of FFRD. The sensitivity analysis of the key parameters in the QT model was conducted using the NRC 192 test results [9] performed at Studsvik.

2.1 Effect of pulverized particle size

In the QT model, the pulverized particle size is fixed at 100 μm; however, experimental results have demonstrated the presence of various particle sizes. In order to investigate the effect of particle size on the relocated fuel mass, the particle size was varied. As demonstrated in Figure 1, the axial relocated fuel mass is affected by the particle size: as the particle size increases, it becomes more difficult for fuel particles to move from the top (node 11) to the bottom (node 8), leading to a decrease in the relocation amount.

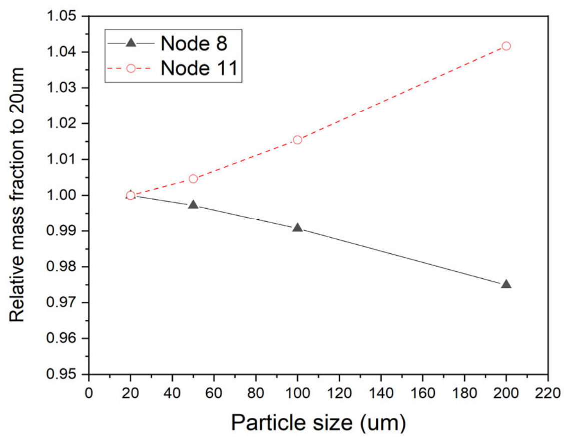

Figure 1. The variation of relative fuel mass according to pulverized particle size

2.2 Effect of strain threshold for relocation

The relocation of fuel is determined by the cladding strain (3.7% ± 1.7% [6]), and therefore its impact was investigated. Figure 2 shows the relative mass changes as a function of the cladding strain threshold. In the NRC 192 test, fuel relocation was observed at a cladding strain threshold of 3.7%, while at 5.7% there was minimal movement of fuel particles within the same time. At a threshold of 5.7%, additional cladding deformation is required for relocation to occur, thereby delaying the onset of fuel relocation. These results indicate that cladding strain influences not only the timing of relocation onset but also the amount of relocated fuel mass

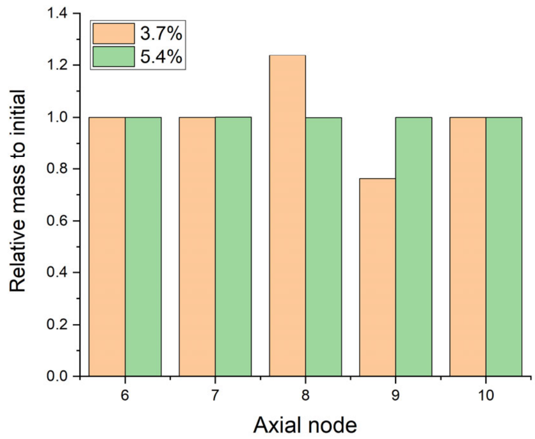

Fig. 2. The variation of relative fuel mass according to cladding strain threshold for fuel relocation

2.3 Effect of packing fraction

The packing fraction refers to the proportion of the ballooning region occupied by fuel fragments—specifically, the fraction of the space within the cladding taken up by the fragments after relocation. According to RIL [6], the packing fraction is defined to range between 70% and 85%. Figure 3 shows that as the packing fraction increases, the relocated fuel mass also increases. These results indicate that an increase in the packing fraction significantly affects the occurrence rate of fuel relocation.

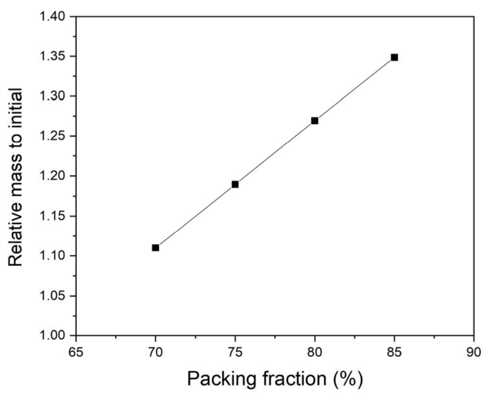

Fig. 3. The variation of relative fuel mass according to packing fraction

3. Operation history based HBS modeling

The threshold values proposed by RIL[6] are quite simple and rely primarily on the observed relationship between the FFRD phenomena and burnup. However, FFRD behavior is affected by various factors—such as microstructure, temperature, and pressure—that change with the operation history, and the current model does not reflect this complexity. Therefore, further research into variables beyond burnup is necessary.

Since fuel pulverization is associated with HBS, a model to predict HBS formation is being developed. It has been proposed that HBS forms when a reduction in fission gases within the fuel matrix leads to pore formation, and the over-pressurization of pores generates a stress field in the surrounding area. [10,11,12]. Based on this mechanism, a predictive model for HBS formation is being developed using a fission gas release model and empirical models of pore properties. The left side of Figure 4 illustrates the pore pressure threshold for HBS formation as a function of temperature, while the right side shows that this model is good agreement with the experimental results[13]

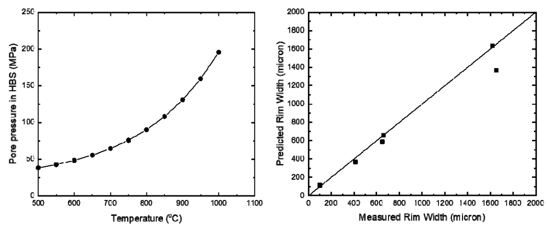

Figure 4. The pore pressure threshold for HBS formation depending on temperature(left) and model validation (right)

4. Summary and Future Plans

A sensitivity analysis of the FFRD effect was performed using the NRC 192 test on the modified QT model. An increase in the particle size of the pulverized fragments resulted in a decrease in the relocated fuel mass. Furthermore, when the cladding strain exceeded approximately 4%, both the timing of the FFRD occurrence and the relocated fuel mass were affected. Finally, the relocated fuel mass exhibited a linear relationship with the packing fraction

Also, a predictive model considering fission gas behavior and pore characteristics, based on HBS formation mechanism, has been developed and shows agreement with experimental results.

Since the FFRD phenomenon is influenced by a variety of factors beyond burnup, these variables must be taken into account when developing models to simulate FFRD. At KAERI, the following models are planned for development to predict the FFRD phenomenon:

- Pulverization model based on the accumulation of irradiation damage and microstructural changes

- Mechanistic axial relocation model incorporating transient fission gas release (FGR) and axial gas communication
- Empirical and semi-empirical dispersal model

Additionally, in order to conduct the experiments required for model development, equipment capable of performing irradiated fuel performance tests is currently being established within KAERI’s hot cell facilities.

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