Modification of QT model and evaluation of its sensitivity to fuel safety

JangSoo Oh [a*], YongSik Yang [a], JuYeop Park [b]
[a] *Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea*
[b] *Dept. of Safety Analysis, Korea Institute of Nuclear Safety, 34124, Daejeon, Korea*
[*]*Corresponding author: jagnsoo@kaeri.re.kr*

Keywords : FFRD, fuel relocation, FRAPTRAN, LOCA

1. Introduction

Fuel Fragmentation, Relocation and Dispersal (FFRD) are typical phenomena that occurs in high burnup nuclear fuels, and it is expected to have significant impacts on safety analyses, such as an increase of the Peak Cladding Temperature (PCT) and criticality effects due to dispersed fuel [1]. As a result, extensive research is actively being conducted to better understand and mitigate the effects of the FFRD.

Although the Quantum Technologies (QT) model [2] has been found very helpful in understanding the FFRD phenomena based on various experimental data, it is not sufficient to simulate the FFRD due to the conservatism of the key factors used in the model and the application of assumptions that are somewhat different from the experimental data.

The U.S. Nuclear Regulatory Commission (NRC)'s Office of Nuclear Regulatory Research (RES), through years of research on FFRD, has made several proposals for considering the FFRD phenomena and their perspectives were recently summarized as a Research Information Letter (RIL 2021-13)[3]. This report outlines the RES position on key factors related to the interpretation of the FFRD.

In this study, some factors of the QT model in the FRAPTRAN 2.0P1 code [4] were modified based on the RIL 2021-13 to update the FFRD model, and sensitivity analyses of the modified factors were performed based on in-pile test data.

2. Modification of QT model factors

2.1 Pulverization size

Fuel pulverization occurs due to the elevated temperatures and high burnup structure under a Loss-Of-Coolant Accident (LOCA) condition. The size of nuclear fuel fragments is widely distributed when the FFRD occurs, but the QT model uses a fixed value of size (100μm). Since the size of pulverized fragments is a factor that affects the amount of relocated fuel, in the present, the QT model has been updated to allow the size of pulverized fragments to be determined by a user input.

2.2 Relocation threshold

Cladding ballooning can increase the gap between the fuel pellet and the cladding, leading to formations of empty spaces. When these empty spaces form, the fragmented fuel above the empty spaces can move downward, called axial relocation. In the QT model, the possibility of relocation is determined based on the gap width, and the threshold value is set at 0.2 mm. However, the RIL 2021-13[3], based on various experimental results, proposes a relocation threshold defined by the cladding strain of 3.7±1.7%. In the present study, the gap width criterion of the QT model for fuel relocation has been updated from 0.2 mm to the cladding strain, and the cladding strain threshold value has been made available as a user input.

2.3 Packing fraction

The packing fraction is closely related to the cladding temperature because higher packing fraction lead to increased local heat generation. In the QT model, the packing fraction is calculated using the Westman equation [5] based on the size of the fragmented/pulverized particles. However, this approach oversimplifies the complex phenomena and makes it difficult to account for the effect of the different sizes of fine particles, as it assumes a fixed particle size (100μm). To address this, the QT model has been modified to allow a user input of the packing fraction. According to the RIL 2021-13[3], the suggested range for the packing fraction is 70–85%.

3. Sensitivity analysis

For the sensitivity analysis of the modified QT model based on key parameters, the results of the NRC 192 test conducted under the Studsvik [6] were used. In the Studsvik test, there are no thermal-hydraulic conditions external to the fuel rod, and the surface temperature is determined through radiation heating. This results in relatively straightforward interpretation conditions, making it suitable for model sensitivity evaluations. The fuel rod used in the NRC 192 test has a burnup of approximately 78 MWd/kgU.

The NRC 192 test was simulated by use of FRAPTRAN 2.0P1 with QT model. The result showed that ballooning occurred at 1158 seconds, and shortly thereafter, at 1159 seconds, axial fuel relocation was first observed at axial node 8 to 11. Fig. 1 shows that relative fuel mass distribution and cladding strain at the time of the FFRD occurrence. At node 11, the relocation condition was satisfied, and significant deformation occurred at node 8, leading to the movement of the fuel rod towards the bottom.

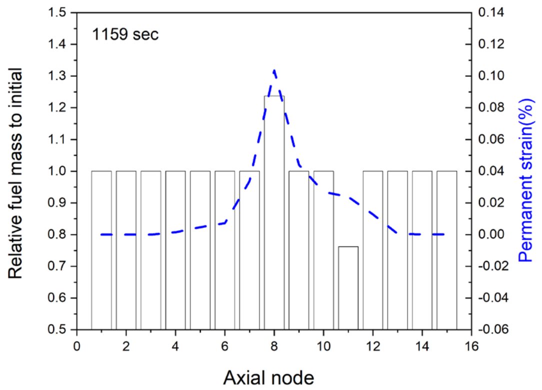

Fig. 1. Relative fuel mass distribution and cladding strain at the time of the FFRD occurrence.

3.1 Effect of pulverized particle size

The pulverized particle size was varied between 20 and 200 μm to examine the effects of the FFRD. As shown in Fig. 2, the relative fuel mass at the time of FFRD occurrence was found to be influenced by the particle size. As the particle size increases, the movement to downward becomes more difficult, resulting in a decrease in the relocated relative fuel mass. The relative fuel mass tends to change linearly with respect to particle size.

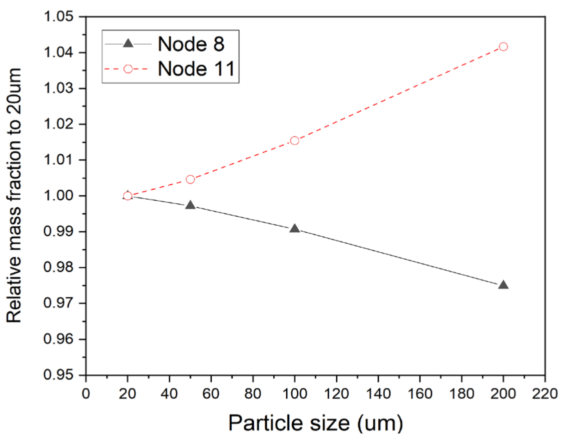

Fig. 2. Changes in pulverized particles size and relative mass fraction.

3.2 Effect of axial relocation threshold strain

The sensitivity analysis of the relocated fuel mass was conducted using cladding strain threshold, which is a variable for the occurrence of fuel relocation. The value presented in the RIL 2021-13[3] is 3.7±1.7%. Up to a cladding strain threshold of 3.7%, the occurrence time of the FFRD remains the same at 1159 seconds. However, it is delayed to 1176 seconds at 5.4%. This delay is due to the increased amount of cladding strain required for fuel relocation, which necessitates additional time for further strain to occur. Furthermore, as shown in Fig. 3, when the cladding strain threshold increases to 5.4%, the relocated fuel mass is very small, indicating almost no change. In conclusion, the cladding strain seems to influence both the timing of FFRD and relocated fuel mass.

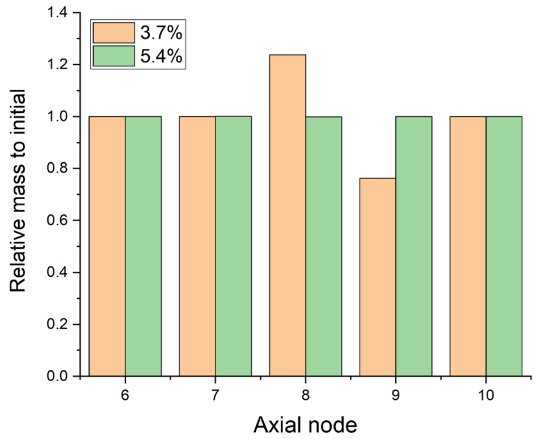

Fig. 3. Change in relative mass fraction with respect to cladding strain threshold for fuel relocation.

3.3 Effect of packing fraction

The range of 70-85% packing fraction, as presented in RIL 2021-13 [3], was used to analyze the effect of relocated fuel mass on the packing fraction. The occurrence time of the FFRD remains the same at 1159 seconds for packing fraction up to 80%, but it decreases to 1157 seconds at the packing fraction of 85%. This is because the packing fraction affects the determination of the FFRD occurrence index in the QT model, resulting in an increased probability of fuel relocation as the packing fraction increases. The packing fraction represents the fuel mass relative to the empty space. Therefore, an increase in the packing fraction is proportional to an increase in the relocated fuel mass. This trend is shown in Fig. 4, where both the packing fraction and relative fuel mass increase linearly.

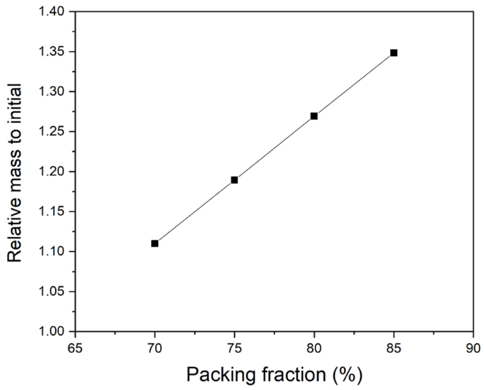

Fig. 4. Change in the relative fuel mass at the occurrence timing of FFRD on the packing fraction.

3. Conclusions

A sensitivity evaluation of the effect of the FFRD was conducted using the NRC 192 test on the modified QT model. As the particle size of the pulverized fragments increased, the relocated fuel mass decreased, and the cladding strain threshold affected both the timing of the FFRD occurrence and the relocated fuel mass when the strain exceeded about 4%. Finally, the relocated fuel mass increased linearly with the packing fraction.

Based on this study, we plan to propose default values for the FFRD models through additional validation.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS) and the Nuclear Safety and Security Commision(NSSC), Republic of Korea(Grant No. 2106002)

REFERENCES

[1] Report on Fuel Fragmentation, Relocation and Dispersal, NEA/CSNI/R(2016)16.

[2] L.O. Jernkvist and A. Massih, Models for axial relocation of fragmented and pulverized fuel pellets in distending fuel rods and its effects on fuel rod heat load, SSM, 2015:37.

[3] Bales et al. Interpretation of Research on Fuel Fragmentation, Relocation and Disposal at High Burnup, RIL 2021-13.

[4] K.J. Geelhood et. al., FRAPTRAN-2.0: A Computer Code fur the Transient Analysis of Oxide Fuel Rods", PNNL-19400, Vol.1, Rev2, 20163.

[5] Westman, A.E.R., The packing of particles: Empirical equations for intermediate diameter ratios. Journal of the American Ceramic Society, 19: pp. 127-129, 1936.

[6] M. Flanagan, P. Askeljung and A. Puranen, Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory, NUREG-2160, 2013