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A Way to Homogenize Burnup of Fuels Based on Gamma-ray Spectrum Emitted from Fission Products

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1. Introduction

In HANARO, the safety evaluation in terms of thermal-hydraulics for irradiated samples has been performed based on nuclear heating rate by prompt gamma-rays with large margin [1]. There are various routes of nuclear heating caused by various types of interactions such as radioactive captures or inelastic scatterings with nuclei by neutrons, prompt neutrons and gamma-rays emitted from fissions, delayed radiations emitted from decay, and etc. Detailed analysis of nuclear heating by various interactions is required in order to estimate the temperature increase of irradiation samples accurately.

As a preliminary study for calculation of nuclear heating by delayed gamma-ray from fission product, the size of homogenized fuel segments considering burnup is studied in this paper. In an extreme case, if fuel is divided into very small sized segments, the simulation results will be very accurate. Whereas there will be limitations such as lack of performance of hardware or huge calculation time. In the opposite extreme case, if the burnup of all fuels are assumed to same, the calculation time will be reduced, however, the results might be unreliable. In this study, the burnup distribution in a fuel assembly is estimated from power distribution and the correlation of burnup and emitted gamma-ray spectrum. Finally, the size of homogenized fuel segments is contemplated.

2. Burnup Distribution

Because the burnup is linearly proportional to the power, the burnup distribution could be estimated from the power distribution. The core and heavy water pool of the HANARO was modeled by the MCNP6 code in order to calculate the power distribution. It was assumed that all fuels were a fresh fuel and were divided into uniform-sized segments of 5 cm in axial direction. In radial direction, it was assumed to be uniform power in a fuel rod. The control rod was located at 450 mm height from bottom of the core because it could be regarded as a representative control rod position in one operation cycle.

Among fuel assemblies with 36-element, one which the power distribution was most non-uniform was considered as the most non-uniformly burned fuel assembly in core. The burnup distribution was estimated by assuming to be same with power distribution. The average discharged burnup of fuel assembly with 36-element was designed 55.85 at% ^{235}U [2], and it is equivalent to about 93 GWD/MTU. The average discharged burnup of considered assembly was assumed to be 93 GWD/MTU and burnup of all fuel segments were calculated by using the ratio of power density of each segment to average power density of the assembly. The maximum and minimum burnup of segment were calculated to be 154.6 and 25.7 GWD/MTU. In real fuel assembly, the burnup distribution is expected to be flatter because the power contribution at middle of fuel rod will be decreased along burnup increased.

Figure 1, 2 and 3 are indicated the estimated burnup distribution in radial direction at the lowest layer, the most burned layer, and the highest layer, respectively. Figure 4 is indicated estimated burnup distribution in axial direction for a “rod 01” rod located at upper left corner and a “rod 16” rod located at left corner. The background color was painted in accordance with their burnup. High and low burnup was distinguished by painting red and blue color, respectively. From the color distribution, the difference of burnup among fuel rods was small in radial direction. The maximum difference was about 50 GWD/MTU. However, the burnup distribution in axial direction was increased and decreased rapidly and the maximum difference is about 117 GWD/MTU.

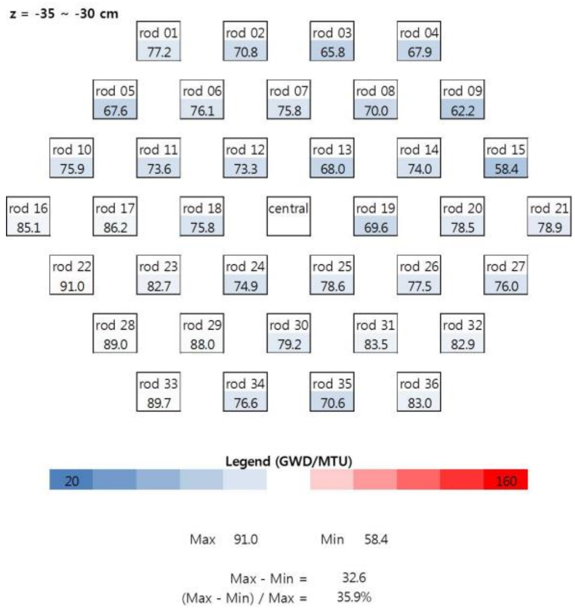

Fig. 1. Estimated burnup distribution of the lowest layer in radial direction

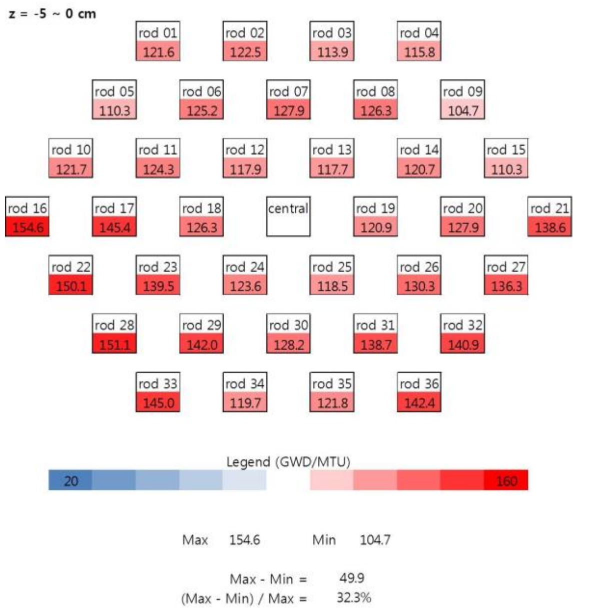

Fig. 2. Estimated burnup distribution of the most burned layer in radial direction

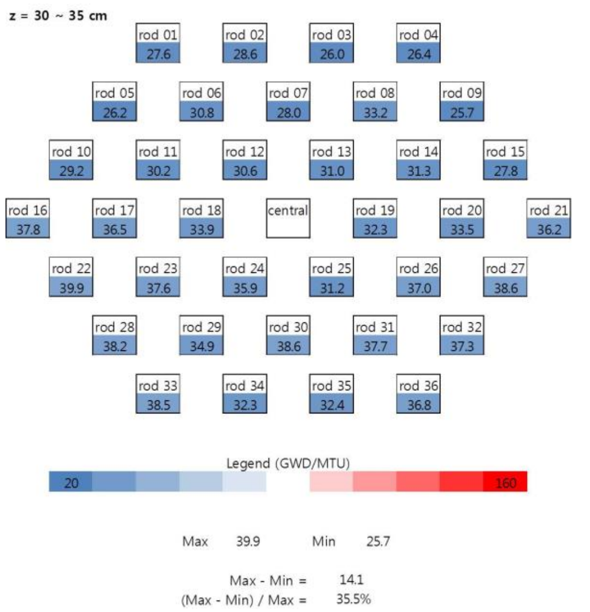

Fig. 3. Estimated burnup distribution of the highest layer in radial direction

3. Gamma-ray Emission Rate According to Burnup

The correlation between burnup and gamma-ray spectrum was evaluated by using the ORIGEN 2 code. The gamma-ray spectrum from fission products of the HANARO fuel which burnup is 10, 20, 30, …, 200 GWD/MTU was calculated in accordance with different cooling time. The energy structure was 18 groups because the ORIGEN 2 code provides only gamma-ray energy structure of 18 groups.

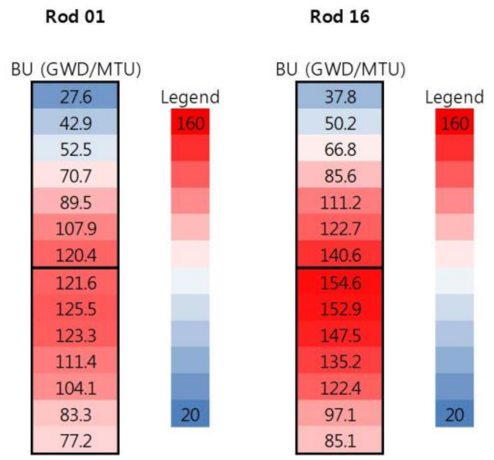

Fig. 4. Estimated axial burnup distribution of “rod 01” located at left and top corner and “rod 16” located at left corner

Figure 5 is shown the delayed gamma-ray spectrum along burmup increase when cooling time is zero. It is indicated that the difference of delayed gamma-ray emission rates can be neglect according to burnup without in range of 70 – 100 keV, 100 – 150 keV, and above 1.5 MeV. In the range of 70 – 100 keV and 100 – 150 keV, the difference of gamma-ray emission rate between the burnup of 20 GWD/MTU and 160 GWD/MTU were calculated less than 50% (the maximum and minimum burnup of fuel segment in whole assembly were 155 and 26 GWD/MTU). In case of the range above 1.5 MeV, the differences are about 20%.

However, gamma-ray spectrum was different in accordance with burnup when reactor cooling after shutdown. Figure 6, 7 and 8 are the delayed gamma-ray spectrum according to burnup in cases of reactor cooling during 1 hour, 1 day and 10 days, respectively. Although it is impossible to discuss the correlation between burnup and gamma-ray spectrum due to the complex trends, however, the more burned fuels emits more gamma-rays. In case of 10 days cooling (in figure 8), the difference of gamma-ray emission rates between 100 GWD/MTU and 160 GWD/MTU in energy range of 45 – 75 keV and 150 – 300 keV were less than 50%, in range of 1 – 1.5 MeV and 2 – 2.5 MeV were less than 140%, and in the other energy ranges were less than 30% (the maximum and minimum burnup were 155 and 105 GWD/MTU in figure 2). In the range of 1 – 1.5 MeV and 2 – 2.5 MeV, the importance were relatively low because the absolute values of gamma-ray emission rates were about 1/10 compared with in lower energy range. If the gamma-rays in this energy ranges could be neglected, it can be assumed to be homogenized the burnup among all fuel rods in same height with a little uncertainty.

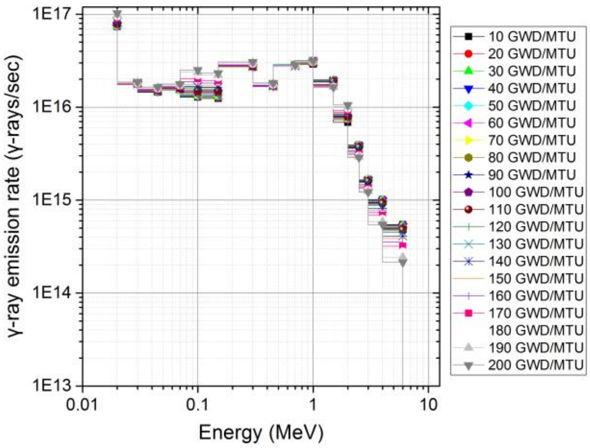

Fig. 5. Delayed gamma-ray emission rates along burnup increase without cooling time (cooling time = 0 sec)

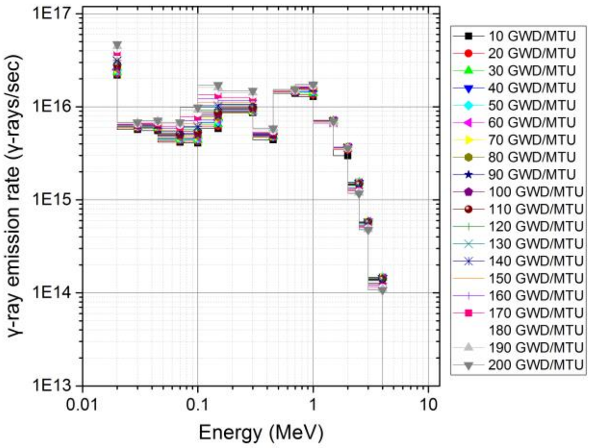

Fig. 6. Delayed gamma-ray emission rates along burnup increase 1 hour cooling after reactor shutdown

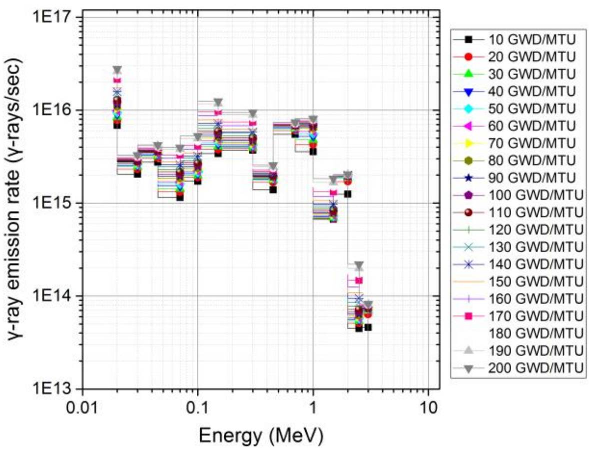

Fig. 7. Delayed gamma-ray emission rates along burnup increase 1 day cooling after reactor shutdown

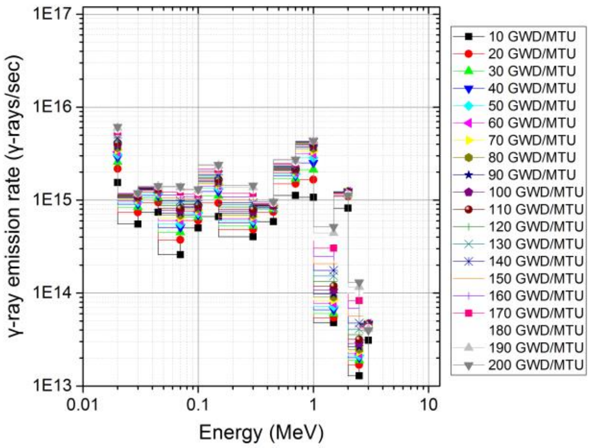

Fig. 8. Delayed gamma-ray emission rates along burnup increase 10 days cooling after shutdown

4. Conclusion

In this study, the burnup distribution in a fuel assembly was estimated from power distribution calculated by using the MCNP6 code. And the delayed gamma-ray emission rates according to the burnup were evaluated by using the ORIGEN 2 code. From the results, the way to homogenize burnup of fuel segments could be considered.

The maximum difference of burnup among all fuel rods in same height was 50 GWD/MTU and it could be assumed to be homogenized burnup of fuels in same height with a little uncertainty. However, the burnup distribution in axial direction was increased and decreased rapidly. In the future study, it will be able to homogenize burnup all fuel rods in same height, but do not homogenize fuel segments in different height.

In the case of reactor operating condition, which is equivalent to the zero cooling time, the maximum difference of delayed gamma-ray emission rates among all segments was less than 50%. Therefore it could be assumed to be homogenized burnup of all fuel segments in reactor. However, more cooling time made more difference of delayed gamma-ray emission rates and more complex trend of these. In general, high burnup emitted larger delayed gamma-rays. If it is focused on the accurate calculation, fine segments in axial direction will be better. But conservative calculation could be performed with enough margins by assuming homogenized high burnup for all fuels.

REFERENCES

[1] Sung-Taek Hong, et al., Status of the Safety Evaluation for an Irradiation Experiment of HANARO (2010-2013), KAERI/TR-5352/2013, Internal Technical Report, Korea Atomic Energy Research Institute, 2013.

[2] Heonil Kim, et al., Design Characteristics and Startup Tests of HANARO, Journal of Nuclear Science and Technology, Vol.33, No.7, p.527-538, 1996.