Quantitative Estimation of Heating by Delayed Gamma Ray for In-Reactor Testing at HANARO

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1. Introduction

In-reactor irradiation testing at HANARO has been used as a tool for the development of nuclear system and material, production of licensing data and verification of in-core performance to support national nuclear research and development program [1]. Maintaining specimen temperature is the most important factor for in-reactor testing because it affects the formation and migration of radiation-induced defect. During the test, the specimen and structural materials are heated up due to energy deposition of radiation. The specimen temperature is exquisitely adjusted by controlling cooling and heating rate using vacuum pumps and micro-heaters [2]. Therefore, predicting heating rate by radiation is important for the design of test device and evaluation of specimen temperatures during the test.

Nuclear heating is generally divided to be due to the neutrons and gamma rays. The materials such as fissionable elements and boron generate a lot of heat by neutrons, but most metallic materials are mainly affected by gamma rays. It can be classified into prompt and delayed gamma according to the emitting mechanism. Until now, the heating amount of delayed gamma rays was assumed to be 50% than the prompt gamma rays for the HANARO irradiation testing to guarantee the test performance conservatively. However, in order to enhance the quality of the test, it is important to estimate the heating rate by delayed gamma rays precisely. Therefore, in this paper, we quantitatively evaluate it by calculating emitting rate of delayed gamma rays and simulating the transport of neutrons and gamma rays.

2. Evaluation methods

The estimation of heating rate is conducted for the test using instrumented capsule which is currently being irradiated in the CT irradiation hole. The Advanced Reduced Activation Alloy (ARAA), which is being developed as a material for fusion reactor, is installed in the capsule for the multi-purpose tests [3]. Fig. 1 shows the MCNP model to simulate ARAA irradiation test. Six impact specimens are installed in the hexagonal direction at the lowest stage of capsule. There is a hole in the center of the test capsule, which is a helium atmosphere, and aluminum thermal media surrounds the specimen to maintain the temperature during the test. The light water coolant flows outside the SS316L external tube. Each area of irradiation hole and fuel assembly is divided into zircaloy-4 hexagonal flow tubes. Since the CT hole is located in the center of the core, it is surrounded by six fuel bundles, so the neutron fluence rate is the highest at HANARO.

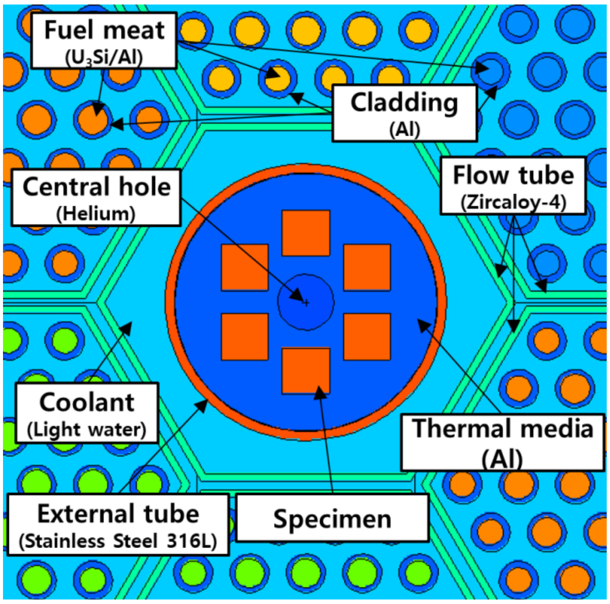


Fig. 1. Horizontal MCNP model for ARAA irradiation testing (capsule ID : 16M-02K)

Total seven sub-sections such as aluminum thermal media, alumina insulation, STS316L external tube, Zircaloy-4 flow tube, fuel cladding, and driver fuels were considered for this evaluation. Since delayed gamma rays emitting nuclides are generated by fission and activation of driver fuels and the others, so the inventory of the nuclides should be evaluated. The neutron transport simulation for HANARO core was conducted by MCNP6 [4] to determine the amount of heat generated by prompt gamma rays and the neutron flux/spectrum. The generation and destruction of nuclides by neutron-induced reaction and decay were calculated using ORIGEN 2.2 [5]. However, since there is no built-in-library to be applied to this estimation in ORIGEN 2.2, the libraries at each location and material were produced through MCNP6 calculation. ENDF/B-VIII [6] nuclear data were used for the library production. Finally, the heating rate of the capsule by the delayed gamma rays was evaluated and compared with the prompt gamma rays by gamma transport simulation using MCNP6 again. Figure 2 shows the evaluation method applied in this study.

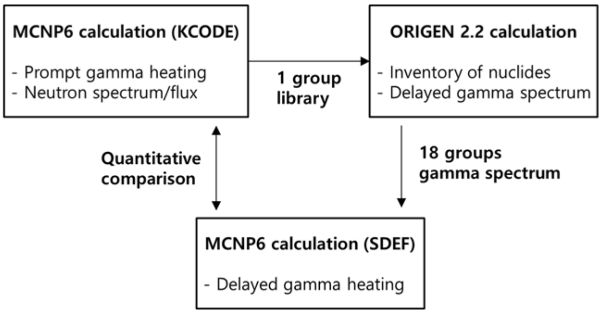
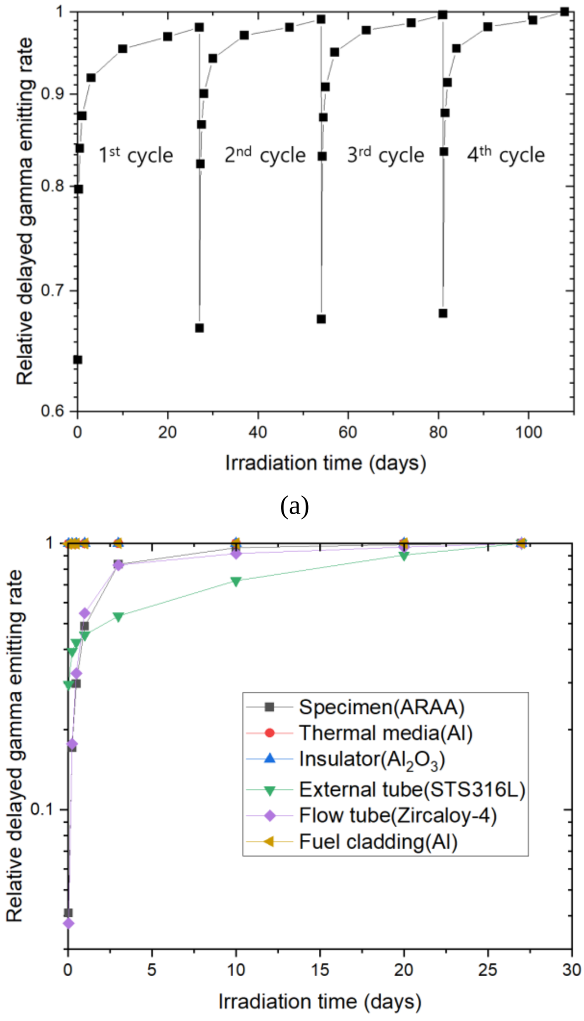


Fig. 2. The schematic evaluation flow chart

3. Results and Discussions

3.1. Delayed gamma emitting rate

In the case of the in-reactor testing for ARAA, it can be divided into four materials. The test specimen and the external tube of the capsule are made of iron-based alloy. The thermal media, the insulating material and the cladding tube are aluminum-based materials. The flow tube is zirconium-based alloy and the driver fuel meat is uranium-based material. Thus, delayed gamma rays emitting nuclides in each material are differently generated. In the case of aluminum, the half-life of Al-28 produced by the (n,γ) reaction is only 2.28 min, so it is saturated within a short time. On the other hand, the other elements have a relatively long half-life. Fig. 3 shows the relative emitting rate of delayed gamma rays in each material according to the irradiating time. In the case of aluminum, the emitting rate of delayed gamma rays is constant from the beginning of the cycle (BOC) to the end of the cycle (EOC). However, in the case of the other materials, the emitting rate is higher at EOC than at BOC. In other words, they may cause different effects on heating rate according to the irradiating time, so this should be considered during the test. In particular, in the case of driver fuel, the difference between BOC and EOC was relatively large. As a result of this calculation, the spectrum of delayed gamma rays of each sub-section in the axial position was determined. ORIGEN 2.2 generates 18 groups photon/sec spectra which were applied as the sources for the MCNP6 gamma transport calculation. Although the relative gamma emitting rate was different according to the depletion amount of driver fuels, the burn-up of driver fuels around the capsule was assumed be the average of equilibrium core considering four cycles operation. The applied burn-up of driver fuels was 47.775 GWD/MTU[7].



(a)

(b)

Fig. 3. Relative emitting rate of delayed gamma rays for (a) driver fuel and (b) the other sub-sections

3.2. Comparison of heating

Table I shows the results of evaluating heating amount of major sub-parts and locations in the capsule. In this evaluation, since it was evaluated at the middle of the cycle (MOC), the highest heat generation was calculated at the specimen located in the center. As the result of the effect on delayed gamma rays, most of the contributions were determined by the driver fuel. The effect of the sub-parts in the capsule and the core structure was insignificant. Based on the result for specimen heating, the result of quantitative evaluation of delayed gamma rays compared to prompt gamma rays was about 12.5% on average. This is much lower than 50% of the heating amount of delayed gamma, which was over-estimated by nearly 37.5%. If we have the methods to control the specimen temperatures in the capsule and high temperature test is not applied, the test can be carried out relatively safely. Therefore, it would be more appropriate to apply a realistic value rather than the conservative delayed gamma heating rate. Since accurate evaluation can be applied by knowing the rod burnup history of HANARO driver fuel and operation history of core, it is appropriate to apply accurate data of the target test cycle when designing and evaluating the in-reactor test. The difference between BOC and EOC due to the heating rate of driver fuel by delayed gamma rays is estimated to be about 30%, so the effect on this should be considered during the test.

Table I : Quantitative estimation results of heating by delayed gamma rays originated from each sub-section

Part name	Axial position	Prompt gamma heating (W/g)	Delayed gamma heating (W/g)			
			Specimen	Thermal media	Insulator	External tube
			ARAA	Al	Al_2O_3	SS316L
Specimen	1(bottom)	2.95E+00	2.13E-03	1.94E-02	8.85E-04	9.87E-05
	2	4.10E+00	3.00E-03	2.78E-02	1.92E-03	1.39E-04
	3(center)	4.28E+00	3.19E-03	2.82E-02	1.99E-03	1.46E-04
	4	3.50E+00	2.62E-03	2.42E-02	1.68E-03	1.22E-04
	5(top)	2.25E+00	1.72E-03	1.51E-02	7.14E-04	7.96E-05
Thermal media	1(bottom)	2.51E+00	7.74E-04	2.18E-02	7.55E-04	1.09E-04
	2	3.49E+00	1.10E-03	3.11E-02	1.63E-03	1.54E-04
	3(center)	3.64E+00	1.13E-03	3.29E-02	1.73E-03	1.62E-04
	4	2.97E+00	9.62E-04	2.70E-02	1.43E-03	1.35E-04
	5(top)	1.91E+00	6.06E-04	1.76E-02	6.23E-04	8.86E-05
External tube	1(bottom)	2.11E+00	2.52E-04	6.80E-03	4.05E-05	1.70E-04
	2	3.20E+00	5.88E-04	1.57E-02	1.34E-03	2.88E-04
	3	4.09E+00	7.99E-04	2.19E-02	9.87E-04	3.69E-04
	4	4.34E+00	8.21E-04	2.19E-02	1.89E-03	3.93E-04
	5	3.92E+00	7.37E-04	1.97E-02	1.92E-03	3.61E-04
	6	3.01E+00	5.92E-04	1.59E-02	1.43E-03	2.81E-04
	7	1.98E+00	3.80E-04	1.03E-02	1.31E-04	1.84E-04
	8(top)	1.42E+00	5.74E-05	1.59E-03	1.73E-05	1.08E-04
Part name	**Axial position**	**Prompt gamma heating (W/g)**	**Delayed gamma heating (W/g)**			
			Flow tube	Cladding	Fuel (BOC)	Fuel (EOC)
			Zircaloy-4	Al	U_3Si/Al	U_3Si/Al
Specimen	1(bottom)	2.95E+00	1.14E-04	1.45E-03	2.31E-01	3.40E-01
	2	4.10E+00	1.47E-04	1.96E-03	3.10E-01	4.56E-01
	3(center)	4.28E+00	1.54E-04	2.08E-03	3.30E-01	4.85E-01
	4	3.50E+00	1.28E-04	1.76E-03	2.78E-01	4.09E-01
	5(top)	2.25E+00	9.09E-05	1.22E-03	1.92E-01	2.82E-01
Thermal media	1(bottom)	2.51E+00	1.06E-04	1.47E-03	2.16E-01	3.18E-01
	2	3.49E+00	1.36E-04	1.98E-03	2.91E-01	4.27E-01
	3(center)	3.64E+00	1.43E-04	2.09E-03	3.07E-01	4.51E-01
	4	2.97E+00	1.20E-04	1.78E-03	2.60E-01	3.83E-01
	5(top)	1.91E+00	8.40E-05	1.22E-03	1.78E-01	2.62E-01
External tube	1(bottom)	2.11E+00	1.27E-04	1.07E-03	1.69E-01	2.49E-01
	2	3.20E+00	1.62E-04	1.82E-03	2.91E-01	4.28E-01
	3	4.09E+00	2.01E-04	2.25E-03	3.58E-01	5.26E-01
	4	4.34E+00	2.14E-04	2.40E-03	3.83E-01	5.64E-01
	5	3.92E+00	1.96E-04	2.22E-03	3.53E-01	5.19E-01
	6	3.01E+00	1.53E-04	1.79E-03	2.85E-01	4.19E-01
	7	1.98E+00	1.20E-04	1.24E-03	1.97E-01	2.90E-01
	8(top)	1.42E+00	1.55E-04	8.51E-04	1.33E-01	1.95E-01

4. Conclusions

Quantitative evaluation by delayed gamma was conducted for the HANARO irradiation test and the following conclusions were obtained.

(1) The heating amount due to delayed gamma rays compared to prompt gamma rays is about 12.5%, which was much lower than conservative value (50%).

(2) The most important material for heating rate by delayed gamma rays is driver fuel, about 90% is generated.

(3) There is no difference of heating rate by delayed gamma rays in aluminum between BOC and EOC. However, it is necessary to consider the effect of driver fuel according to the test duration.

Since the effect on driver fuel is dominant, it is necessary to consider the operation history of HANARO and the burnup history of driver fuel. Based on the results of this evaluation, we plan to conduct thermal analysis in the future. In addition, we also plan to evaluate whether there is any problem in using best estimated value by conducting the safety analysis.

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