

Neutron Fluence Evaluation of the 22F-01U Irradiation Capsule at HANARO Using Activation Wire Monitors

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1. Introduction

A fuel and graphite irradiation test was conducted in the IP9 irradiation hole of the HANARO research reactor using the non-instrumented 22F-01U capsule[1]. The capsule consisted of three clusters that were withdrawn at different stages of the irradiation campaign. Because the accumulated neutron exposure of each cluster depends on both irradiation history and axial position, a post-irradiation evaluation of the neutron fluence was required. Neutron fluence monitor (FM) wires were therefore installed in Rod 3 of Cluster 1 and Rod 6 of Cluster 2. This study evaluates the neutron fluence of the two monitored clusters by combining post-irradiation gamma-ray spectrometry with cycle-dependent ORIGEN2[2] calculations. Effective one-group reaction cross sections were generated using MCNP6[3], and the evaluated neutron fluxes were compared with the MCNP reference fluxes at the corresponding rod positions.

2. Methods and Results

2.1 Fluence monitors and gamma-ray measurement

Rod 3 contained Al-Co, Ni, and Fe wires, whereas Rod 6 contained Nb, Ti, and Ni wires in aluminum containers. Cluster 1 was irradiated from cycles 108-1 to 111-3, corresponding to approximately 2,790.9 MWD and 93 effective full-power days (EFPD), while Cluster 2 remained in the reactor through cycle 116, corresponding to approximately 5,924.3 MWD and 197 EFPD. The cooling periods before measurement were approximately 490 days for Rod 3 and 270 days for Rod 6.

After capsule dismantling, the FM wires were measured with the HPGe detector #2 of PTS facility[4]. Each sample was counted for 4 h at the N3 position, 15 cm from the detector window. The photopeak efficiency was determined using a multi-gamma standard source traceable to the Korea Research Institute of Standards and Science. The principal analysis peaks included 1332 keV for Al-Co, 811 and 1332 keV for Ni, 835, 1099, 1292, and 1332 keV for Fe, 889 and 1121 keV for Ti, and 703 and 871 keV for Nb. For each peak, the activity at the end of irradiation (A_{EOI}) was derived from the net peak area with corrections for detector efficiency, gamma-ray branching ratio, cooling decay, and decay during counting.

2.2 Neutron flux and fluence evaluation

The measured A_{EOI} was reproduced by an iterative ORIGEN2 calculation that explicitly reflected the irradiation and shutdown history of each cluster. A reference full-power flux was varied until the calculated A_{EOI} agreed with the value obtained from gamma-ray spectrometry, and cycle-by-cycle fluxes were scaled in proportion to reactor thermal power. Effective cross-section libraries for the relevant activation reactions were calculated with the HANARO MCNP6 model. The 30 MW MCNP reference fluxes at the Rod 3 and Rod 6 positions were 1.14×10^{14} and 1.48×10^{14} n/cm²/sec, respectively. The difference between the evaluated and calculated reference fluxes was expressed as E/C.

2.3 Evaluation results

For Rod 3, the aluminum-container monitors showed good agreement with the MCNP calculation. The Al-Co result differed by 3.4%, the Ni result based on the 1332 keV peak of Co-60 by 9.2%, and the representative Fe results by 11.0-14.6%. These measurements corresponded to an accumulated neutron fluence of approximately 9.5×10^{20} to 1.05×10^{21} n/cm².

Table I: Representative neutron fluence evaluation results

Rod	FM	Peak (keV)	Fluence (n/cm ²)	E/C
3	Al-Co	1332	9.464E+20	3.4%
3	Ni	1332	9.991E+20	9.2%
3	Fe	835	1.048E+21	14.6%
3	Fe	1332	1.016E+21	11.0%
6	Ni	1332	2.827E+21	12.3%
6	Ti	889	2.158E+21	-14.3%
6	Nb	703	2.617E+21	3.9%
6	Nb	871	2.522E+21	0.1%

For Rod 6, the selected Ni, Ti, and Nb results were also consistent with the MCNP reference within approximately $\pm 15\%$. The Ni result based on Co-60 differed by 12.3%, the Ti result based on the 889 keV peak by -14.3%, and the Nb-94 results at 703 and 871 keV by 3.9% and 0.1%, respectively. The corresponding accumulated fluence was approximately 2.2×10^{21} to 2.8×10^{21} n/cm². The representative fluence of Cluster 2 was therefore about 2.7 times that of Cluster 1, which is consistent with the longer irradiation history and the axial position of Cluster 2 closer to the core mid-plane.

Several spectral anomalies were identified during the analysis. A Co-60 signature in the Ti spectrum suggested contamination from the aluminum container or fabrication tools, and additional unidentified peaks were observed in the Nb spectrum. Although the principal activation peaks used for the comparison were clearly identified and yielded values close to the MCNP prediction, these spectral features introduce additional uncertainty. In addition, a direct comparison of the common Ni monitors produced a mass-normalized count ratio of approximately 18 between Rod 6 and Rod 3, much larger than expected from the irradiation history, further indicating that contamination or sample-related effects can strongly bias simple count-based comparisons.

3. Conclusions

The accumulated neutron fluence of the 22F-01U irradiation capsule was evaluated using activation wire monitors, HPGe gamma-ray spectrometry, and cycle-dependent ORIGEN2 calculations with MCNP6-derived effective cross sections. Aluminum-container monitors provided evaluated fluxes that were generally consistent with the MCNP predictions within approximately $\pm 15\%$, yielding fluence ranges of 9.5×10^{20} - 1.05×10^{21} n/cm² for Cluster 1 and 2.2×10^{21} - 2.8×10^{21} n/cm² for Cluster 2. The results also reproduced the expected higher exposure of Cluster 2. Quartz-container impurities and possible Co contamination were identified as important sources of uncertainty. Future irradiation tests should employ high-purity aluminum containers and common monitor materials, particularly Al-Co or Nb, in each rod to enable more direct and reliable inter-cluster comparison.

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