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

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Introduction

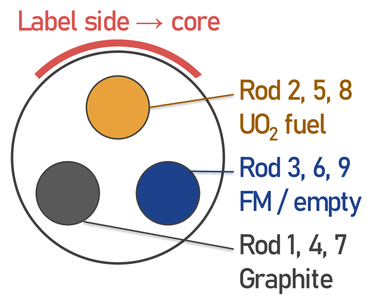
- A fuel and graphite irradiation test was conducted in the IP9 irradiation hole of HANARO using the non-instrumented capsule 22F-01U [1].
- The capsule was irradiated over multiple cycles and consisted of three clusters that were withdrawn at different stages. Thus, the neutron exposure of each cluster depends on its irradiation history and axial position. Fluence monitor (FM) wires were installed in Rod 3 (Cluster 1) and Rod 6 (Cluster 2).
- Objective: evaluate the fluence of the two clusters by HPGe γ-ray spectrometry and cycle-dependent ORIGEN2 [2] calculations with MCNP6 [3] effective cross sections, and compare the evaluated flux with the MCNP reference flux (E/C).

Table 1. Capsule configuration and irradiation period

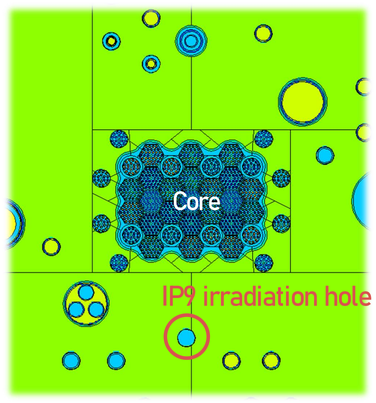
Cluster	Axial position	Graphite	UO_2 fuel	FM	Irradiated cycles
1	Top	Rod 1	Rod 2	Rod 3	108-1 – 111-3
2	Middle	Rod 4	Rod 5	Rod 6	108-1 – 116
3	Bottom	Rod 7	Rod 8	Rod 9 (empty)	108-1 – 115



22F-01U capsule (3 clusters)



Rod arrangement in a cluster



IP9 hole position (HANARO MCNP model)

Methods

Fluence Monitors & Irradiation History

- Rod 3 held Al-Co, Ni and Fe wires in both aluminum (Al-60 series) and quartz containers. Rod 6 held Nb, Ti and Ni wires in aluminum containers.

Table 2. FM wire masses (μg)

Rod / container	Al-Co (0.1% Co)	Ni (99.994%)	Fe (100%)	Ti (99.99%)	Nb (99.9%)
Rod 3 / Al	236	289	253	–	–
Rod 3 / quartz	197	297	222	–	–
Rod 6 / Al	–	455	–	478	379



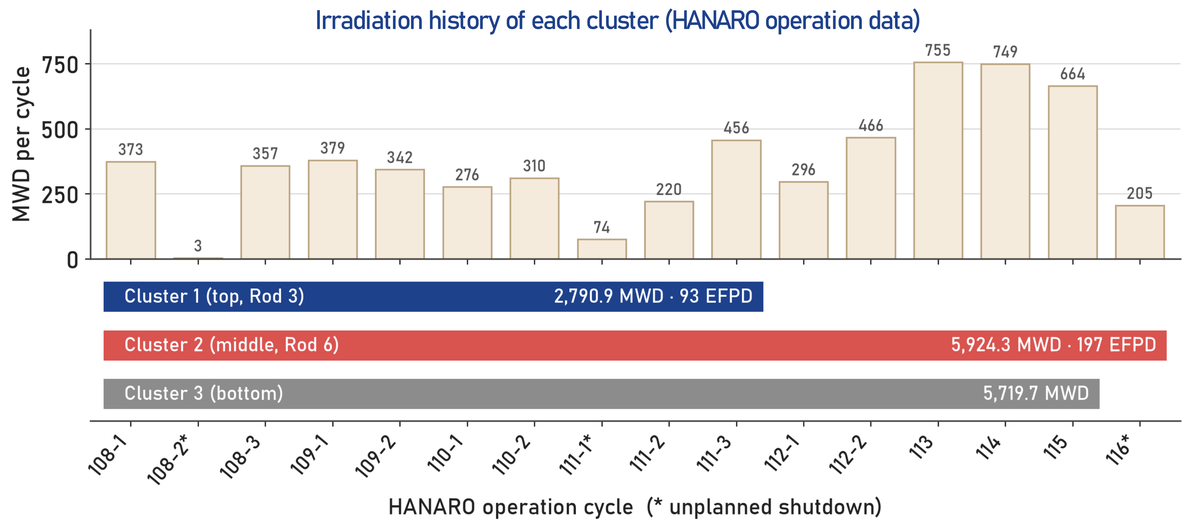
Rod 3 FM



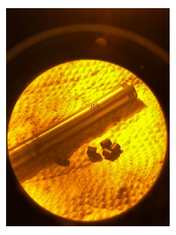
Rod 6 FM

- Cluster 1: cycles 108-1 to 111-3 (93 EFPD)
- Cluster 2: cycles 108-1 to 116 (197 EFPD)
- Cooling before counting: ~490 d (Rod 3) and ~270 d (Rod 6).

Irradiation history of each cluster (HANARO operation data)



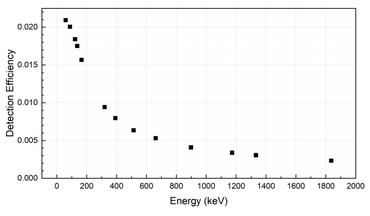
Gamma Measurement & Flux Evaluation



IMEF hot cell



HPGe #2 (PTS)



Efficiency (KRISS source)

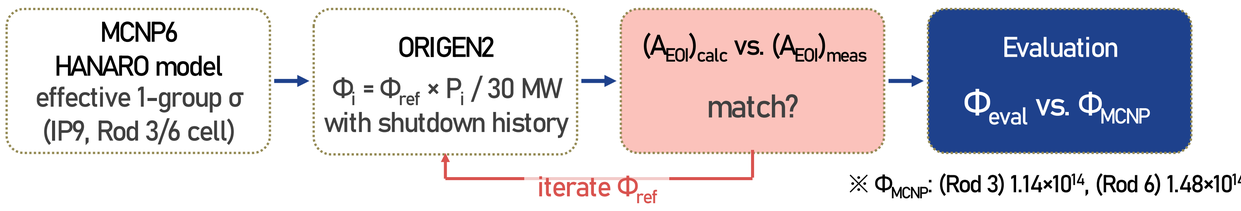
- Each wire was counted for 4 h with HPGe #2 of the PTS facility [4] at 15 cm (N3 position), and the A_{EOI} (activity at end of irradiation) was derived from the net peak area:

$$A_{EOI} = C\cdot\lambda\cdot\exp(\lambda t_c) \,/\, [\, \varepsilon\cdot I\cdot(1 - \exp(-\lambda t_m))\,]$$

C: net count, λ: decay constant, ε: photopeak efficiency, I: γ branching ratio, t_c: cooling time, t_m: live time

Table 3. Activation reactions and analysis peaks

FM	Reaction → product	Peaks (keV)
Al-Co	$^{59}Co(n,\gamma)^{60}Co$	1332
Ni	$^{58}Ni(n,p)^{58}Co$ / $^{60}Ni(n,p)^{60}Co$	811 / 1332
Fe	$^{54}Fe(n,p)^{54}Mn$ / $^{58}Fe(n,\gamma)^{59}Fe$	835 / 1099, 1292
	$^{58}Fe(n,\gamma)^{59}Fe(\beta^-)^{59}Co(n,\gamma)^{60}Co$	1332
Ti	$^{46}Ti(n,p)^{46}Sc$	889, 1121
Nb	$^{93}Nb(n,\gamma)^{94}Nb$	703, 871



※ Φ_{MCNP}: (Rod 3) 1.14×10^{14}, (Rod 6) 1.48×10^{14}

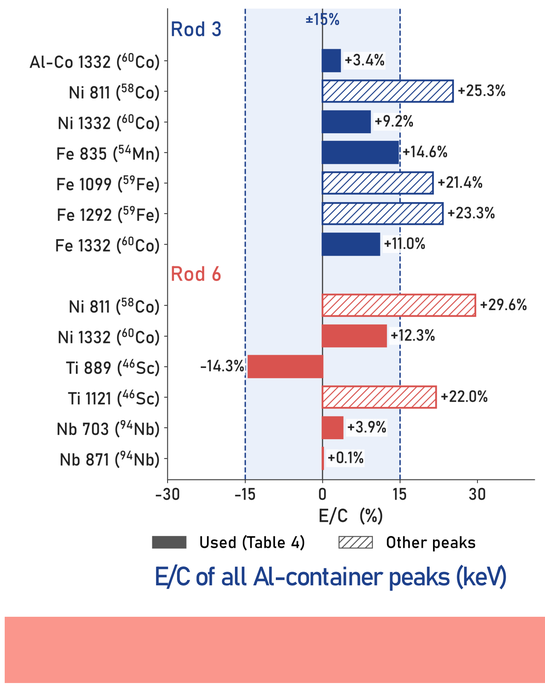
Results and Discussion

Evaluated Flux and Fluence

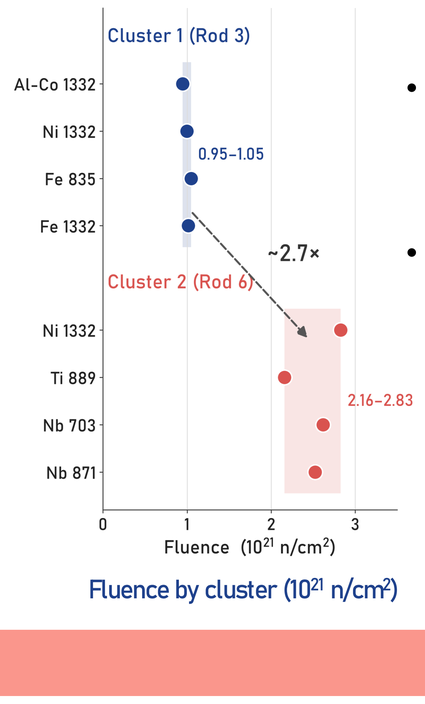
Table 4. Representative evaluation results (aluminum containers)

Rod	FM	Reaction	Peak (keV)	Φ_{eval} (n/cm²/s)	Fluence (n/cm²)	E/C
3	Al-Co	$^{59}Co(n,\gamma)^{60}Co$	1332	1.177×10^{14}	9.464×10^{20}	3.4%
	Ni	$^{60}Ni(n,p)^{60}Co$	1332	1.243×10^{14}	9.991×10^{20}	9.2%
	Fe	$^{54}Fe(n,p)^{54}Mn$	835	1.304×10^{14}	1.048×10^{21}	14.6%
	Fe	$^{58}Fe \rightarrow {}^{60}Co$	1332	1.264×10^{14}	1.016×10^{21}	11.0%
6	Ni	$^{60}Ni(n,p)^{60}Co$	1332	1.657×10^{14}	2.827×10^{21}	12.3%
	Ti	$^{46}Ti(n,p)^{46}Sc$	889	1.265×10^{14}	2.158×10^{21}	-14.3%
	Nb	$^{93}Nb(n,\gamma)^{94}Nb$	703	1.534×10^{14}	2.617×10^{21}	3.9%
	Nb	$^{93}Nb(n,\gamma)^{94}Nb$	871	1.478×10^{14}	2.522×10^{21}	0.1%

E/C = (Φ_{eval} – Φ_{MCNP}) / Φ_{MCNP}; fluence = Φ_{eval} × EFPD



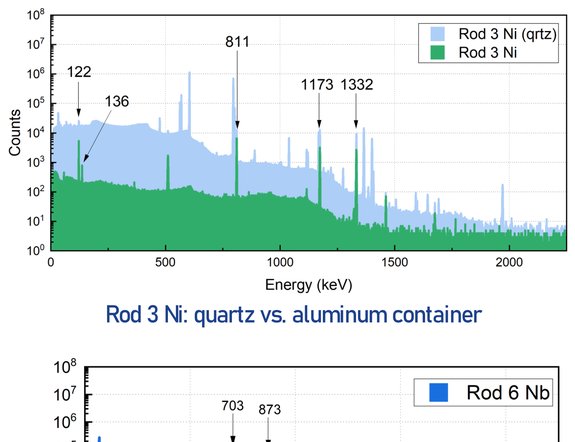
E/C of all Al-container peaks (keV)



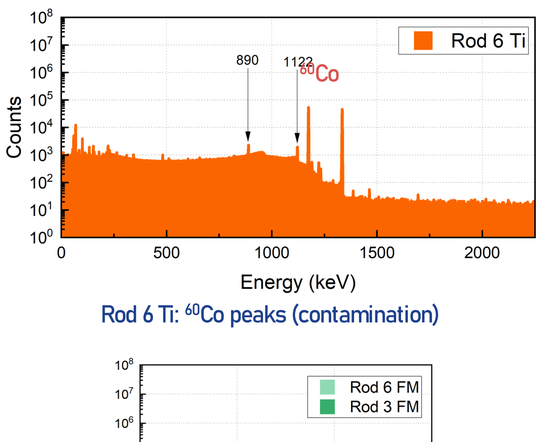
Fluence by cluster (10^{21} n/cm²)

- All representative results agree with MCNP within ~±15%.
- Cluster 2 received ~2.7 times the fluence of Cluster 1, consistent with its longer irradiation and its position closer to the core mid-plane.

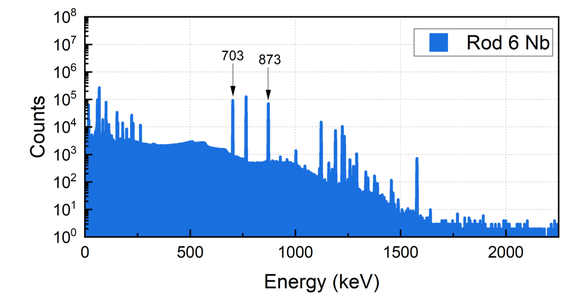
Spectral Anomalies and Uncertainty



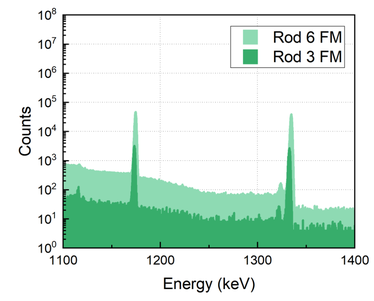
Rod 3 Ni: quartz vs. aluminum container



Rod 6 Ti: ^{60}Co peaks (contamination)



Rod 6 Nb: unidentified peaks



Ni (^{60}Co, 1332 keV): Rod 6 vs. Rod 3

- Quartz containers carried substantial impurities: E/C of -27.8% to +368.8% (Rod 3), so they were excluded.
- ^{60}Co peaks in the Ti spectrum suggest Co contamination from the container or cutting tools. Thus, 889 keV was used (1121 keV may overlap the 1332 keV Compton edge).
- Unidentified peaks (1000 – 1500 keV) appeared in the Nb spectrum, though the ^{94}Nb peaks were clear.
- Mass-normalized Ni count ratio Rod 6 / Rod 3 = ~18, far above that expected from irradiation history: simple count-based comparisons can be strongly biased.

Conclusions

- The fluence of the 22F-01U capsule was evaluated with activation wires, HPGe γ-ray spectrometry and cycle-dependent ORIGEN2 calculations with MCNP6-derived σeff.
- Al-container monitors agreed with MCNP within ~±15%: 9.5×10^{20} – 1.05×10^{21} n/cm² (Cluster 1) and 2.2×10^{21} – 2.8×10^{21} n/cm² (Cluster 2), reproducing the higher exposure of Cluster 2.
- Quartz-container impurities and possible Co contamination are key uncertainty sources.
- Future tests should use high-purity Al containers and common monitors (Al-Co or Nb) in every rod.

[1] S. W. Yang et al., KAERI/CR-785/2022 (2022).
[2] ORNL, ORIGEN2 V2.2, RSICC CCC-371 (2002).
[3] D. B. Pelowitz et al., MCNP6 User's Manual, LA-CP-13-00634 (2013).
[4] Y. S. Chung et al., KAERI/TR-3574/2008 (2008).