Analysis of fission products during long-term shutdown of research reactor

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1. Introduction

The research reactor HANARO has recently performed test operation, however it has been in long-term shutdown since the 96^{th} operation cycle in 2014. This long-term shutdown is the first time since the construction of HANARO. If the reactor is re-operated after a long-term shutdown, it is necessary to evaluate whether the criticality of the reactor is possible using the delayed neutrons in the core.

If the neutrons in the core is insufficient, the criticality of the reactor should be reached by loading an external neutron source into the core. In this study, the trends of the fission products during long-term shutdown was analyzed based on the RPS signals. The photonuclear reaction rate of H-2 reflector was calculated to evaluate the neutron source term in the core.

2. Methods

Neutron powers measured by Reactor Protection System (RPS) channels A, B and C are shown in figure 1. The x-axis is the time from 2014-07-01 to 2016-04-05 and, the y-axis denotes the percent full power (%FP). After the 96th operation cycle on 2014-07-01, the neutron power sharply decreased to about 4E-08 %FP on 2014-12-01. Considering the declining slope of the power, the half-life of the major contributing nuclides until December 2014 is estimated to be about 13 days. And after December 2014, it is estimated that nuclides with a half-life of about 10 months contribute to the neutron power.

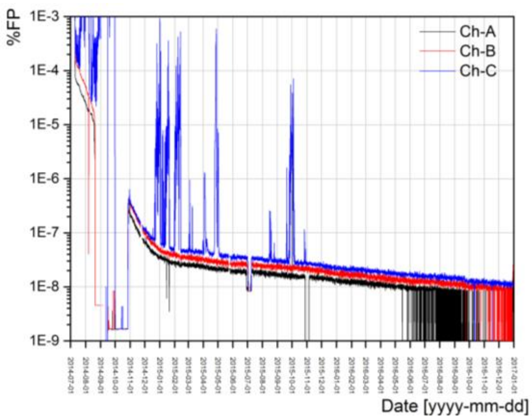

Fig. 1. Neutron power signals during the long-term shutdown of HANARO measured by RPS channel A, B and C

When the reactor is shut-down for a long time, the contribution to the output signal of RPS can be inferred to three sources in the core. 1) Neutrons generated by reaction of gamma rays with energy over 2.23 MeV emitted from fission products or activation products with heavy water 2) Neutrons generated by fission after gamma rays with an energy over 5 MeV emitted from fission products or activation products are absorbed by U-235, U-238 and etc. 3) Neutrons emitted from a nuclide with a long half-life among delayed neutron precursors. Among them, neutrons emitted by photonuclear reaction of deuterium with gamma rays of 2.23 MeV are dominant to the output signals of the RPS.

In order to identify radionuclides with a half-life of about 10 months after December 2014, fission products and activation daughters were calculated during the long-term shutdown of HANARO using the ORIGEN2.1 code. In the calculations, it is assumed that the nuclear fuel is 1 kg of fresh fuel, and the average burn-up is 60,000 MWD/MTU. The nuclear fuel is assumed to have been burned for 200 days.

3. Results

Table 1 shows the activity as a function of the decay time in descending order based on 50 days of decay of the top 15 nuclides. In the table, the half-life is calculated based on the activity of 550 and 600 days, and it is different from the actual half-life of each nuclide.

Table 1. Activity of the top 15 nuclides after 200 days of burnup.

Nuclide	0	50	100	500	550	600	Half-life [days]
Nb-95	7.19E3	6.43E3	4.58E3	7.91E1	4.61E1	2.69E1	64.17
Zr-95	8.08E3	4.70E3	2.74E3	3.59E1	2.09E1	1.22E1	64.01
Y-91	7.41E3	4.13E3	2.28E3	2.00E1	1.10E1	6.11E0	58.50
Sr-89	6.24E3	3.14E3	1.58E3	6.52E0	3.28E0	1.65E0	50.49
Ce-141	8.14E3	2.82E3	9.70E2	1.92E1	6.61E-2	2.28E-2	32.51
Pr-144	3.10E3	2.68E3	2.37E3	8.94E2	7.01E2	7.01E+02	284.35
Ce-144	3.03E3	2.68E3	2.37E3	8.94E2	7.00E2	7.00E2	284.02
Ru-103	4.59E3	1.90E3	7.87E2	6.77E1	1.16E-1	1.16E-1	39.28
Rh-103m	4.14E3	1.71E3	7.09E2	6.10E1	1.05E-1	1.05E-1	39.28
Pr-143	7.75E3	6.70E2	5.20E1	6.91E8	4.17E-10	4.17E-10	13.56
La-140	8.49E3	6.43E2	4.28E1	1.65E8	7.29E-11	7.29E-11	12.79
Ba-140	8.40E3	5.59E2	3.72E1	1.43E8	6.34E-11	6.34E-11	12.79
Pm-147	2.91E2	3.14E2	3.04E2	2.28E2	2.12E2	2.12E2	957.86
Ru-106	2.57E2	2.34E2	2.13E2	1.00E2	8.29E1	8.29E1	368.42
Rh-106	3.93E2	2.34E2	2.13E2	1.00E2	8.29E1	8.29E1	368.42

Candidate nuclides with a half-life of about 13 days or 10 months and emit gamma rays over 2 MeV are Ce-144 (parent) and Pr-144 (daughter). In addition, Rh-106

($T_{1/2}$=368.42 days), has high activity and emits high energy photons, and thus it may be a dominant nuclide to the RPS signals since 2015.

In order to calculate the photonuclear reaction rate, the emitted gamma rays of each nuclide and the photonuclear cross-section of H-2 are investigated. The photonuclear reaction rate at decay time, *i* was obtained by multiplying the activity and the gamma-ray emission rate and the cross-section as given by

$$R_i = A_i \times \sum_{j=1}^{n} I_j \sigma_j \tag{1}$$

where, j is the index of the gamma-ray, A_i is the activity of at decay time, I_i is the emission rate of j^{th} gamma-ray, and σ_j is the photonuclear cross-section corresponding the energy of j^{th} gamma-ray.

Figure 2 shows the calculated photonuclear reaction rate as a function of decay time in consideration of the gamma rays of the Rh-106, La-140 and Pr-144. Ratio of the photonuclear reaction rate on 700 days to the 10 days of decay time is 1.13E-04 when all three nuclides are considered.

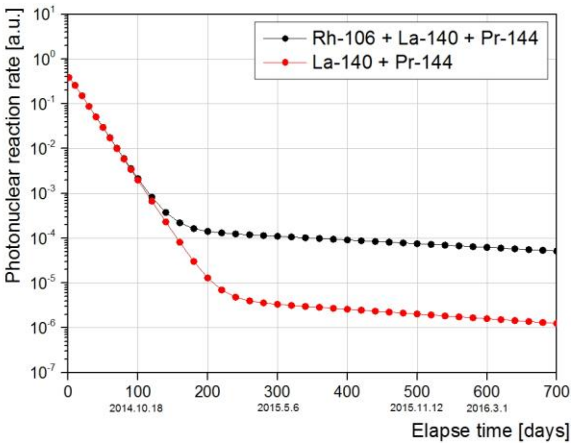

Fig. 2. Photonuclear reaction rate of H-2 by emitted gamma rays of Rh-106, La-140 and Pr-144

4. Conclusions

The neutron power in the core was reduced to 1E-4% FP and 1E-8% FP at 10 days and 600 days after shutdown, respectively. From the calculation results of the photonuclear reaction rate, it was confirmed that the trend of the photonuclear reaction rate by Rh-106, La-140 and Pr-144 was in good agreement with the trend of neutron power. However, when the decay time is longer than 600 days, the photonuclear reaction rate by the three nuclides is relatively higher than the neutron power. This is because other nuclides not considered in this study except La-140, Pr-144, and Rh-106 cause photonuclear reactions.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea government (MSIP) (NRF-2017M2A2A6A05018527)

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