Calculation of Gaseous Activation Products by Neutron Reactions in Horizontal Beam Tubes and Cold Neutron Guides of HANARO

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1. Introduction

HANARO, a 30 MW research reactor at KAEI, has been widely utilized in various fields such as industry, engineering, environment and medicine. Researches on these areas are possible through the capabilities provided by horizontal beam tubes, vertical irradiation holes and cold neutron guides of HANARO. Among the horizontal beam tubes, ST3 beam tube has been utilized with helium filled inside. And the cold neutron guides have been operated in vacuum. However, if air is entered into the facilities by planned or by accident, the air inside the facility is activated and radiations are emitted from the air. In this study, activity of Ar-41 is evaluated assuming that air is entered into the beam tube and the neutron guide.

2. Methods and Results

2.1 Generation of Ar-41 by neutron capture

Natural argon is composed of Ar-36, Ar-38, Ar-40, with Ar-40 being the most abundant (99.6% natural abundance). Ar-40 in the reactor interacts with neutrons and gets converted to Ar-41 by neutron capture reaction. Microscopic neutron capture cross-sections of Ar-40 are 0.66 b for 0.0253 eV neutrons and 1.02 mb for fission spectrum average [1]. Ar-41 decays with a half-life 109.34 min, and 99.16% and 0.052% of the decay emits 1.294 MeV and 1.677 MeV gamma rays, respectively.

Number density of Ar-40 is given by

$$N_{Ar\text{-}40} = \frac{\rho C N_A \theta_{Ar\text{-}40}}{A_{Ar\text{-}40}} \quad (1)$$

where, ρ is density of air, C is the concentration of argon, and N_A is the Avogadro's number. $\theta_{Ar\text{-}40}$ and $A_{Ar\text{-}40}$ are the natural abundance and the atomic mass of Ar-40, respectively. If the pressure of the air in the ST3 beam tube or the cold neutron guide is 1 atm, the number density of Ar-40 is 2.32E17 atoms/cm^3.

Saturated activity of Ar-41 which is generated by activation of the air is given by

$$R = N_0 \sigma_0 \phi_t \quad (2)$$

where, N_0 is number density of Ar-40, σ_0 is the (n,γ) cross-section of Ar-40 for thermal neutrons and ϕ_t is the total neutron flux. Eq. (2) is advantageous in terms of safety analysis for thermal neutron reactors such as HANARO. For irradiation time of 12 hours, activity of Ar-41 is reached 99% of the saturated activity in consideration of the half-life. Therefore, activity of Ar-41 can be evaluated by using the neutron flux in the beam tube or cold neutron guide.

2.2 Ar-41 Activity in ST3 Beam Tube

In order to evaluate the activity of Ar-41 in the ST3 beam tube, the MCNP6 code was used to calculate the neutron flux. The MCNP equilibrium model (burned core model for 96 operation cycle) was employed for a whole core representation of the HANARO. In the core model, position of the control rod was assumed to be 450 mm from the bottom of the core. Fig. 1 (a) shows the core of HANARO and position of the ST3 beam tube. Fig. 1 (b) shows the beam tube model that is located from the inner core to the concrete island. The beam tube model is divided into 3 regions of (1) Front end region, (2) Coarse collimator region and (3) Rotary shutter region.

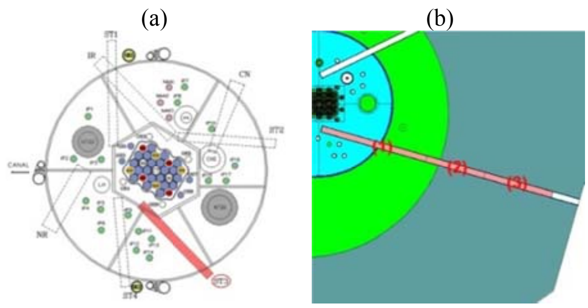

Fig. 1. Core of HANARO (a), ST3 beam tube model (b)

Neutron flux at each region of the beam tube was calculated by using the criticality mode of the MCNP code. Calculation results are listed in Table I. As shown in Table I, the neutron fluxes are classified into 5 groups according to the neutron energy. In the regions (1), (2) and (3), the neutron flux decreases as the distance from the core is increased. The saturated activities of Ar-41 in the regions (1), (2), (3) were estimated to be 1.208E7 Bq/cm^3, 3.701E4 Bq/cm^3, 7.874E3 Bq/cm^3, respectively.

2.3 Ar-41 Activities in Cold Neutron Guides

Fig 2 shows the cold neutron guides of HANARO. As shown in the figure, the cold neutron guide is branched to the 7 guides of CG1, CG2A, CG2B, CG3, CG4A, CG4B and CG5 at the front of the main shutter.

Table I: Neutron flux in each region of ST3 beam tube

Group	Neutron flux [n/cm^2/s]		
	(1)	(2)	(3)
E ≤ 0.625 eV	7.14E13	2.25E11	4.49E10
0.625 eV < E ≤ 4 eV	1.24E12	2.53E9	1.05E9
4 eV < E ≤ 9.12 keV	4.13E12	9.28E9	3.41E9
9.12 keV < E ≤ 0.82 MeV	1.55E12	3.00E9	8.86E8
0.82 MeV < E ≤ 10 MeV	5.29E11	1.84E9	1.22E9
Total	7.89E13	2.42E11	5.14E10

If there is a problem with the vacuum pump in the shield structure of the cold neuron guides or if the guide tube is broken, air can be flowed into the guide from the main shutter to the second shutter. In the case of the cold neutron guide, it is not easy to evaluate the neutron flux using the core model because the cold neutron guides are far from the core and the length of the guide is long (about 25 m). Furthermore, since the temperature of neutrons is low, the assumption of Eq. (1) that all neutrons are thermal neutron cannot be used for the cold neutrons.

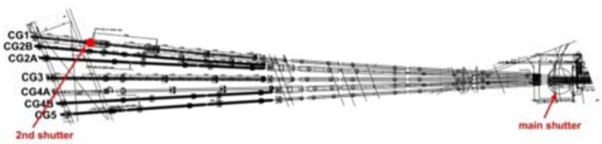

Fig. 2. Cold neutron guides of HANARO

In this case, the neutron fluxes and the reaction rate of Ar-40(n,γ)Ar-41 in each neutron guide were calculated by using the neutron fluxes and neutron wavelength distributions measured at the position of the main shutter [2]. The energy spectrum of the cold neutrons in each guide is determined using the Maxwellian distribution function based on the neutron temperature. The transport of neutrons and nuclear reaction s of neutrons and Ar-40 in the neutron guides were simulated using the PHITS (Particle and Heavy Ion Transport Code System) code [3]. In the simulation, the guide tube material was assumed to be nickel, and the reflectivity of the supermirror was 0.99, and the critical scattering vector was 0.0217 Å.

Spatial distribution of the neutron flux and energy differential flux in each region of the CG1 neutron guide are shown in Fig. 3 and Fig. 4, respectively. In Fig. 3, the neutrons move along the guide from region 100 to region 105. All guides were divided into five regions (101 ~ 105) of uniform length. The neutron flux decreases by collision with the air inside the guide. As shown in Fig. 4, the energy spectrum of neutrons tends to be flattened along the guide. The saturated activities of the Ar-41 in each guide are listed in Table II.

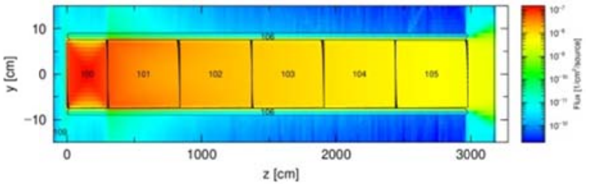

Fig. 3. Spatial distribution of neutron flux in CG1 neutron guide

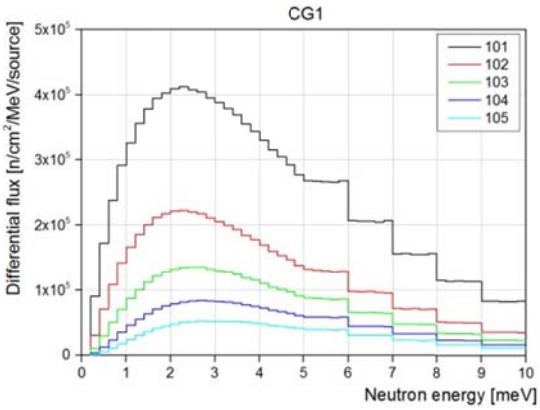

Fig. 4. Energy differential neutron flux in each region of CG1 neutron guide

Table II: Saturated activities of Ar-41 in cold neutron guides

Name	Saturated activity of Ar-41 [Bq/cm^3]				
	101	102	103	104	105
CG1	4.81E3	2.42E3	1.44E3	8.83E2	5.66E2
CG2A	5.78E3	3.58E3	2.50E3	1.70E3	1.15E3
CG2B	6.07E3	3.53E3	2.22E3	1.44E3	9.74E2
CG3	6.10E3	2.81E3	1.81E3	1.21E3	8.57E2
CG4A	6.48E3	3.99E3	2.47E3	1.62E3	1.06E3
CG4B	6.66E3	3.93E3	2.46E3	1.57E3	1.05E3
CG5	6.63E3	3.21E3	2.00E3	1.30E3	8.40E2

3. Conclusions

During reactor operation, if air enters into the beam tube, or vacuum in the cold neutron guide breaks, the radiation dose near the facilities may increase by Ar-41. In this study, we focused on assessing the activity concentration of gamma emitter Ar-41. The activity concentration distributions of Ar-41 in the ST3 beam tube and in the cold neutron guides were determined. Average activities of Ar-41 in the ST3 beam tube was 5.26E6 Bq/cm^3, and in the cold neuron guides were 2.0E3 ~ 3.1E3 Bq/cm^3. The obtained results of this study is significant for determining the dose at working areas and can be utilized as data for designing the radiation shield.

REFERENCES

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