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Computational Analysis of Ex-core Neutron Facility Beam in HANARO for TEPC Dosimetry

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1. Introduction

Microdosimetry is a powerful method to evaluate the relative biological effectiveness (RBE) of radiation on the human body. The importance of microdosimetry in a mixed-radiation environment is a significant factor in various fields including radiation treatment, healthcare, aerospace, environmental safety, and many more. The Tissue Equivalent Proportional Counter (TEPC) is considered as gold-standard for measuring microdosimetric parameters[1]. Korea Astronomy and Space Science Institute (KASI) has been developing its own TEPC model for mixed-field dosimetry for aerospace missions.

To establish the microdosimetric evaluation method in a neutron/gamma-ray mixed field environment with TEPC developed in KASI, Ex-core Neutron Facility (ENF) in HANARO was selected as a development and validation environment, as the facility was originally developed for boron neutron capture therapy and has sufficient thermal neutron flux[2] ($\sim 1.5\times 10^9 n\ cm^{-2}\ s^{-1}$)

2. Methods and Results

2.1 Simulation Settings

The characteristic analysis of the neutron beam as well as the photon contamination were made for detector calibration and validation. In this study, the ENF beam specification was conducted by MCNP6 code. As the probability of a neutron generated in the reactor core reaching the beam exit port is around one in a billion, the simulation was divided into 3 steps to reduce the computational time. The first plane for tallying the phase-space file was placed in the reflector region, the second in front of the neutron beam filter, and the last on the beam exit port. Every phase-space plane is perpendicular to the beam axis. For each step of the simulation, 2.5×10^8 histories were generated. The energy distribution, spatial distribution, directionality, and fluence rate were analyzed in every step assuming a 30 MW operating condition.

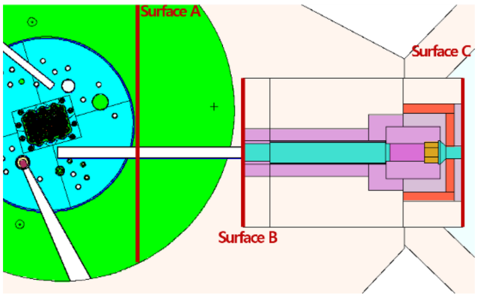

Fig. 1. MCNP model of HANARO Ex-core Neutron Facility

2.2 Crystal Filter Thermal Neutron Cross-section Calculation

HANARO ENF utilizes silicon and bismuth monocrystalline and polycrystalline materials as thermal neutron and gamma-ray filter, respectively, due to their miniscule thermal neutron cross-section[3]. Since the cross-sections of these crystals differ from those in the amorphous state, the thermal neutron cross-sections for neutron filter crystals were calculated using NJOY21 with NCrystal toolkit[4]. The base cross-section for NJOY calculation was obtained from the ENDF VIII library. The resulting thermal cross-sections are shown in Fig. 2. The black solid lines represent the polycrystalline cross-sections, while the blue dotted lines represent the monocrystalline cross-sections. The constructed data were validated by comparing them with the KENDF data[3] and subsequently implemented in MCNP for ENF simulation.

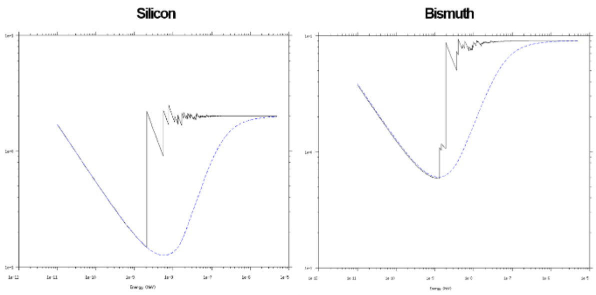

Fig. 2. Thermal neutron cross-section for silicon and bismuth crystals.

2.3 D-60 TEPC Specification

D-60 TEPC is a Benjamin-type TEPC that was designed and developed by the KASI[5]. It consists of a spherical sensitive volume with a diameter of 60 mm, surrounded by a 3 mm-thick A150 tissue equivalent plastic. (Fig. 3.) A 30μm diameter anode wire made of stainless steel was mounted along the central axis. The whole detector was sealed within an aluminum case with a thickness of 1.5 mm to create an air tight seal and protect the TEPC.

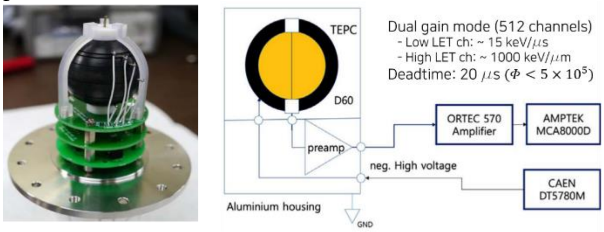

Fig. 3. D-60 Tissue Equivalent Proportional Counter (TEPC)[5].

2.4 Results

The emittance and directionality of the ENF neutron beam was analyzed using the acquired phase-space file in plane (or surface) C. Computational analysis confirmed that the beam is predominantly highly collimated and parallel, with a slight tendency for fine divergence in the horizontal direction. (Fig.4.)

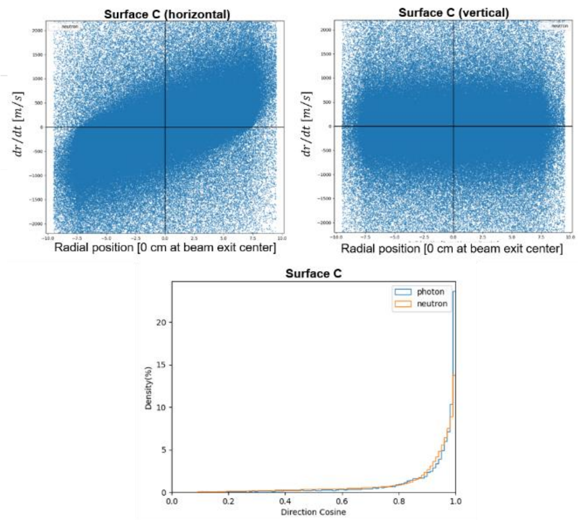

Fig. 4. Beam emittance and direction cosine of ENF neutron beam

The ENF neutron energy spectrum was calculated from three different cross-section values for three different states of the filter: the base amorphous state, the polycrystalline state, and the combination of mono and polycrystalline state. In the thermal neutron range, the mono and polycrystalline combined filter transmitted approximately 1.5 times more neutrons compared to the polycrystalline state filter and 16 times more compared to the amorphous state filter.

Finally, the response of D-60 TEPC for ENF beam was simulated as microdosimetric spectrum at the lineal energy range from 0.001 keV μm^{-1} to 1 MeV μm^{-1} and shown in Fig.5 for later validation of actual beam measurement.

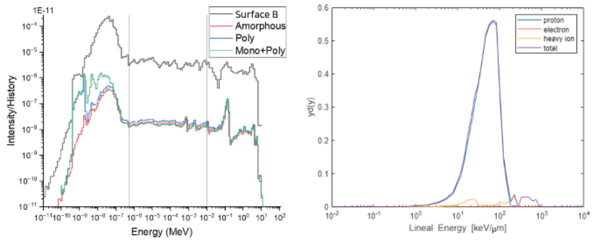

Fig. 5. Neutron spectrum from ENF beam port and D60 response spectrum

3. Conclusions

The simulation of HANARO ENF was divided into three steps due to low neutron yield. Beam characterization, including spatial distribution, directionality, and energy distribution, was conducted using MCNP6.2 code. The thermal neutron cross-section for silicon and bismuth crystals (both mono and poly) were generated using NJOY21+NCrystal with ENDF VIII library. The response spectrum simulation was carried out to for future TEPC measurement.

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