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Characterization of the Neutron Spectrum at NAA Irradiation Positions in the HANARO Reactor from Low Power to Full Power

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1. Introduction

Neutron spectrum characterization is a fundamental aspect of research reactor operations, particularly for applications such as neutron activation analysis (NAA), isotope production, and material testing. The HANARO reactor, a 30 MW high-performance research reactor, provides a well-thermalized neutron spectrum, making it an ideal facility for precise analytical applications. Accurate determination of neutron spectrum parameters, including integrated, thermal, epithermal, and fast neutron flux at NAA irradiation positions, is crucial for ensuring the reliability and reproducibility of experimental results.

The NAA group of the HANARO utilization division has established a methodology for the characterization of about 40 elements in various matrix samples, including those from archaeology, biology, environmental, and high-purity industrial materials, as well as candidate reference materials developed by KRISS. However, certain elements cannot be quantified or exhibit low precision due to matrix effects, high sensitivity to thermal neutrons, and the impracticality of Cd-wrapped experiments at maximum power (30 MW). Utilizing neutron flux at lower reactor power levels can expand elemental characterization, particularly for short-lived radionuclides (e.g., ^{20}F, ^{28}Al, ^{38}Cl), high thermal cross-section nuclides (e.g., ^{54}Mn), and complex matrix samples. Additionally, epithermal NAA methods can be employed to improve detection limits and reduce uncertainties. While computational approaches provide valuable insights, experimental validation remains crucial for capturing real-time flux variations across different reactor power levels.

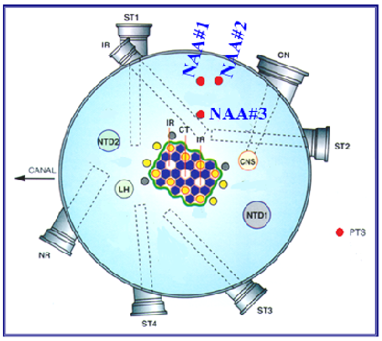

Fig.1 NAA irradiation position at HANARO core

Earlier studies have focused on neutron flux characterization at select irradiation sites (NAA#1 and NAA#3) (Fig.1) under steady-state conditions at 30 MW[1]. However, limited research has explored flux characterization at varying power levels. Given that neutron flux is directly influenced by reactor power, fuel composition, and moderator efficiency, a comprehensive experimental study is necessary to understand flux stability, spectral shifts, and potential anomalies during power ramp-up or at different power levels.

The k_0-based NAA method, developed by F. De Corte et al. [2], is used for absolute elemental characrization using neutron spectrum paramters. The k_0-INAA method considers several key input parameters: (1) thermal and epithermal neutron fluxes, (2) the deviation from the ideal 1/E epithermal neutron flux distribution (α), and (3) the thermal-to-epithermal neutron flux ratio (f) [3]. These input parameters can be evaluated through activation experiments and computer simulations. However, activation foil experiments must account for corrections related to all neutron effects to minimize systematic errors.

This study aims to bridge this gap by experimentally determining the absolute neutron flux at NAA irradiation positions (NAA#1, NAA#2, and NAA#3) in the HANARO reactor across a power range from 1 MW to 30 MW. Different flux monitors were used to measure flux values, providing key insights into neutron field uniformity and its dependence on reactor power levels. The findings will contribute to improved calibration of irradiation conditions, enhanced accuracy in NAA experiments, and optimized reactor utilization strategies.

2. Experimnetal Details

The multi-flux monitors, Zr (^{94}Zr, ^{96}Zr) and IRMM Al-Au 0.1% foils (^{197}Au), were used in this study to characterize the neutron spectrum at three different NAA irradiation positions in the HANARO reactor core (Fig.1). The masses of the 0.1 mm thick disc-shaped flux monitors were 9 mg for the Al-Au foil and 10 mg to 50 mg for the Zr foil. Two sets of monitors were prepared: bare and Cd-covered with 0.84 mm-thick cadmium. Additionally, temperature markers (50, 70, 90, and 110 ºC) were inserted in the rabbits to monitor the temperature of the foils during irradiation. The samples were irradiated at different reactor power levels at 1, 10, 15, 20, 27, and 30 MW, for 3 to 30 minutes. To minimize flux variations, bare and Cd-covered rabbits were irradiated simultaneously. After an appropriate cooling period, the activities of radionuclides formed were measured using an n-type HPGe detector with 45% relative efficiency, and γ-ray spectra of the Zr foils are shown in Fig.2. The relevant nuclear data were obtained from the NNDC database. Neutron flux was calculated using the Al-Au foil, while the thermal-to-epithermal neutron flux ratio (*f*) and the epithermal spectrum shape factor (α) were determined using the bare and Cd-covered multi-monitor method [4].

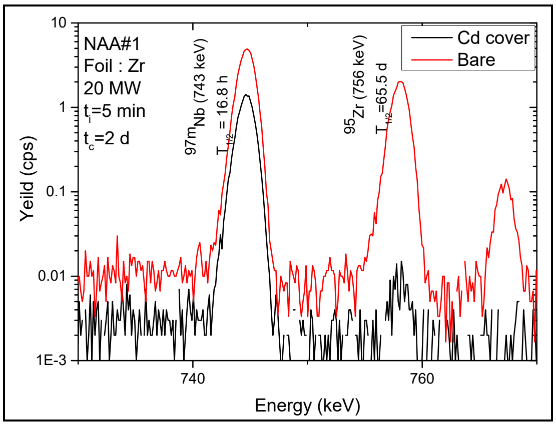

Fig. 2 Gamma-ray spectrum of Zr foil with and without Cd cover

3. Results and Discussion

Neutron flux, including thermal and epithermal flux, as well as spectrum parameters (*f* and α), was measured at different reactor power levels at NAA#1, NAA#2, and NAA#3. In the bare rabbits, the foil temperature remained below 50 ºC. However, in the Cd-covered rabbits, the temperature increased from 50 ºC to over 110 ºC. As shown in Fig.3, neutron flux at NAA#1 increases proportionally with reactor power. The limitations on irradiation time will be presented during the presentation.

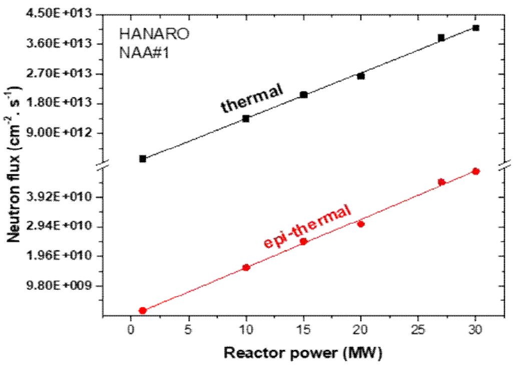

Fig.3 Neutron flux variation with reactor power at NAA#1

The Cd-covered multi-monitor method provides a more accurate determination of the thermal-to-epithermal neutron flux ratio compared to the bare method, as more than 98% of thermal neutrons are absorbed by the Cd cover. The Cd-covered method was applied at reactor power levels ranging from 1 MW to 27 MW. However, at 30 MW, the use of Cd was not permitted due to excessive heat generation. As shown in Fig.4, the f values remain consistent across the reactor's power range, demonstrating a linear trend from low to high power levels. This indicates that the thermal-to-epithermal flux ratio remains unchanged, confirming the stability of the neutron spectrum.

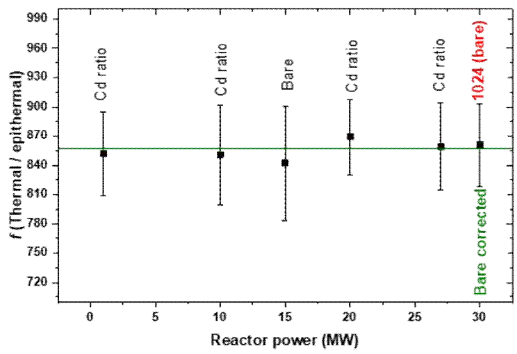

Fig.4 The *f* value changes with reactor power at NAA#1

4. Conclusions

In this study, neutron spectrum parameters and absolute neutron flux were experimentally determined at different reactor power levels using the Au and Zr multi-monitors. The results confirmed that the thermal-to-epithermal neutron flux ratio (*f*) remained stable across all power levels, indicating a consistent neutron spectrum. The Cd-covered multi-monitor method provided more accurate *f* values by effectively absorbing thermal neutrons. The fiindings showed good agreement with previous studies carried out in 2003 [1].

These findings are crucial for improving neutron activation analysis (NAA), isotope production, and elemental characterization using the k_0-based INAA method. The experimentally determined neutron flux values were further validated by applying them to the quantification of elements in certified reference materials, demonstrating their accuracy and reliability. This study enhances the precision of irradiation conditions, ultimately contributing to better analytical outcomes and more efficient reactor utilization.

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