

MCNP Simulation Analysis of the Lunar Environment Under Varying H₂O Conditions

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1. Introduction

Galactic Cosmic Rays (GCRs), mainly consisting of high-energy protons and alpha particles, interact with the lunar surface and produce secondary neutrons. These neutrons are moderated through interactions with the lunar regolith, and their energy distributions are strongly affected by hydrogen-bearing materials such as H₂O. Therefore, variations in water content can change the relative populations of thermal and epithermal neutrons, allowing neutron measurements to be used as an indicator of hydrogen abundance on the Moon.

The Lunar Vehicle Radiation Dosimeter (LVRAD) is a science payload proposed to the Commercial Lunar Payload Services (CLPS) program by the Korea Astronomy and Space Science Institute (KASI) and Seoul National University (SNU) [1,2]. Among the detectors in LVRAD, the NS-E detector is designed to investigate evidence of water and the composition of the lunar regolith using neutron measurements. In this study, the neutron response of the lunar environment under varying H₂O concentrations was investigated using the MCNP transport code. The resulting neutron energy spectra and epithermal-to-thermal neutron ratios were analyzed to evaluate their dependence on lunar water content.

2. Methods and Results

2.1 NS-E Detector and Neutron Measurement

The LVRAD instrument consists of four detector systems: APDS, TED, NS-F, and NS-E. NS-F is designed to evaluate the biological effects of neutrons generated from the lunar surface, whereas NS-E is used to investigate evidence of water and the composition of the lunar regolith. In this study, the neutron response of the NS-E detector was investigated.

The NS-E detector contains a ⁶Li-based detection material. Neutrons interacting with ⁶Li produce charged particles through the ⁶Li(n,α) reaction, resulting in a characteristic reaction peak near 4.8 MeV. The counts corresponding to this peak were used to evaluate the neutron response.

To distinguish between thermal and epithermal neutron components, measurements were performed with and without a Cd cover on the NS-E detector. The detector without Cd measures contributions from both thermal and epithermal neutrons, whereas the Cd-covered detector primarily measures the epithermal neutron component because Cd strongly absorbs thermal neutrons. The thermal neutron contribution was therefore estimated from the difference between the two measurements.

2.2 Experimental Verification Using Polyethylene

An experimental measurement was performed to evaluate the neutron moderation response of the NS-E detector. A ²⁵²Cf source was used as the neutron source, and the distance between the source and the ⁶Li detector was fixed at 117 mm. Polyethylene (PE, C₂H₄) was placed between the source and detector as a hydrogen-rich moderator to reproduce the effect of increasing hydrogen content.

The PE thickness was varied to 15, 35, 50, and 78 mm. For each thickness, neutron spectra were measured using both the uncovered and Cd-covered NS-E detectors. The count values at the approximately 4.8 MeV reaction peak were obtained, and the thermal and epithermal neutron responses were determined from these measurements.

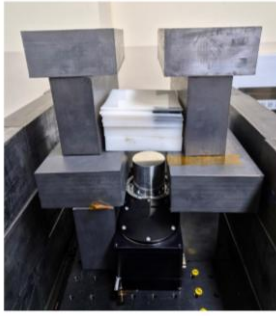


Fig. 1. Experimental configuration of the ^{252}Cf source, PE moderator, and NS-E detector.

The measured neutron responses were compared with the corresponding simulation results. As the PE thickness increased, changes in the thermal and epithermal neutron components were observed due to neutron moderation by hydrogen.

As summarized in Table I, the experimental and simulated responses differ in their absolute values, whereas they exhibit a comparable overall decrease in the epithermal neutron fraction with increasing PE thickness. In the experiment, the moderator was assembled by stacking individual PE layers, which can introduce small air gaps between adjacent layers. In contrast, the MCNP model assumed a continuous, gap-free PE moderator with an idealized geometry and material density. These differences can alter the effective moderation path and, consequently, the thermal and epithermal neutron responses. Nevertheless, the comparable overall trend indicates that the simulation reasonably reproduces the neutron moderation behavior observed in the experiment.

• Simulation				
CLYC-6	PE 15 mm	PE 35 mm	PE 50 mm	PE 78 mm
Without Cd (Th+Epi)	62900	410000	665000	849000
With Cd (Epi)	33800	114000	131000	104000
Ratio (Epi/Th+Epi)	0.5374	0.2780	0.1970	0.1225
• Experiment				
CLYC-6	PE 15 mm	PE 35 mm	PE 50 mm	PE 78 mm
Without Cd (Th+Epi)	2835	10649	15181	20533
With Cd (Epi)	1667	3565	4114	4155
Ratio (Epi/Th+Epi)	0.588007	0.334773	0.270997	0.202357

Table I: Comparison of experimental and simulated neutron responses for different PE thicknesses.

2.3 MCNP Simulation of the Lunar Environment

An MCNP model was constructed to investigate changes in the neutron response of the lunar surface according to H_2O concentration. FAN soil was used as the lunar regolith material, and an NS-E detector and a Cd-covered NS-E detector were positioned above the soil surface. GCR protons and alpha particles were incident on the lunar surface to generate secondary neutrons through interactions with nuclei in the regolith.

The H_2O concentration in the FAN soil was varied among 0, 0.5, 1, and 2 wt%. For each H_2O concentration, the neutron energy spectrum and the thermal and epithermal neutron responses were calculated. The epithermal-to-thermal neutron ratio was

then obtained to evaluate its dependence on the amount of H_2O in the lunar regolith.

The calculated neutron energy spectra showed a systematic variation with increasing H_2O concentration. As the amount of H_2O increased, neutron moderation became more significant because of interactions with hydrogen. Consequently, the epithermal neutron population gradually decreased as neutrons lost energy and shifted toward the thermal energy region.

The thermal neutron response showed a different behavior. With increasing H_2O concentration, the thermal neutron population initially increased because more high-energy neutrons were moderated into the thermal energy range. However, as neutron moderation increased further, thermal neutrons had a greater probability of being absorbed by nuclei in the lunar regolith, resulting in a reduction of the escaping thermal neutron population.[3]

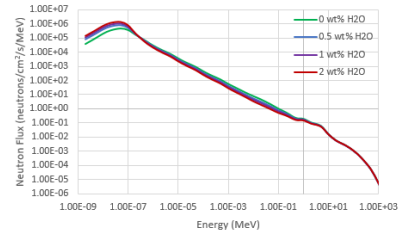


Fig. 2. Neutron energy spectra for FAN soil with different H_2O concentrations.

The epithermal-to-thermal neutron ratio also changed with increasing H_2O concentration. The calculated trend was similar to the dependence of neutron response on hydrogen abundance reported by Feldman et al. [3]. However, the magnitude and variation of the ratio may depend on the elemental composition of the lunar soil because neutron moderation and absorption are affected by the constituent materials.[4]

H_2O	0 wt%	0.5 wt%	1 wt%	2 wt%
F_{total}	1.91E+06	1.83E+06	2.05E+06	2.14E+06
F_{epi}	8.76E+05	7.88E+05	6.60E+05	5.13E+05
F_{therm}	1.04E+06	1.04E+06	1.39E+06	1.62E+06
$F_{\text{epi}}/F_{\text{therm}}$	0.846	0.759	0.475	0.316

Fig. 3. Epithermal-to-thermal neutron ratio as a function of H_2O concentration.

3. Conclusions

The neutron response of the lunar environment under varying H_2O concentrations was investigated using MCNP simulations. The results showed that increasing H_2O content affects both thermal and epithermal neutron populations through neutron moderation and absorption processes. The calculated epithermal-to-

thermal neutron ratio also changed systematically with H₂O concentration and showed a trend similar to previous lunar neutron studies. These results indicate that the NS-E detector can be used to evaluate variations in hydrogen and water content in the lunar regolith.

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