Simulation of a Tissue Equivalent Proportional Counter for a Low Earth Orbit Radiation Environment

Sukwon Youn [a], Uk-won Nam [b], Jeonghyun Pyo[b] Won-Kee Park [b], Jongdae Sohn [b], Bongkon Moon [b], Won-Ho Cha [c], Joung-Ki Seo [c], Hong-Young Park [c], Tae-Seong Jang [c], and Sung-Joon Ye [a,d*]
[a]*Department of Applied Bioengineering, Graduate School of Convergence Science and Technology, Seoul National University, Seoul 08826, Republic of Korea*
[b]*Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea*
[c]*Satellite Technology Research Center, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*
[d]*Advanced Institutes of Convergence Technology, Seoul National University, Suwon 16229, Republic of Korea*
[*]*Corresponding author: sye@snu.ac.kr*

1. Introduction

A low Earth orbit (LEO) is an orbit close to Earth's surface where various kinds of satellites exist, and also the International Space Station (ISS) is located to perform human-crewed space missions. Therefore, it is necessary to analyze the radiation environment in LEO and evaluate their effects on humans. Seoul National University (SNU) and Korea Astronomy and Space Science Institute (KASI) are working together to develop and optimize a Tissue Equivalent Proportional Counter (TEPC) to detect radiation environment in LEO and evaluate its biological effect on humans [1]. TEPC can evaluate the biological effects of radiations by obtaining the radiation dose by measuring linear energy transfer (LET) spectra of radiations [2]. The developed TEPC will be loaded on the Korea Next Generation Small Satellite 2 (NEXTSat-2) as a part of the LEO-DOS (Low Earth Orbit Radiation Dosimeter) science payload to measure the radiation environment in LEO for two years. In this study, Monte Carlo simulations using MCNP particle transport code were performed to evaluate the performance of the LEO-DOS TEPC and predict the radiation environment in LEO. Three major components in LEO: galactic cosmic rays (GCR), solar particle events (SPE), and trapped particles from radiation belts [3] were simulated to calculate the dose rate and dose equivalent rate of charged particles in the TEPC.

2. Methods and Results

2.1 Radiation Environment in Low Earth Orbit (LEO)

The Radiation environment in LEO mainly consists of three components: galactic cosmic rays (GCR), solar particle events (SPE), and trapped particles from radiation belts [3]. To simulate the radiation environment, space radiation models for GCR, SPE, and trapped particles from Space ENVironment Information System (SPENVIS) (https://www.spenvis.oma.be/) developed by European Space Agency (ESA) were used in this study. Because the TEPC will be loaded on the NEXTSat-2, which will be operated in 550 km LEO for two years in solar maximum, radiation models for a circular orbit of 550 km altitude in solar maximum were used considering the shielding effect of the Earth's magnetic field.

GCR originated outside the solar system consist of charged particles from protons to uranium with broad energy ranges from MeVs to GeVs. Protons consist of about 87% of total GCR flux, helium ions consist of about 12% of total GCR flux, and other heavy ions consist of less than 1% of total GCR flux. However, heavy ions with a high Z number contribute a lot to the total GCR dose to humans because of their high LETs [4]. For the GCR model, the ISO-15390 model developed by Lomonosov Moscow State University (MSU) and the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) was used [5]. Refer to the GCR spectra of the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) which measures energetic charged particles, proton (H), helium (He), carbon (C), oxygen (O), neon (Ne), magnesium (Mg), silicon (Si), and iron (Fe) ions which transfer a lot of LETs were used in the simulation of GCR [6].

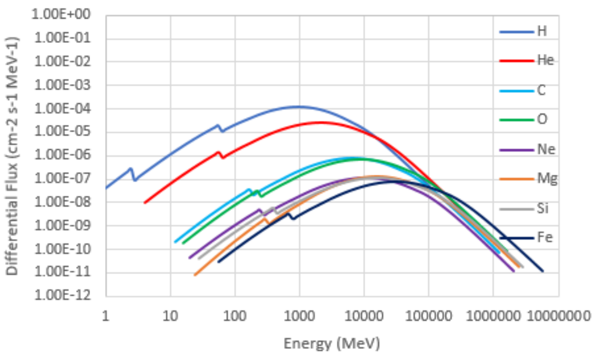

Fig. 1. Differential fluxes of GCR protons (H), helium (He), carbon (C), oxygen (O), neon (Ne), magnesium (Mg), silicon (Si), and iron (Fe) ions (ISO-15390 model).

SPE mainly consist of protons with relatively lower energies than GCR, which most protons have energies below hundreds of MeVs. Their flux highly increases in the active periods of the solar cycle, which may have a lot of damage to humans and electronic devices [3]. Because the NEXTSat-2 will be operated in the solar maximum period, the ESP (Emission of Solar Protons) model developed by the National Aeronautics and Space Administration (NASA) was used as the SPE model to predict the effect of solar activity in the solar maximum [7].

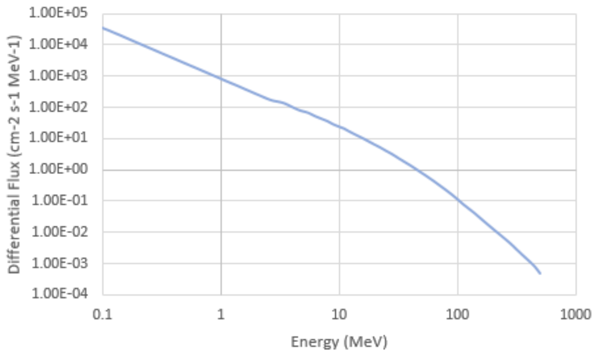

Fig. 2. Differential flux of SPE protons (ESP model).

When the NEXTSat-2 passes the South Atlantic Anomaly (SAA) region, it can be affected by trapped particles moving along the Earth's magnetic field. Trapped particles mainly consist of protons with energies up to about 700 MeV and electrons with energies up to 10 MeV [8]. For trapped proton model, AP-8 model of developed by NASA was used [9].

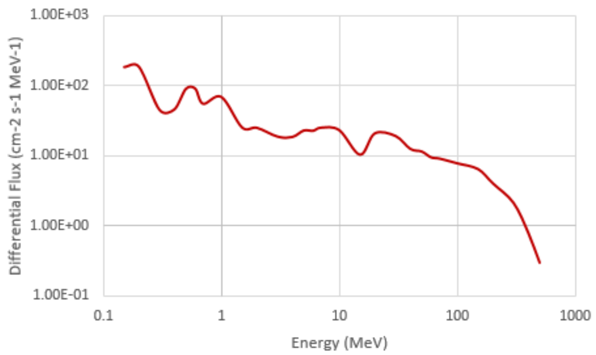

Fig. 3. Differential flux of trapped protons in South Atlantic Anomaly (SAA) region (AP-8 model).

2.2 Tissue Equivalent Proportional Counter (TEPC)

Responses of a Tissue Equivalent Proportional Counter (TEPC) to the LEO radiation environment were simulated to evaluate the performance of the TEPC and predict the radiation environment in LEO using a Monte Carlo N-Particle transport code version 6.2 (MCNP6.2) [10]. The LEO-DOS (Low Earth Orbit Radiation Dosimeter) science payload, which includes TEPC, was modeled for Monte Carlo simulations. 34 mm diameter spherical TEPC filled with propane gas (C_3H_8) to simulate 2 μm human tissue, a neutron spectrometer, a plastic detector for anti-coincidence shielding to separate the charged particle and neutron response, and an aluminum electronic box was modeled. Energy distributions inside the TEPC for GCR, SPE, and trapped charged particles were obtained from simulations to obtain LET spectra and dose rates of the LEO radiation environment.

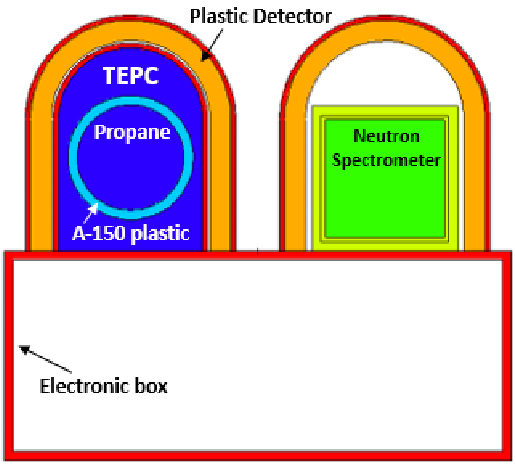

Fig. 4. MCNP simulation geometry of Tissue Equivalent Proportional Counter (TEPC) included in the LEO-DOS science payload.

2.3 TEPC LET Spectra for LEO Radiation Environment

LET (linear energy transfer) spectra of TEPC for GCR, SPE, and trapped particles in LEO were obtained from energy distributions of TEPC obtained by Monte Carlo simulations. The deposited energy (ε) of TEPC was converted to LET (y) by dividing it into the mean chord length (l). LET spectra ($yd(y)$) for GCR proton (H), helium (He), carbon (C), oxygen (O), neon (Ne), magnesium (Mg), silicon, (Si), and iron (Fe) were acquired as shown in Fig. 5. It was shown that the particles with a higher Z number show a peak in the high LET region.

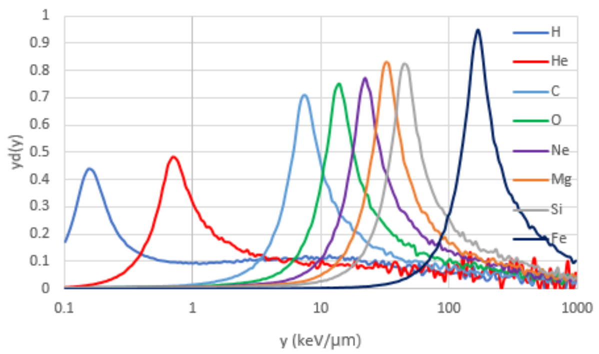

Fig. 5. LET spectra for GCR protons (H), helium (He), carbon (C), oxygen (O), neon (Ne), magnesium (Mg), silicon (Si), and iron (Fe) ions.

LET spectra for SPE and trapped protons in LEO were also obtained from TEPC energy distributions. As shown in Fig. 6. and Fig. 7., SPE protons and trapped protons show a peak in the higher LET region than GCR protons due to their lower energies with higher LETs.

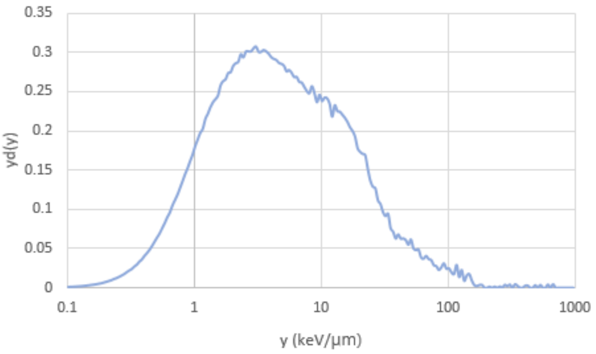

Fig. 6. LET spectra for SPE protons.

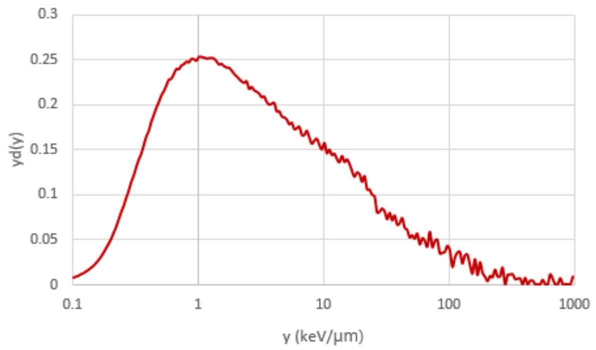

Fig. 7. LET spectra for trapped protons in SAA.

2.4 TEPC Dose Rates for LEO Radiation Environment

Absorbed dose rate (*D*) and dose equivalent rate (*H*) of GCR, SPE, and trapped particles were acquired from energy distributions in TEPC. According to ICRP Publication 60, the absorbed dose was given by $d\varepsilon/dm$, where $d\varepsilon$ is the deposited energy in TEPC, and dm is the mass of TEPC. The dose equivalent was given by $H=Q{\cdot}D$, where Q is the quality factor, a function of LET.

Table. 1. LET spectra for trapped protons in SAA.

	GCR	SPE	Trapped
D (μGy/h)	2.18	224.34	7481.02
H (μSv/h)	15.12	568.90	20940.45

Table. 1. showed the absorbed dose rate and the dose equivalent rate of TEPC for GCR, SPE, and trapped particles. The simulated absorbed dose rate of TEPC for GCR was 2.18 μGy/h, and it showed good agreement with Liulin measurement in LEO of about 2~3 μGy/h [8]. The absorbed dose rate and the dose equivalent rate of TEPC for SPE and trapped particles showed much higher results than GCR, which means that the NEXTSat-2 can get more radiation damage when it passes through the SAA region or solar activity occurs.

3. Conclusions

LET spectra and the dose rates of TEPC for GCR, SPE, and trapped particles in LEO were predicted using Monte Carlo simulations. LET spectra for GCR, SPE, and trapped particles showed peaks in different regions according to the different LETs of charged particles. The simulated absorbed dose rates of GCR showed good agreement with Liulin measurement in LEO. The simulated dose rates of SPE and trapped particles showed much higher results than GCR.

6. Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea government (MSIP) (NRF-2017M1A3A4A01077173 and NRF-2017M1A3A4A01077220).

REFERENCES

[1] J. Malimban, U. -W. Nam, J. Pyo, S. Youn, and S. -J. Ye, Characterization of a New Tissue Equivalent Proportional Counter for Dosimetry of Neutron and Photon Fields: Comparison of Measurements and Monte Carlo Simulations, Physics in Medicine and Biology, Vol. 64, p.13, 2019.
[2] F. Ali, Design and Characterization of Next-Generation Tissue Equivalent Proportional Counters for use in Low Energy Neutron Fields, University of Ontario Institute of Technology, 2014.
[3] J. W. Norbury, *et al.*, Advances in Space Radiation Physics and Transport at NASA, Life Sciences in Space Research, Vol.22, pp.98-124, 2019.
[4] L. C. Simonsen, T. C. Slaba, P. Guida, A. Rusek, NASA's First Ground-based Galactic Cosmic Ray Simulator: Enabling a New Era in Space Radiobiology Research, PLoS Biology, Vol.18, p.e3000669, 2020.
[5] American National Standards Institute, Space Environment - Galactic Cosmic Ray Model, Technical Report ISO 15390, 2004.
[6] A. W. Case, et al., The Deep Space Galactic Cosmic Ray Lineal Energy Spectrum at solar Minimum, Space Weather, Vol.11, pp.361-368, 2013.
[7] M. A. Xapsos, G. P. Summers, J. L. Barth, E. G. Stassinopoulos, E. A. Burke, Probability Model for Cumulative Solar Proton Event Fluences, IEEE Transactions of Nuclear Science, Vol.47, pp.486-490, 2000.
[8] T. P. Dachev, et al., Overview of the Liulin Type Instruments for Space Radiation Measurement and their Scientific Results, Life Sciences in Space Research, Vol.4, pp.92-114, 2015.
[9] D. M. Sawyer and J. I. Vette, AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum, NSSDC/WDC-A-R&S 76-06, 1976.
[10] Los Alamos National Laboratory, MCNP Home Page, 〈https://mcnp.lanl.gov/〉