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Impact of Terrain on Doses for Fission Surface Power

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ABSTRACT

The Fission Surface Power (FSP) nuclear system should be capable to provide enough energy for the missions focused on exploration and colonization of the Moon and Mars. The FSP shielding components are essential for the protection of humans, electronics, and sensitive components, but they are also often the heaviest components of the system for which each kilogram matters. One of the possible solutions to reduce the FSP shielding mass is to use the terrain for radiation dose reduction. This paper explores this idea using real lunar terrain data as well as theoretical studies. The research was funded through DOE and NASA collaboration and the contract.

Keywords: Fission Surface Power, Radiation Shield, Monte Carlo, Lunar Terrain

1. INTRODUCTION

The FSP project is focused on development, construction, and deployment of an operational space nuclear reactor on the Moon in the frame of the Artemis program [1]. The FSP system developed for the Moon can be adapted for use as a viable energy source on Mars. Initially, an FSP reactor power of 40 kWe was proposed based on the mission's assessment. The National Aeronautics and Space Administration (NASA) partnered with the Department of Energy and national laboratories to work on maturing key technologies that still needed further research and development such as radiation shielding. The purpose of radiation shielding for space nuclear reactors is to attenuate the reactor radiation for the protection of humans, electronics, and sensitive equipment, such as control drum motors and power conversion system electronics. Another source of radiation – space radiation including low-flux high-energy galactic cosmic rays and bursts of particles from the Sun – was not considered in this work.

The radiation shield for the FSP nuclear reactor must attenuate fast neutron and gamma fluxes to protect the human habitant and sensitive components. Sensitive components can include control systems, instrumentation, electronics, and materials that undergo changes in their performance and properties due to irradiation (i.e., semiconductors). FSP components that require protection from radiation include the reactor control system, control drum actuators and motors, instrumentation, Power Conversion System (PCS), and Power Management and Distribution (PMAD). Other components can change their properties as result of the material structure changes caused by irradiation, but they are less sensitive than the aforementioned systems. The material selection for those components can be made based on the temperature and dose limits

permissible to maintain adequate system performance throughout the reactor lifetime. However, for the sensitive components, the material pool is very limited.

The shielding components are essential for FSP, but they are often also the heaviest components. In the frame of this project, different shield layouts, shapes, and material compositions were evaluated to reduce the shield mass while remaining effective in its dose reduction capabilities. In addition to that, it was assessed whether the shield mass can be reduced or its effectiveness can be enhanced by using a particular reactor placement in conjunction with the terrain to provide additional shielding.

Overall, the purpose of this paper is to summarize the results of the terrain impact assessment as well as to provide a brief overview of the past and present work on the terrain considerations with respect to the reactor placement. Section 2 provides a brief overview of the past work. Section 3 outlines the major assumptions. Section 4 summarizes the study's results. The paper concludes with a summary of the results and recommendations for the next steps.

2. HISTORY OF SPACE NUCLEAR REACTOR SHIELDING DEVELOPMENT

Historically, a directional or shadow shield was considered for space nuclear reactors. The purpose of the shield is to protect sensitive payloads, equipment, and systems in a particular location relative to the nuclear reactor. The ideal solution would be, of course, to have an omnidirectional shield, but the shield's mass makes this ideal solution currently impractical when integrated with the reactor. As a result, a directional shield has been the major design option since the 1960's. Figure 1 illustrates traditional shadow shield designs used for SNAP-10A in 1965 (left) and the conceptual design for a 5 kWe reactor proposed in 2024 (right).

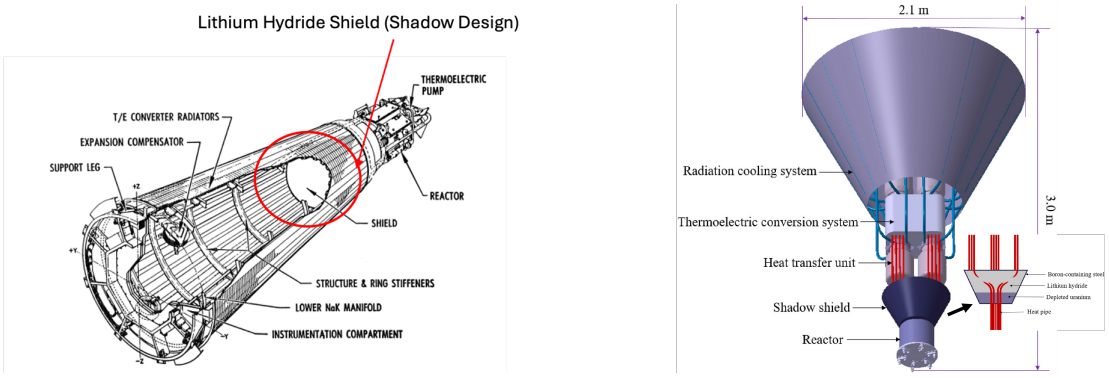

Figure 1. Shadow shield for systems for Space Nuclear Auxiliary Power (SNAP) [2] (left) and shadow shield for a conceptual design of a 5 kWe reactor [2] (right)

The SNAP-10A shield design consisted of lithium hydride blocks. Type 316 stainless steel was the matrix material. A spring-loaded system was used to support the lithium hydride blocks and to accommodate the difference in thermal expansion between the hydride and the steel. The conceptual shield design shown on the right-hand side of Figure 1 incorporates lithium hydride and depleted uranium encapsulated in borated steel [3]. The majority of the recent papers in the radiation shield development field was focused on the development of shield optimization methods ([4]-[7]), optimization of the shield ([4]-[5]) and material development ([6]-[7]). This paper explores the FSP reactor placement impact in conjunction with the lunar surface considering the previous items.

The FSP shielding approach has the potential to be more flexible in comparison to the shielding design for the nuclear propulsion systems because the FSP reactor is stationary, the lunar regolith might be used to compliment habitat shielding, and some shielding components can be delivered separately and installed

around the reactor. For the FSP shield, the most limiting factor is the maximum allowable weight of the system during the launch and delivery to the desired site on the Moon or Mars. The rocket, lander, and rover maximum load capacities limit the FSP system's mass. The mass goal for the FSP system was 6000.0 kg to fit a planned cargo lander that has acceptable volume dimensions (a 4 m diameter and 6 m in length cylinder) [8]. A 6-wheel, pre-deployed rover chassis should be capable of delivering the FSP system and a pressurized crew cabin to the site selected for the FSP operation. The lander and rover lifting capabilities are currently more limited than the rocket payload capacities. Any additional shielding solutions will be beneficial.

3. TERRAIN IMPACT AND FSP SHIELDING DESIGN ASSUMPTIONS

Review of the existing literature revealed a predilection for reductions in dose from the space environment e.g. [9] rather than addressing dose from reactors, though Caffrey discusses both environment and the use of nuclear systems [10].

For the terrestrial reactors, the particularity of the terrain is assessed for determination of Emergency Planning Zones (EPZs) around nuclear power plants. The size, shape, and terrain characteristics vary from power plant to power plant. The terrain is assessed to determine radioactive plume propagation, possible exposure of population and surroundings contamination in case of accident is assessed for each power plant. It is reasonable to assume that a definition similar to EPZ needs to be determined for nuclear reactors on the Moon and Mars that will power a human habitat. It will be needed to assess the impact of terrain when such a definition is introduced. In the presented studies, the regolith composition was defined using the regolith specifications for basin ejecta in [11].

Table I. Regolith composition for Basin Ejecta (A-14) [11]

Element	Weight Fraction	Element	Weight Fraction	Element	Weight Fraction
13027	0.0921	26056	0.0950012	12026	0.00625816
20040	0.0771	26057	0.0021756	25055	0.0011
24050	0.000645	26058	0.0002072	11023	0.0052
24052	0.0012555	19039	0.0042872	8016	0.438
24053	0.0001425	19041	0.0003082	15031	0.0022
24054	0.0000345	12024	0.04504048	16032	0.000830808
26054	0.0060088	12025	0.0056529		

Figure 2 shows the lithium hydride shield design used as the base model in the analysis. The shield size and shape were optimized. The radiation transport analysis was performed using the Monte Carlo N-Particle transport code (MCNP) Version 6.3.0 [12] with the ENDF/B-VIII.0 library.

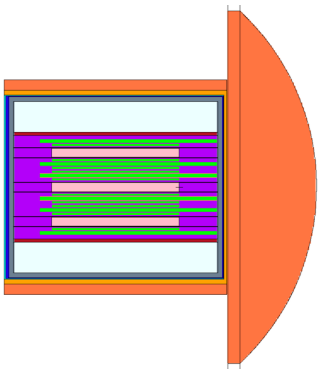

Figure 2. FSP Reactor with lithium hydride shield

Figure 3 illustrates the key five locations for the shield design evaluation. They include Power Conversion System (PCS), Power Management and Distribution System (PMAD), and the human habitat that is at a distance of 1000 m from the reactor. The following dose limits were assumed in the analyses: 1) For the PCS located 2 meters from the reactor edge, the gamma dose limit is 10 Mrad after 10 years of operation and the neutron fluence limit is 10^{14} n/cm^2 after 10 years. 2) For the PMAD located 50 meters from the reactor edge, the gamma dose limit is less than 300 krad after 10 years of operation and the neutron fluence limit is 10^{11}-10^{14} n/cm^2 after 10 years. 3) The dose rate 1 km away to a hypothetical human was constrained to 5 rem/year above background levels. As a point of reference background doses are the moon were recently measured as approximately 50 rem/yr [13.]

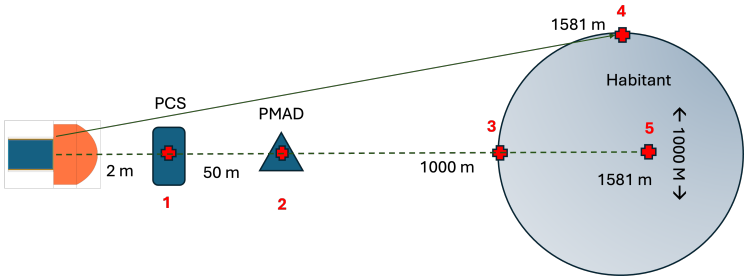

Figure 3. Layout of dose points (in Red)

4. SUMMARY OF THE RESULTS

4.1. Conceptual Analysis

The sensitivity analysis was first performed for two theoretical cases in which the reactor was placed on simulated regolith such that a substantial mass lies between the reactor and the colony. In the first case, a crater depression was modeled surrounded by walls mimicking regolith (see Figure 4). Due to the lander limitations, the sides could not exceed 18 degrees of slope. The second case assumes that you place the reactor on the other side of a hill or berm, as shown in Figure 5, however, due to convergence issues, the slope had to be increased to 5 degrees dramatically shortening the width of the berm, from 340 meters to 68 meters. In both cases, the reactor is 1.5 meters above ground to facilitate transportation on the rover, and the dose at the colony was measured 2 m above the ground. A 3-meter depression or hill is sufficient to cover the top of the reactor so there is no direct line of sight. In both cases, doses to the colony were dramatically reduced, suggesting that shielding for these configurations should be targeted at maintenance

activities and preservation of the PCS and PMAD functions. The dose values are presented in Table II for the crater studies, and in Table III for the berm studies.

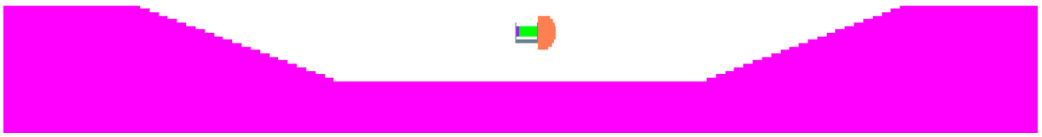

Figure 4. Reactor surrounded by regolith (approximation of the real shape)

Table II. Impact of crater with and without reactor shield at Position 3 (as defined in Figure 3)

Depth of Crater	Unshielded Neutron Dose [rem/yr]	Unshielded Photon Dose [rem / yr]	Shielded Neutron Dose [rem/yr]	Shielded Photon Dose [rem/yr]
3 m	0.093	0.0031	0.068	0.0063
5 m	0.080	0.0028	0.057	0.0023



Figure 5. Reactor positioned behind a regolith hill (approximation of the real shape)

Table III. Impact of hill at Position 3 (as defined in Figure 3)

Height of Berm	Narrow Berm Neutron Dose [rem/yr]	Narrow Berm Photon Dose [rem / yr]	Wide Berm Neutron Dose [rem/yr]	Wide Berm Photon Dose [rem/yr]
3 m	0.068	0.0063	0.068	0.0063
5 m	0.057	0.0023	0.057	0.0023

4.2 Impact of Lunar terrain

At the second stage, the real terrain map was used for the analysis. One of the proposed locations for the FSP reactor is Connecting Ridge (left plot in Figure 6), a formation at the Lunar South Pole. From the existing NASA map data of Connecting Ridge, an unstructured mesh map was generated for the MCNP calculations (right plot in Figure 6).

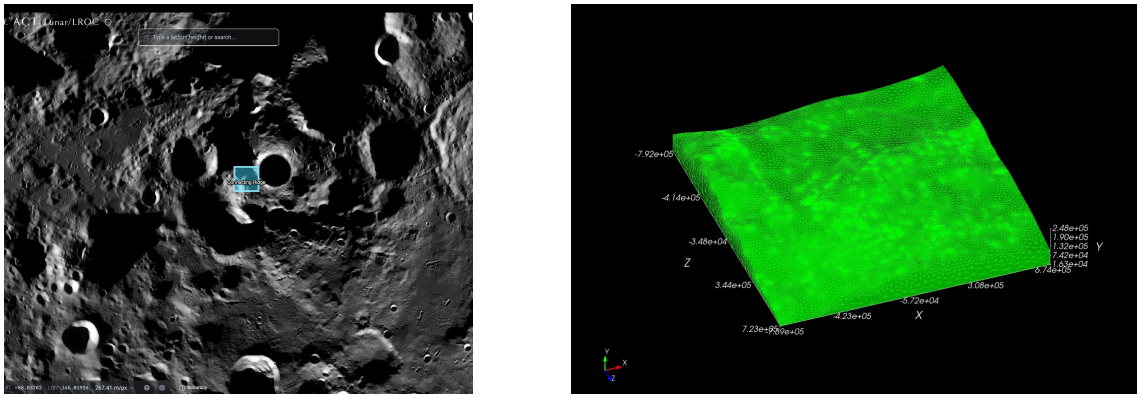

Figure 6. Connecting Ridge (Blue Square) located at Lunar South Pole (left) and Connecting Ridge Region for MCNP calculations on unstructured mesh with distances in centimeters (right)

The landing site and reactor operation location have restrictions due to the current technical limitations. In particular, the maximum slope should not exceed 18 degrees. The crater should not be too small with a big crater wall slope. The crater radius should also be less than 1 km to be able to place the habitat behind the crater wall. Figures 7 and 8 show the neutron and gamma fluxes respectively for the selected reactor and habitat locations. The maximum terrain angle is ~12-14 degrees and the crater wall height is ~120 m.

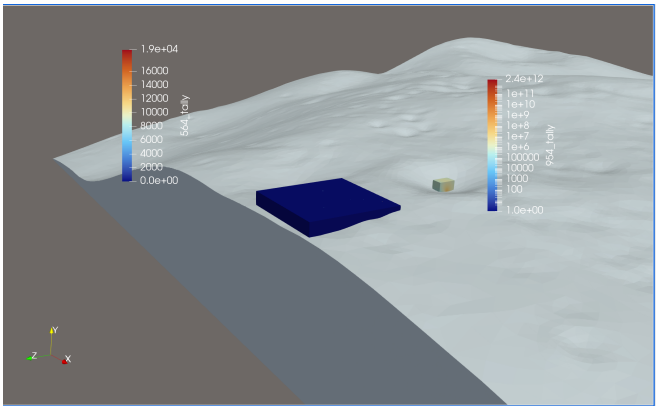

Figure 7. Neutron flux (n $cm^{-2}s^{-1}$) in habitant (Blue Box 1000 m x 1000 m x 142 m) and around the reactor. The reactor shield is on the left side of the reactor, towards the Positive Z

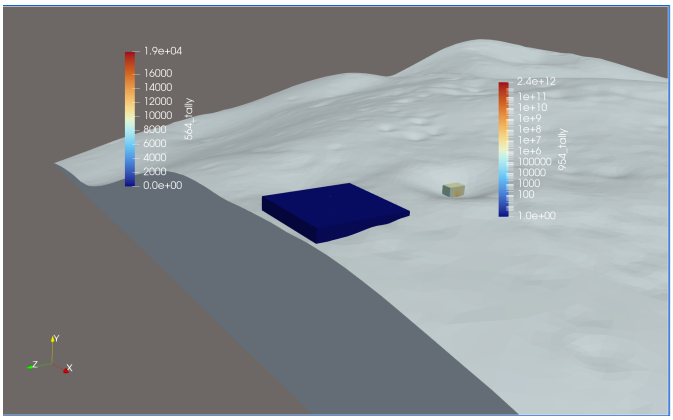

Figure 8. Gamma Flux (p $cm^{-2}s^{-1}$) in habitant (Blue Box 1000 m x 1000 m x 142 m) and Around the Reactor. The Reactor Shield is on the Left Side of the Reactor, towards the Positive Z

Table III. Dose Values for the Considered Reactor Locations (Range of Values is provided for the three Positions in the Habitant). Positions are defined in Figure 3.

Near Reactor	Shielded Neutron Dose [rad/yr]	Shielded Photon Dose [rad/yr]
Pos 1 at 2 m	9.53E+4	5.11E+6
Pos 2 at 50 m	6.05E-9	1.39E-4
Habitant	[rem/yr]	[rem/yr]
Pos 3 - 5	8.E-6-3.98E-2	2.E-7-2.5E-3

Scattering from the regolith is accounted for in the calculations, but it was not estimated separately from the total dose. The absorbed doses (deposited energy) in rad/yr and the dose equivalent in rem/yr were calculated. MCNP built-in ANSI/ANS-6.1.1-1991 tables were used for the equivalent dose calculations. The doses at five locations are presented in Table III. Figure 8 shows the absorbed doses around the reactor. It can be concluded from the presented data that the dose in the habitat will be negligible while, as expected, the radiation dose around the reactor is prohibitive for anyone to be in the crater during the reactor operation.

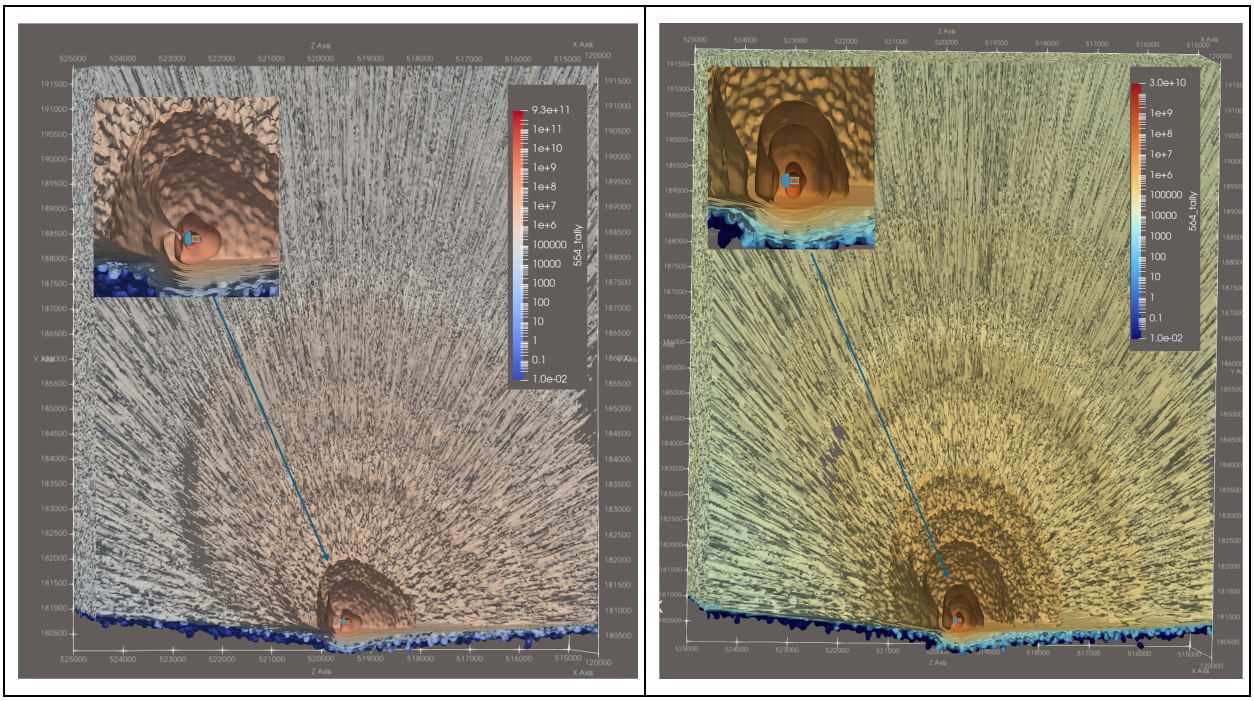

Figure 9. Neutron (Left) and gamma (Right) doses [REM/Yr] near the reactor (100 m x100m x118 m)

5. CONCLUSIONS

Based on the performed analysis, it can be concluded that placement of an FSP reactor behind a hill with a slope of 5 degrees or in a crater or in a depression of 3 m will make the radiation doses on the other side of the hill, outside of the crater, and in the habitat negligible. Considerations of a particular location in the Connecting Ridge region showed that there is a potential location for the FSP reactor that meets the current technical transportation and landing limitations and makes it possible to have a negligible dose from the

reactor in a habitat. However, the radiation dose around the reactor, in the crater, will be significant and will not allow anyone to fly above it or to be in the crater during operation. Based on the performed work, it is recommended to further look at the use of regolith for shielding purposes. In particular, the following options should be considered: partial reactor embedment in the regolith with some amount of shield above the reactor, combination of the location behind a hill or in the crater and additional transportable shielding blocks for the placement around the reactor, and search of a location on the Moon allowing to combine a depression and additional transportable shielding blocks. It is also recommended to assess the amount of scattering from the regolith and its contribution to the radiation doses around the reactor.

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REFERENCES

1. NASA, Fission Surface Power https://www.nasa.gov/exploration-systems-development-mission-directorate/fission-surface-power/
2. R. A. Johnson, W.T. Morgan and S.R. Rocklin, “Design, Ground Test and Flight Test of SNAP 10A, First Reactor in Space”, Nuclear Engineering and Design, 5 (1967) 7-21.
3. H. Mei et al., “Conceptual Design for a 5 kWe Space Nuclear Reactor Power System,” Nuclear Engineering and Technology, 56 (2024), 3644-3653.
4. I. Khan, L et al, “Development of a novel neutron-gamma spectrum-based composite material optimization process for the shielding design of a space reactor,” Nuclear Engineering and Design, Volume 442, 2025, 114215.
5. B. Jiang, Y. Ji, J. Sun, L. Shi, “Shielding mass estimation model for gas-cooled space nuclear reactors,” Nuclear Engineering and Design, Volume 424, 2024, 113238.
6. M. T. A. El-Magd et al, “Improving mechanical and nuclear attenuation properties for Ethylene Propylene Diene Monomer (EPDM) /Tungsten powder compounds as a shielding material,” Radiation Physics and Chemistry, Volume 238, 2026, 113231.
7. G. S. Anunike, O. A. Hisseine, “A novel two-phase mixture optimization framework for radiation shielding UHPC: Advancing ultra-high-performance shielding materials for improved nuclear safety and security, Construction and Building Materials,” Volume 496, 2025, 143659.
8. S. Oleson et al, “A Deployable 40 kWe Lunar Fission Surface Power Concept, Nuclear and Emerging Technologies for Space (NETS-2022) Cleveland, OH, May 8-12, 2022.
9. B. Ehresmann et al, “Natural Radiation Shielding on Mars Measured with the MSL/RAD Instrument,” Journal of Geophysiical Research: Planets, Volume 126, Issue 8, August 2021
10. J.A. Caffrey et al, “Radiation and Nuclear Technology in Planetary Cave Environments,” 4th International Planetary Caves Conference, Lanzarote, Spain, May 3-7, 2023, https://ntrs.nasa.gov/citations/20230006716
11. D.B. Stoeser, D.L. Rickman, “Design and Specifications for the Highland Regolith Prototype Simulants NU-KHT-1M and -2M,” NASA/TM-2010-216438, August 2010.
12. J. A. Kulesza et al., **MCNP® Code Version 6.3.1 Theory & User Manual**. Los Alamos National Laboratory Tech. Rep. LA-UR-24-24602, Rev. 1. Los Alamos, NM, USA. May 2024.
13. S. Zhang et al, “First measurements of the radiation dose on the lunar surface,” Science Advances Volume 6 Issue 39, September 2020