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Lunar Nuclear Reactor Neutron Fluence and Gamma Dose Estimates

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ABSTRACT

NASA aims to deploy a fission reactor on the lunar surface by 2030 to generate 100 kWe of power for at least 10 years without maintenance or refueling. To assess system and subsystem survivability according to those requirements, a model of the reactor pallet was created in the radiation transport code MCNP to determine the neutron fluences and gamma doses that the materials and systems would be exposed to. The model was based on the 2025 government design. The model indicated that the control drum motors, Brayton cycle engines, and pipes and valves would be exposed to neutron fluences of 1×10^{15} – 1×10^{16} n/cm^2 per year and gamma doses ranging from 10 to 500 Mrad per year. The electronics box housing the instrumentation and control elements is expected to receive 1×10^{14} – 1×10^{15} n/cm^2 per year and gamma doses in the range of 1–5 Mrad per year. These doses necessitate that the control drum motors, Brayton cycle engines, valve components, control electronics, and other components be radiation-hardened (>10^{16} n/cm^2 and >10 Mrad gamma dose) or additionally shielded to survive the 10-year lunar mission.

Keywords: Fission Surface Power, Radiation Transport, Space Reactors, Radiation-Hardened Materials

1. INTRODUCTION

NASA has a goal of deploying a nuclear reactor on the lunar surface by 2030 to power a sustained human presence. The requirements for this reactor are to provide 100 kWe of electric power for over 10 years to the Moon base, without maintenance or refueling. The suggested system capabilities include, autonomous operation, single-fault tolerance, and more [1]. The target radiation dose from the fission source is 5 rem per year at 1 km away in the shadow of the primary shield and 50 rem per year while 1 km away outside the primary shield's shadow. In addition, the size and weight of the system must be such that it can fit in a stowed space of 4 m by 6 m in length with a total mass of less than 6000 kg [2]. These design targets, size and weight, create a unique design space and environment with regard to shielding the reactor components.

In traditional terrestrial reactors, reactor components can be adequately shielded with water, concrete, or other materials so that minimal, if any, radiation from the reactor reaches them. For instance, in pressurized water reactors, control rod drives, instrumentation and control (I&C) lines, valve components, data acquisition (DAQ) systems, and power generation equipment are shielded by several meters of water and concrete. For a lunar reactor, that is not the case: the mass and space limits of the rocket payload prohibit the use of excess shielding. Thus, control drum motors, power conversion equipment, I&C

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lines, and DAQ systems will be exposed to significant ionizing radiation coming from the reactor.

This atypical high-radiation environment for these components and materials creates a large unknown potential for radiation-induced failure in equipment and material degradation. The behavior and structure of polymers and oils (power conversion equipment, drum motors) tend to change under neutron and gamma irradiation [3-5]. Additionally, I&C cable insulation and electronics tend to experience material breakdowns when exposed to neutron and gamma radiation [6-8]. This manuscript is intended to provide rough estimates of the neutron fluence and gamma dose that these components are likely to receive during a fission surface power (FSP) mission. A government FSP design has been created and was used as the source term for this study [2]. Using the government design and a standard shield concept, radiation mapping of the reactor and the nearby components was simulated in this work using the Monte Carlo N-Particle (MCNP) radiation transport code [9]. By identifying the likely radiation doses that the reactor components will receive, research, development, and testing can occur to ensure that these components and materials are capable of surviving the harsh radiation environments associated with a lunar reactor.

2. FISSION SURFACE POWER DESIGN

NASA issued a call for proposals in 2022 for an FSP reactor for the Moon, and three industry teams were selected and produced preliminary designs of a complete FSP system. Since these designs are proprietary, this study used a design by NASA Glenn along with Los Alamos and Idaho National Laboratories. This design was created to be shared with the public to help further address this technology's open science questions. The NASA and Department of Energy design, referred to as the *government design*, followed the same design requirements and design goals as those of the industry teams. It is a publishable design and was used in this work to provide the likely neutron fluence and gamma dose ranges to all parts of the FSP reactor and power conversion system pallet. This section briefly describes the current government design of the lunar reactor; for more detailed information on the design, refer to Mason et al. [2].

The government design for the FSP reactor had two variations: 1) a direct gas-cooled (GC) reactor with Brayton power conversion and 2) a heat-pipe reactor using Stirling engines for power conversion. Recent indications from NASA appear to favor the closed Brayton cycle version of the reactor; therefore, we analyzed only that design in this study. The FSP model consists of five parts: 1) reactor, 2) shield, 3) power conversion system, 4) heat rejection system, and 5) power management and distribution system (PMAD). The reactor is a 500 kWth design with a planned electrical output of 100 kWe. The reactor core (seen in Figure 1) is made up of uranium nitride (UN) fuel elements with an enrichment of 19.75% (i.e., high-assay low-enriched uranium, or HALEU). These fuel elements (reddish-brown annuli in Figure 1), along with yttrium hydride (green circles in Figure 1), are embedded in a beryllium oxide moderator (red hexagons in Figure 1). Coolant channels for the 40 g/mol HeXe working gas are shown as the teal circles in Figure 1.

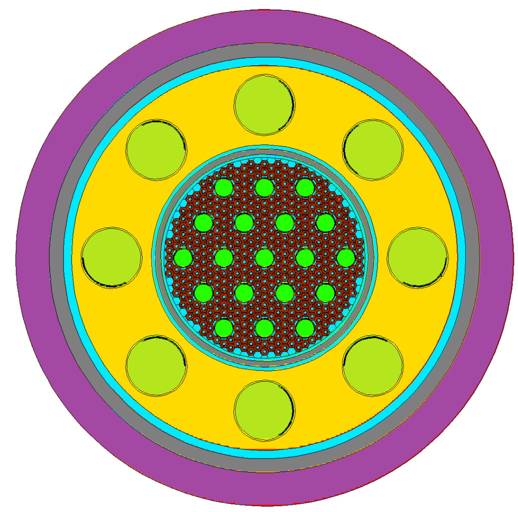

Figure 1: Cross-sectional MCNP image (y,z) of the reactor design.

The control drums (sage green in Figure 1) consist of beryllium oxide with a boron nitride poison section (black crescents in Figure 1). A beryllium reflector (gold in Figure 1) encompasses the reactor, along with a Haynes 230 alloy pressure vessel (gray in Figure 1). The operating temperature of the reactor is around 1100 K, with a gas inlet temperature of 950 K and an outlet temperature of 1100 K. The main gas pipes (made of titanium grade 2) run through the shield and into the Brayton engines on the other side (see Figure 2). Control drum shafts also run through the shield to help protect the motors from the harsh radiation environment.

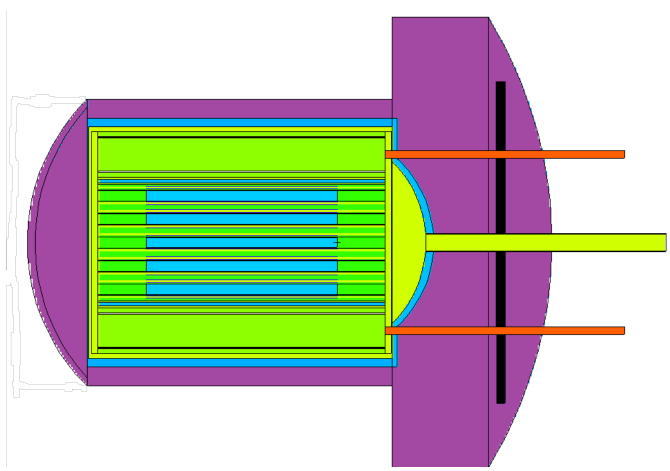

Figure 2: Cross-sectional MCNP image (x,z) of the reactor and shield design

The shield for the reactor is designed to reduce radiation and dose primarily in the direction of the habitat and sensitive power conversion equipment. The total system mass limits necessitate minimizing weight wherever possible, and the reactor shield's geometry reflects this approach: most of the shielding mass is oriented toward the habitat. The shield consists of a layered design, incorporating lithium hydride (enriched to 50% Li-6, shown as purple in Figure 2) as a neutron absorber and tungsten as a gamma shield (shown as the black plate in Figure 2). In addition to the reactor, the entire lander and power conversion systems were modeled. In Figure 3, images of the entire FSP system, along with the Moon surface, can be seen. The FSP system includes a large retractable radiator to dissipate the heat from the reactor system (large gray rectangle in Figure 3). Four Brayton cycle engines were modeled as stainless-steel purple rectangular prisms; the actual design and layout of the engines will be highly design-dependent. Similarly, the electronics for the I&C of the system are shown as a red cube in Figure 3. This component will also likely change in size, shape, and potential location on the lander. The lander was modeled as titanium grade 2, as was the piping for the system. Finally, the Moon surface was modeled as regolith and was assumed to be completely flat.

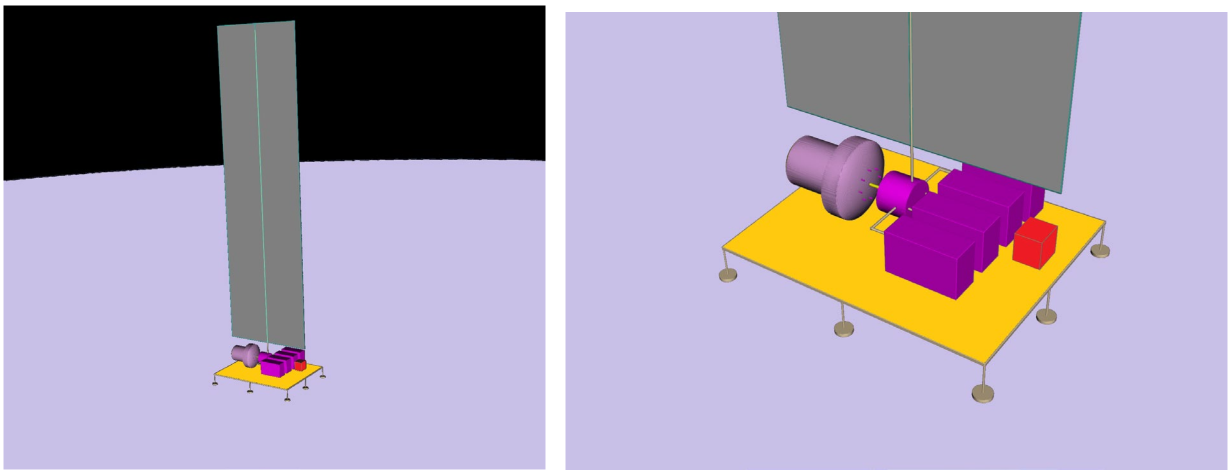

Figure 3: MCNP image of the FSP system.

3. RADIATION MODELING RESULTS

To simulate the radiation transport and doses from the reactor to its components, the radiation transport code MCNP was used. The government design for the reactor, shield, radiators, and power conversion equipment was modeled 1:1 in MCNP, as can be seen above in Figures 1–3. Neutron and gamma transport was simulated throughout the entire system using a mesh tally over the entire lander. The reactor was assumed to be running at a power level of 500 kWth for an entire year (the data for the neutron fluences and gamma dose is the accumulated dose per year). In Figures 4 and 5, the neutron fluence (n/cm^2) over the course of one year for the entire system can be seen in different cross-sectional planes. Figure 4 shows the x–z plane, and Figure 5 shows the x–y plane.

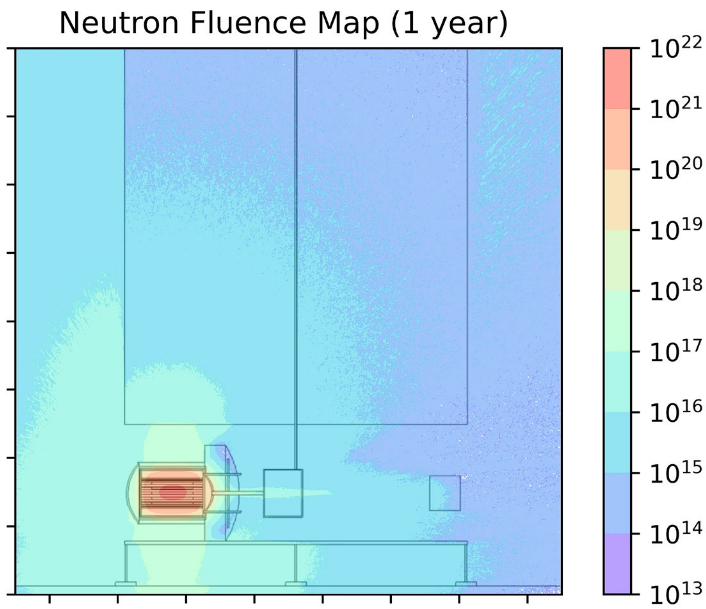

Figure 4: Neutron fluence (n/cm^2 per year) map of the FSP system (x,z plane).

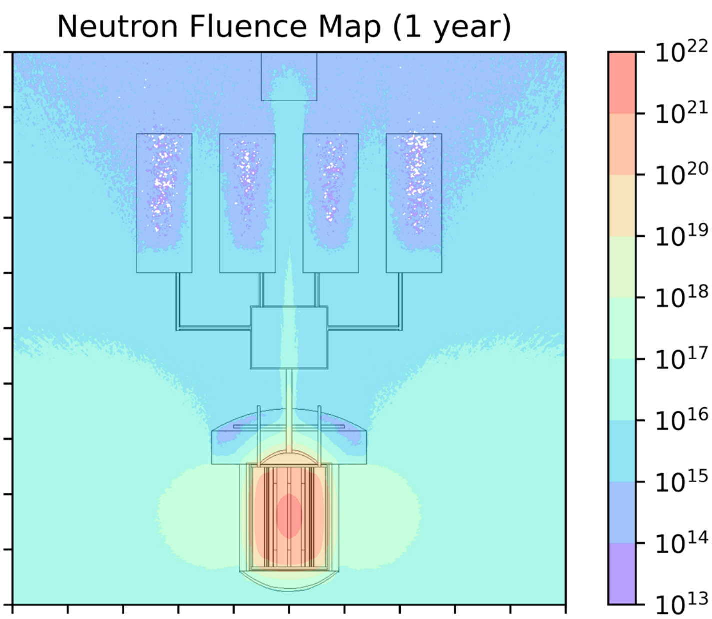

Figure 5: Neutron fluence (n/cm^2 per year) map of the FSP system (x,y plane).

The LiH shield is highly effective in limiting the neutron flux (three orders of magnitude) that can penetrate the shield. The inlet pipe through the shield creates a large streaming port for neutrons; orienting this pipe such that it zigzags or is angled through the shield can help with the neutron flux on the other side. Besides the streaming path from the inlet pipe, neutron scatter off the lander, radiator, and lunar surface also contributes to the elevated neutron fluence on the other side of the shield; the lander and lunar surface have a larger scattering impact, as seen in the asymmetries of the neutron fluence outside the shield in

Figure 4. Finally, the electronics box for the I&C is currently located in the path of the main outlet pipe of the reactor; future designs should locate it at the corner of the lander to further reduce the radiation dose. The gamma dose (Mrad per year) is shown in Figures 6 and 7 below.

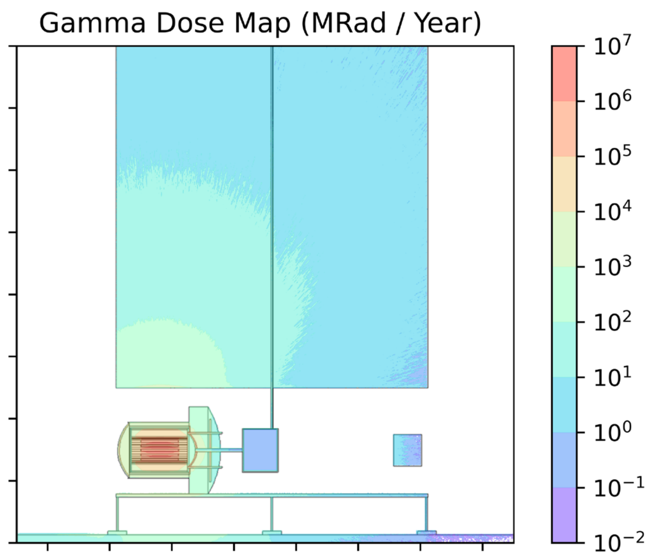

Figure 6: Gamma dose (Mrad per year) map of the FSP system (x,z plane).

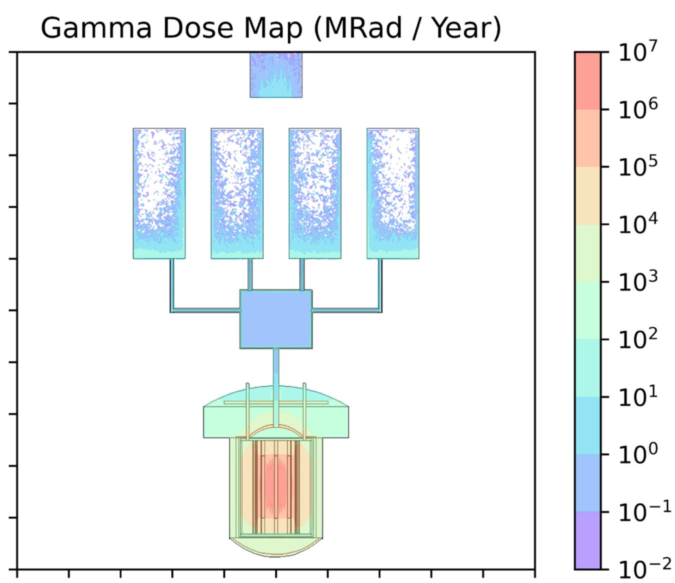

Figure 7: Gamma dose (Mrad per year) map of the FSP system (x,y plane).

The gamma shield (tungsten plate) is not as effective in curtailing the gamma dose as the neutron shield (dropping the gamma dose by an order of magnitude). Gamma rays are difficult to shield as they require large amounts of dense material to stop them, which is not conducive to the low mass loads needed for rocket launches. As a result, the gammas primarily have a $1/r^2$ dependence away from the reactor. The gamma doses in Figures 6 and 7 are the energy deposited in the materials. Therefore, the density of the material is important with respect to how much dose a material or system incurs (hence no dose is recorded in the vacuum surrounding the system on the Moon). Similarly to the neutron fluence models, placing the electronics box at the corner of the lander or behind the Brayton engines could help in reducing the gamma dose on the sensitive electronics.

4. DISCUSSION

The objective of these models is to provide rough estimates of the neutron fluences and gamma doses that the FSP system components and materials must be able to withstand if the system is to run for multiple years. In Table I, radiation estimates based on the models are shown for all of the different FSP components. Because of the spatial dependency of the neutron and gamma fields over the different FSP systems, ranges are given.

Table I. Neutron Fluence and Gamma Dose Estimates for different FSP reactor components

FSP Reactor Component	Neutron Fluence (n/cm^2 / Year)	Gamma Dose (Mrad / Year)
Core Materials	1×10^{21}	$5\times10^{5} – 1\times10^{6}$
Reflector Materials	$1\times10^{20} – 5\times10^{20}$	$5\times10^{4} – 1\times10^{5}$
Pressure Vessel Materials	$1\times10^{19} – 5\times10^{19}$	1×10^{5}
Lander	$1\times10^{15} – 5\times10^{17}$	$1\times10^{1} – 5\times10^{3}$
Radiator	$1\times10^{15} – 1\times10^{17}$	$1\times10^{1} – 1\times10^{2}$
Control Drum Motors	$5\times10^{15} – 1\times10^{16}$	$1\times10^{2} – 5\times10^{2}$
Piping & Valves	$1\times10^{15} – 1\times10^{16}$	$1\times10^{1} – 5\times10^{1}$
Brayton Cycle Engines	$1\times10^{15} – 1\times10^{16}$	$1\times10^{1} – 5\times10^{1}$
I&C Cables / Fibers	$1\times10^{15} – 1\times10^{16}$	$1\times10^{1} – 5\times10^{1}$
Control Electronics	$5\times10^{14} – 1\times10^{15}$	$1\times10^{0} – 5\times10^{0}$

A few important takeaways from the table above are the large neutron fluences and gamma doses that the control drum motors, Brayton cycle engines, and pipes and valves will be exposed to. These systems and materials are typically not placed in high-radiation fields, and so they will have to be specially engineered and designed to ensure that polymers, oils, and other sensitive components do not degrade and fail in these fields. Additionally, the electronics box housing the I&C control elements is expected to receive $1\times10^{14} – 1\times10^{15}$ n/cm^2 per year and gamma doses ranging from 1 to 5 Mrad per year, necessitating the use of radiation-hardened electronics and circuits to ensure that the control elements of the system are not severely damaged or produce an abundance of errors over the 10-year mission duration.

These models did not encompass all of the potential radiation dose that materials and components will be exposed to on the Moon, leaving much room for future improvements to the models. First, the exact dimensions of the reactor, shield, Brayton engines, and so on have not yet been fully determined and designed, so a better shield or different streaming paths of the radiation through the shield could cause changes to the radiation doses. Additionally, the degradation of the neutron shield was not calculated over the course of a year or years. Neutron activation of the FSP structures will cause additional dose to the systems and materials on the other side of the shield. Finally, the contributions of galactic cosmic rays, solar wind, and other space radiation were not factored into the dose to which these components and materials will likely be subjected on the Moon over time.

5. CONCLUSIONS

NASA has a goal of placing a nuclear reactor on the lunar surface by 2030 to generate 100 kWe of power for a sustained human presence for 10 years. Using the government model of an FSP system, the radiation doses of the components were simulated using the radiation transport code MCNP to provide a basis for the radiation limits needed for the various components and materials to survive the mission. The models indicated that the control drum motors, Brayton cycle engines, pipes and valves would be exposed to neutron fluences of 1×10^{15} – 1×10^{16} n/cm^2 per year and gamma doses in the range of 10–500 Mrad per year. The electronics box housing the I&C control elements is expected to receive 1×10^{14} – 1×10^{15} n/cm^2 per year and gamma doses ranging from 1 to 5 Mrad per year. These doses necessitate that the control drum motors, Brayton cycle engines, valve components, control electronics, and other components be radiation-hardened ($>10^{17}$ n/cm^2 and >50 Mrad gamma dose) in order to survive for the 10-year lunar mission. These models are simply rough estimates; additional modeling is needed (inclusion of space radiation, depletion of the shield, higher-fidelity design of the system, etc.) in the future as the design is further refined and augmented.

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