

Multifaceted Considerations for Fission Surface Power Radiation Shielding Design

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ABSTRACT

The purpose of the Fission Surface Power (FSP) nuclear system is to provide energy on the Moon and Mars for supporting their exploration and colonization. The FSP design and deployment can leverage the past research and development work in areas, such as reactor design, but such crucial components as radiation shielding and instrumentation still need material and manufacturing studies, modeling, and testing. The shielding components are needed for the protection of humans, electronics, and sensitive components. They are essential system components, but they are often the heaviest components of the system for which each kilogram matters. Different material combinations and layouts are possible. The studies presented were focused on the evaluation of several options. The initial analysis included their performance assessment, initial temperature distribution evaluation and manufacturability considerations. Several feasible shield design options were identified and discussed in this paper, as well.

Keywords: Fission Surface Power, Radiation Shield, Monte Carlo, Advanced Materials, Manufacturing

1. INTRODUCTION

The goal of the FSP project is to develop, build, and deploy an operational space nuclear reactor on the Moon in the frame of the Artemis program [1]. While the first operating FSP system will be on the Moon, the development of an intricate technical system will also be the first step in developing a viable energy source on Mars. Initially, experts proposed an FSP reactor power of 40 kWe. 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. These technologies included solid moderator encapsulation, instrumentation, and 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 has to 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 as a result of irradiation (i.e., semiconductors). FSP components that require protection from radiation including 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 sensitive 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. The purpose of the studies was to evaluate different shield layouts, shapes, material compositions, impact of reactor location, manufacturing capabilities and supply chain availability.

Overall, the purpose of this paper is to summarize the results of various shielding component designs while illustrating the evolution of technological advancements in manufacturing and the supply chain. Section 2 provides a brief overview of the past radiation shielding development work. Section 3 outlines the major assumptions. Section 4 summarizes the shielding design studies. Section 5 evaluates manufacturing. The paper concludes with the summary of the results and recommendations for the next steps.

2. SPACE NUCLEAR REACTOR SHIELDING APPROACH

Typically, the shield design used for space nuclear reactors is either known as directional or shadow. The purpose of the shield is to protect humans, electronics, and the most sensitive equipment 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 impractical when integrated with the reactor. Figure 1 illustrates traditional shadow shield designs used for SNAP and SP-100's proposed mission in the 1990's.

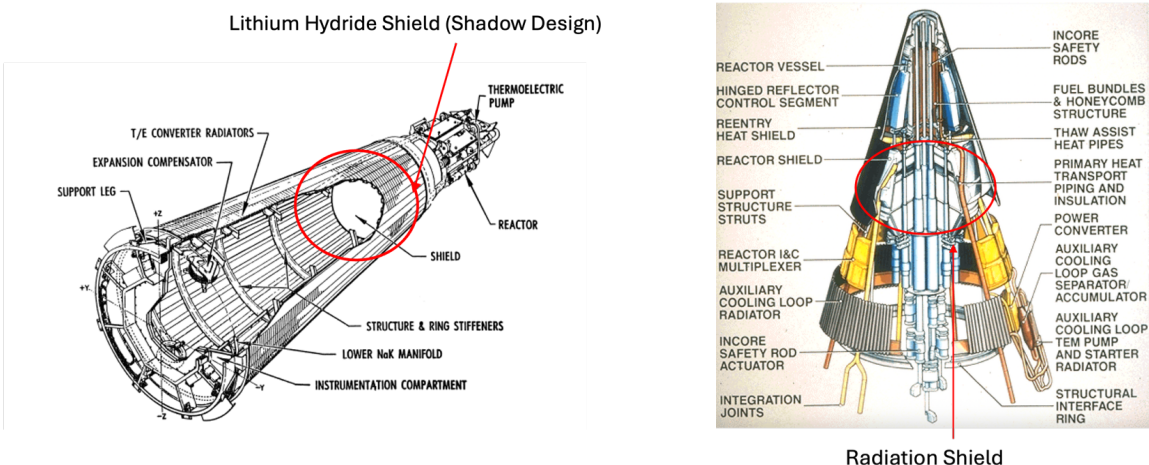


Figure 1. Shadow Shield for Systems for Nuclear Auxiliary Power (SNAP) [2] (left) and Shadow Shield for SP-100 (Multi-layered Design including Lithium Hydride, Tungsten, and Beryllium surrounded by Titanium shell) [3] (right)

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 initial manufacturing and assembly

processes were successful, but many manufacturing iterations were required due to the issues with keeping the LiH integrity and ensuring proper encapsulation. The SNAP-10A reactor operated only 43 days in space. This is an insufficient amount of time to accumulate enough data to properly characterize the shield's operational performance. The SP-100 shield design used a multi-layered approach to make the shield more effective for shielding from both neutron and gamma fluxes. The SP-100 reactor was never launched.

Both the SNAP-10A and the SP-100 shields were designed for propulsion systems. The particularity of the shield design for such systems was due to the need to minimize the shield's mass throughout the nuclear system's operational life because the mass of the shield impacts its performance, acceleration, maximum speed, and efficiency. Another important characteristic is the inability to use "natural" material in space.

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) [4]. A 6-wheel, pre-deployed rover chassis should be capable of delivering the FSP system and a pressurized crewed cabin to the site selected for the FSP operation. The lander and rover lifting capabilities are currently more limiting than the rocket payload capacities.

The FSP shielding approach can be more flexible in comparison to the shielding design for the propulsion systems because the FSP reactor is stationary, the Lunar regolith can enhance the habitat shielding, and some shielding components can be delivered separately and installed around the reactor.

In the studies presented, it was assumed that all the shielding components are integrated in the nuclear reactor's system, and the goal was to see which material and layout options are possible. The impact of the regolith was considered to assess by how much the shielding mass can be reduced if the integral components are used only to protect the sensitive components and power conversion system.

3. FSP SHIELDING DESIGN ASSUMPTIONS AND SCOPE

The FSP shielding studies included shape, layout, and material variations with the purpose of understanding which options below the maximum weight limit are possible. The focus of the project was on the optimization of the shield's shape and composition and the assessment of the Manufacturing Readiness Level (MRL). Based on the approximate mass of the other components, ~2000 kg is the current approximate shielding components' weight limit. It was also planned to perform radiation testing of the manufactured samples since the review of the existing shielding benchmarks showed a lack of experimental data for the results validation. The impact of the terrain was evaluated, as well.

Figure 2 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.

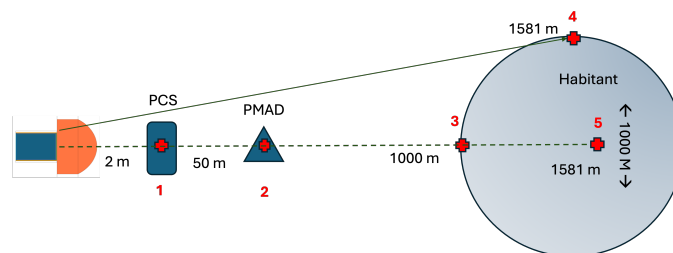


Figure 2. Layout of Dose Points (in Red)

The following dose limits were assumed in the analyses: 1) For the PCS located at 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/cm² after 10 years. 2) For the PMAD located at 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/cm² after 10 years. 3) The dose rate 1 km away to a hypothetical human was constrained to 5 rem/year above background levels.

4. SUMMARY OF THE RESULTS

4.1. Radiation Transport Analysis

The radiation transport analysis was performed using the Monte Carlo N-Particle transport code (MCNP) Version 6.3.0 [5] with ENDF/B-VIII.0. The two design options were considered — omnidirectional (360°) and shadow design concepts. The omnidirectional shield with all shielding components was defined based on the established dose limits and integrated into the reactor design. This is ideal for the protection of components and astronauts, but this option exceeds the mass restrictions. Depending on the landing and installation strategy, different scenarios are possible to reduce the shield weight. One option is based on variations in the density of the components to reduce the mass but to have sufficient shielding in the different directions. The second option includes a combination of the heavy directional shield and the hallow structure that can be built around the reactor on the Earth and filled with the shielding materials on the Moon. However, many of these concepts are practically difficult to accomplish and they require extensive development. As a result, it was beyond the scope of this work to extensively propose and evaluate omnidirectional designs.

The different shadow shield designs were analyzed based on the design shape, layout, and composition. The next few paragraphs will describe the major findings. A number of studies were performed to identify the optimum shield head shape, curvature and configuration that can be used for all material comparison.

Figure 3 illustrates an example of two shields that have differing technical designs parallel to the reactor core. Based on the assessments, shield design a) provides a sufficient protection of the colony and sensitive components.

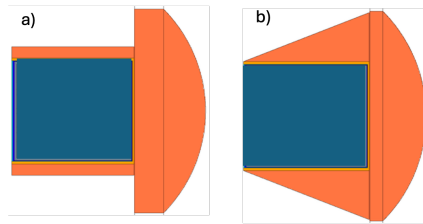


Figure 3. Shield a) has a straight shield line parallel to the side of the reactor, while shield b) is defined by sides sloping such that tracing their angle touches the outer edge of the colony.

In parallel, several material combinations for the shield were selected using a simplified model. In this model, a shielding block with a fixed mass made of different materials was placed in front of the reactor while neutron fluence and gamma dose in silicon were calculated at 2 and 5 meters after 10 years of the reactor operation. Figure 4 and Figure 5 show the neutron fluence and gamma dose for the different materials at 2 m.

Based on this analysis several material candidates were selected. The corresponding shield concepts with optimized shield head are shown in Figure 6 – a) LiH canned in HT-9 and LiH-40% wt% WC composite canned in HT-9; b) multi-layer LiH, B₄C, and WC; c) multi-layer BeO, B₄C, and HT-9; and d) WC (70% wt%)/B₄C (30 wt%) composite.

All options were close in terms of the shielding performance except the multi-layered design using BeO, B₄C, and HT-9. However, any reactor component design involves multi-physics and should include manufacturing and assembly considerations. Based on the review of the existing shielding benchmarks, radiation testing should be performed for all the materials used in these shielding designs to validate the obtained results. Table I reflects a comparison of the shield mass and absorbed doses (deposited energy) at specific locations for the selected shields. In order to obtain the dose equivalent to understand the radiation impact on humans, these values must be multiplied by the quality factors reflecting the radiation type.

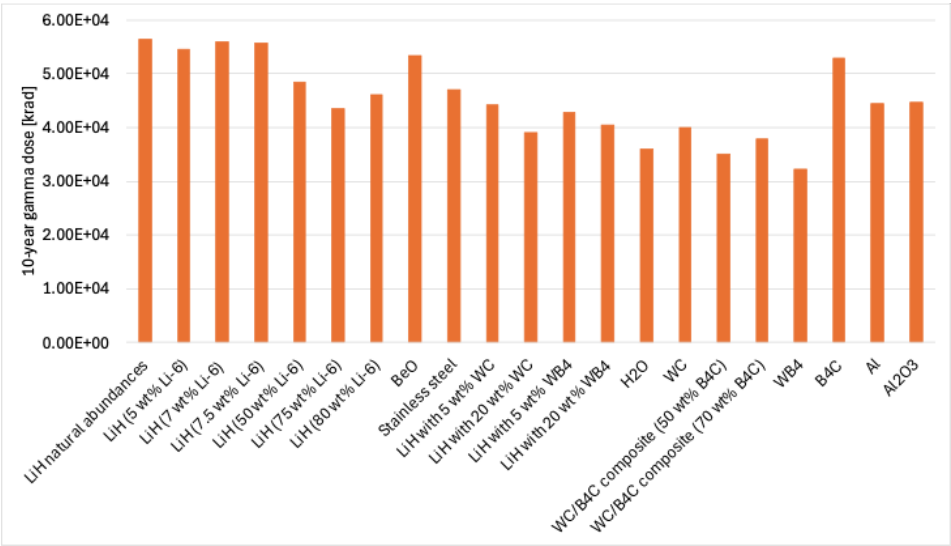


Figure 4. Gamma 10-year dose in silicon at 2m

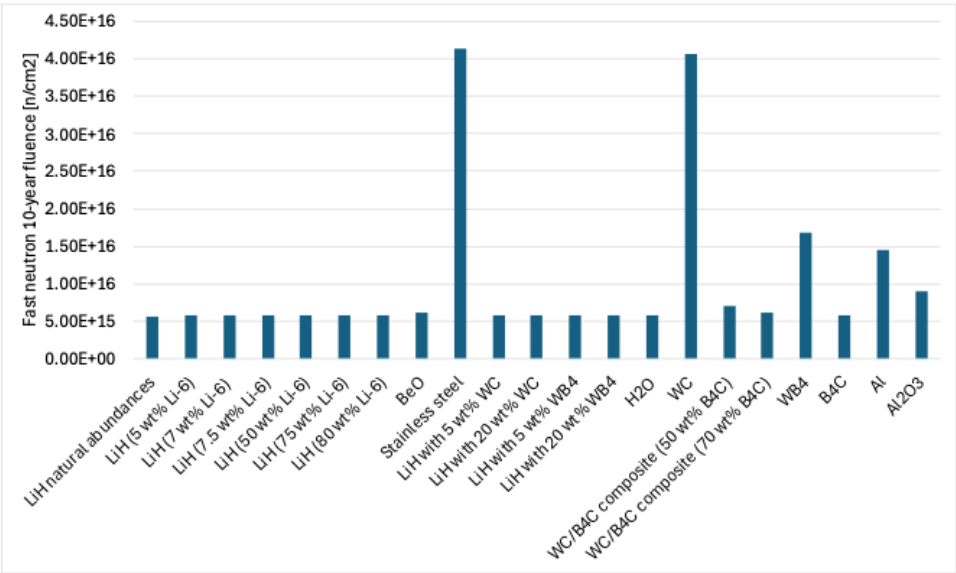


Figure 5. Fast neutron 10-year fluence at 2m

a)

b)

c)

d)

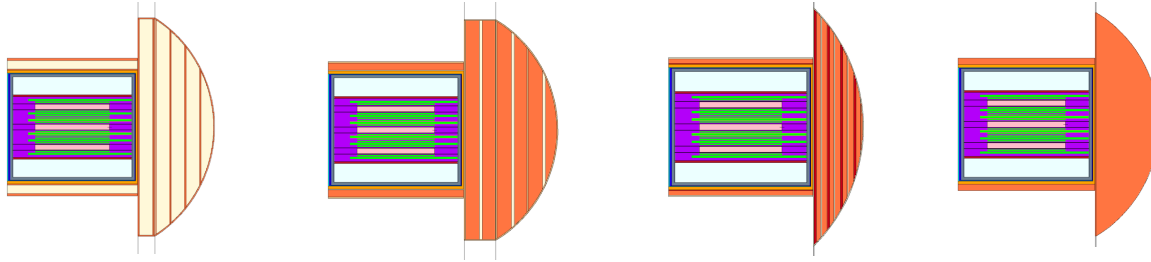


Figure 6. Several Shield Design Concepts for the Most Effective Shielding Materials (a) LiH canned in HT-9 and LiH-40% wt% WC composite canned in HT-9; b) Multi-layer LiH, B₄C, and WC; c) Multi-layer BeO, B₄C, and HT-9; d) WC (70% wt%)/B₄C (30 wt%) composite)

Table I. Comparison of Shielding Designs (Positions 1-5 are defined in Figure 2)

Shield Design	Mass [kg]	Pos 1 Neutron / Photon [rad/ decade]	Pos 2 Neutron / Photon [rad/ decade]	Pos 3 Neutron / Photon [rem/ year]	Pos 4 Neutron / Photon [rem/ year]	Pos 5 Neutron / Photon [rem/ year]
LiH canned in HT-9	1300	1.37E+12 5.72E+14	3.71e+9/ 1.13E+12	0.428/ 4.761	0.12/ 2.08	0.12/ 1.73
LiH-40% wt% WC composite canned in HT-9	1500	1.48E+12 5.21E+14	3.84E+9/ 9.95E+11	0.549/ 4.28	0.17/ 1.88	0.167/ 1.70
Multi-layer LiH, B ₄ C, and WC	1500	2.57E+12 2.22E+14	5.5E+9/ 4.76E+11	1.941/ 2.015	0.682/ 0.903	0.721/ 0.805
Multi-layer BeO, B ₄ C, and HT-9	1800	2.11E+13 3.83E+14	1.52E10 5.78E+11	3.21/ 1.94	1.65 / 0.91	1.13/ 0.78
WC (70% wt%)/ B ₄ C (30% wt%) composite	1500	2.81E+12 2.71E+14	5.93E+9 5.88E+11	2.28/ 2.41	0.79/ 1.07	0.86/ 0.96

4.2. Thermal Analysis

Shielding components will surround the high temperature reactor core. It is assumed that the temperature of the core will be at least 800 °C. In addition to the high temperature, it is expected that the FSP reactor will operate for 10 years. While the neutron flux is not high due to the low power, the operating conditions are challenging for the materials. In order to identify the best shielding option, it is necessary to know the temperature and stress distributions in the shield to compare them with the material limits.

In the frame of this project, a model for the thermal and mechanical analyses was developed and the initial thermal analysis was performed. The model was created in Abaqus [6]. The material properties were defined based on the information available at LANL, as well as data from public sources. The initial analysis was performed only for lithium hydride because this material and its composites are the most challenging candidates for the shield due to the relatively low temperature limits above which the material performance will start to degrade. According to recent studies [7], lithium hydride components will be susceptible to mechanical failures above 400 °C. In addition, lithium hydride is susceptible to radiation damage which may lead to swelling and can contribute to potential component failures. These component failures may also result in damage to the shield structure, which can create pathways for neutron streaming and increased doses near the reactor over time.

Figure 7 shows the temperature distribution in the shielding components. Based on the results, the shielding components surrounding the core body should maintain their mechanical integrity under irradiation at least up-to 700 °C. The exact margin must be defined based on the detailed studies supported by the tests. The shield head has a wide temperature distribution requiring selection of the shield materials and their order to consider not only the radiation transport analysis, but also the thermo-mechanical performance of the shielding components. Another area for consideration is the introduction of insulating and/or cooling components into the shield; however, this may increase the mass of the shield while also adding complexity to the system, which may prove to be a significant contributing factor for potential mechanical failure.

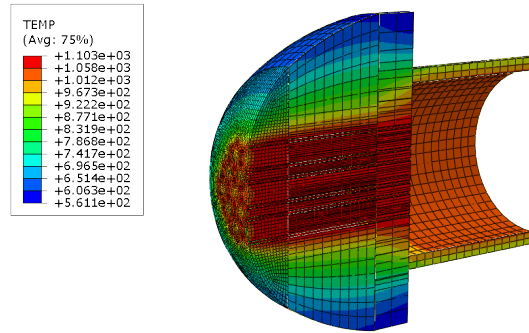


Figure 7. Cross Section of the Shield and Core Showing the Temperature Distribution in Kelvin

Another issue that has to be assessed and addressed is the difference in thermal expansion coefficients among the different materials of the shield and the components that are surrounded by the shield. For example, the lithium hydride coefficient of thermal expansion (CTE) varies from 0 cm/(cm °C) at around -250 °C to around 7×10^{-5} cm/(cm °C) [8]. According to [9], HT-9 does not have a linear thermal expansion coefficient, and it varies from 1.1×10^{-3} cm/(cm °C) at 126 °C to 1.13×10^{-2} cm/(cm °C) at 926 °C while the SNAP-10A report on the shield design [2] indicates that the coefficient of thermal expansion of LiH is approximately 2.5 times greater than that of 300-series stainless steel. For the SNAP-10A, a spring-loaded system was used to support and position the lithium hydride component in the shield casing and accommodate relative thermal expansion between the hydride and the casing made of stainless steel.

5. MANUFACTURING ASSESSMENT

Manufacturing and supply chain assessment was done in parallel to the modeling and simulation work. Lithium hydride (LiH) is an attractive reactor shielding material due to its lightweight and high hydrogen content and neutron shielding properties. However, lithium hydride is an air sensitive material that will form lithium hydroxide when exposed to moisture and typically requires controlled atmospheres for processing and handling, such as gloveboxes. Material compatibility and processing pathways is a major consideration in composite approaches with LiH, as the processes/temperatures needed for densification for some materials could cause issues for LiH. As for the SNAP-10A project, a design including lithium hydride or its composite will require canning of the material. It is convenient to use materials, such as stainless steel or tungsten for canning because they will also provide a gamma attenuation function, but the can material effects as well as air gapping within the can for the CTE tolerancing would need to be considered. From the manufacturing viewpoint, it is preferable to have relatively small LiH or LiH/WC composite blocks. The canning approach, the support system, and the LiH/WC composite manufacturing process still require substantial development and testing work. The same will be relevant for the LiH-based components in the multi-layered shield design.

BeO-based components have several issues stemming from a rather limited supply chain, difficulties with manufacturing, and significant health and safety concerns associated with the handling of beryllium.

Boron carbide and tungsten carbide are attractive materials for shielding applications because of their mechanical and thermal stability in conjunction with their neutron and gamma shielding capabilities, respectively. The raw materials to produce boron/tungsten carbide components are commercially available, which makes production readily accessible. The carbide components can be connected together without much concern for interfaces. There are also fewer concerns from environmental compatibility standpoints. The shield design made of WC/B₄C composite is the design that is “ready today” assuming the material for this design could be assembled. A commercial supplier may be able to machine the required tiles or bricks.

6. CONCLUSIONS

The lightest shielding design with good radiation protection performance is LiH canned in HT-9. However, its manufacturing and thermo-mechanical performance still require significant research and development. Other shields including LiH are heavier by 200 kg and have similar performance issues due to the presence of LiH. The multi-layered BeO, B₄C, and HT-9 design is the heaviest concept. The WC (70% wt%)/ B₄C (30% wt%) composite design is heavier than the LiH canned in HT-9 concept by 200 kg, but it can be manufactured today. Also, presently, it does not have significant concerns regarding its thermo-mechanical performance at the expected temperature range under irradiation. All the materials considered are lacking radiation data to validate the modeling results and establish margins. Based on this assessment, there are several feasible shield design options. The selection of an appropriate shield design should be predicated on mission requirements, budget, and time constraints. Additional multi-physics studies have to be performed for any of the aforementioned shield designs explored within this brief assessment.

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