Optimization of Space Nuclear Reactor Shielding through Computational Analysis

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Introduction

Nuclear reactors emit ionizing radiation that can be harmful to people and electronic equipment. Shielding materials that attenuate this radiation (Fig. 1) can be a significant fraction of the mass of a space nuclear reactor power system (Craft et. al., 2010). Optimizing space reactor shielding geometry and composition allows the design of shields that can reduce neutron and gamma-ray doses from the reactor to an acceptable level using the minimum amount of shielding material. This project is generating software that will allow the user to test arbitrary compositions and geometries for space reactor applications. This software will allow for the streamlining of the design process for space reactors by allowing engineers to computationally model and test shielding compositions and geometry before spending money and resources on testing a physical model.

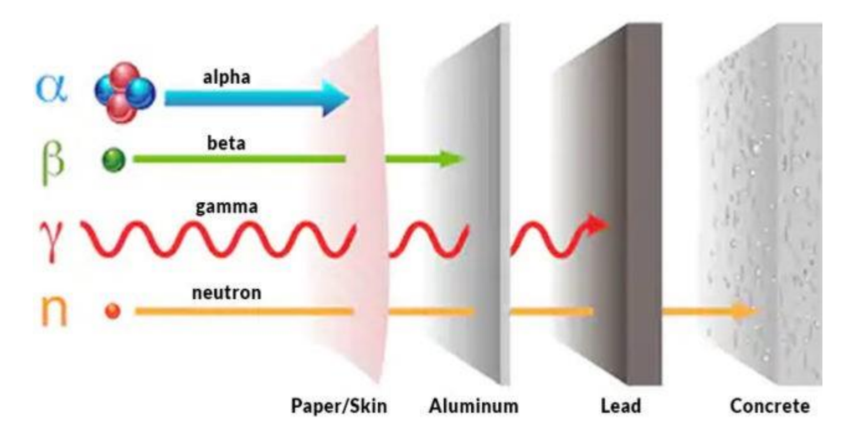

Fig. 1 – Examples of nuclear radiation and materials that attenuate them (ARCAT, 2019).

Methods

This project is creating a program to predict the ability of shields of arbitrary compositions to attenuate neutrons and gamma rays at arbitrary energies at several shielding thicknesses using OpenMC. OpenMC is an open-source Monte Carlo-based code that probabilistically models the movement of neutrons and photons as they interact with a custom environment (Fig. 2).

The shield can be composed of up to five layers, each comprised of user-specified materials. The geometry of the shield is determined by the thickness of the layers as well as the rise and fall angles of the truncated cones. The source strength can be defined as either a neutron, gamma-ray, or combined radiation source. The source is modeled as a point source inside of a beryllium reflector to mimic space reactor radiation distribution (Fig. 3). Once all components are specified, the simulation runs and collects relevant data.

Simulation Flowchart

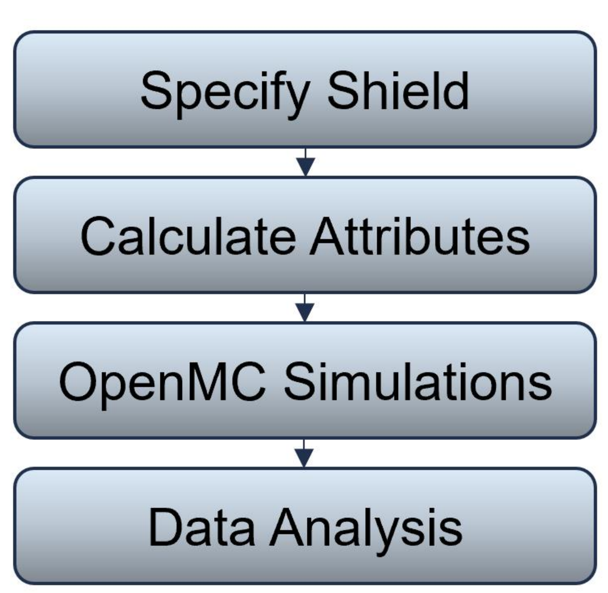

Fig. 2 – A flowchart of program processes

Shadow Shield Geometry

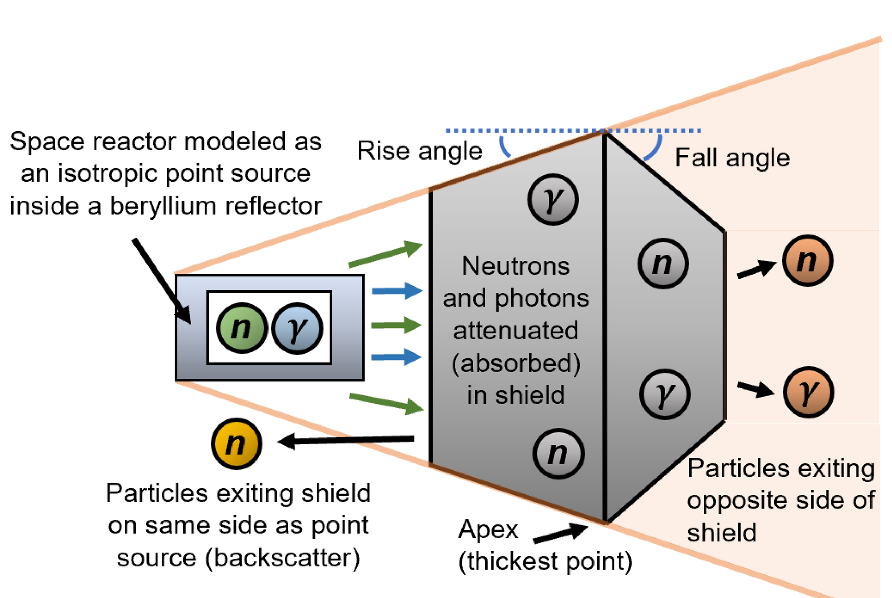

Fig. 3 – The OpenMC simulation geometry.

OpenMC tracks particles and collects data, a Jupyter notebook script manages the code for the OpenMC simulations, and Anaconda Navigator manages the computing environments.

The Chart of the nuclides (KAPL, 2010) provided the abundances and atomic weights for the isotopes used in the composition calculations.

Results and Discussion

This project will estimate shielding effectiveness by estimating dose in various areas in the shadow of the shield. Dose is a measurement of radiological damage to a material and can vary based upon what that material is. For example, dose will be measured differently if biological tissue is exposed to radiation than if electronics are exposed to radiation. In this experiment, dose will be measured in mrem/hr. For radiation to be safe, the dose in an area must be less than 5 mrem/hr.

The most effective shield will likely be composed of, at minimum, three layers. The first and third layers will be neutron absorbers, such as lithium hydride (LiH), enriched lithium hydride, or boron carbide (B_4C). The middle layer will be an effective gamma-ray attenuator, most likely tungsten (W). The gamma-ray attenuator must be placed in the middle of the shield after a sufficient thickness of neutron-absorbing material, for high-energy neutrons can emit tremendous amounts of gamma-ray radiation if they interact with tungsten (Fig. 5). The shield must first absorb or attenuate the neutrons to reduce their energy before the tungsten layer of the shield is reached.

Thus, the placement of the tungsten layer in the shield is critical to the performance of the shield. In addition to greatly impacting overall radiation attenuation ability, the placement of the tungsten layer can greatly impact mass. Placing the layer closer to the apex of the shield will increase shield mass, which could be a major drawback (Fig. 4).

Once the program is complete, we will run 3-layer, 4-layer, and 5-layer simulations for shields with a total thickness of approximately 50 cm. We will do many iterations in which we modify the thickness of various layers as well as the placement of the tungsten layer to determine the lightest and/or thinnest shield that reduces dose to 5 mrem/hr or less.

At this time, we have no data to fully complete this analysis.

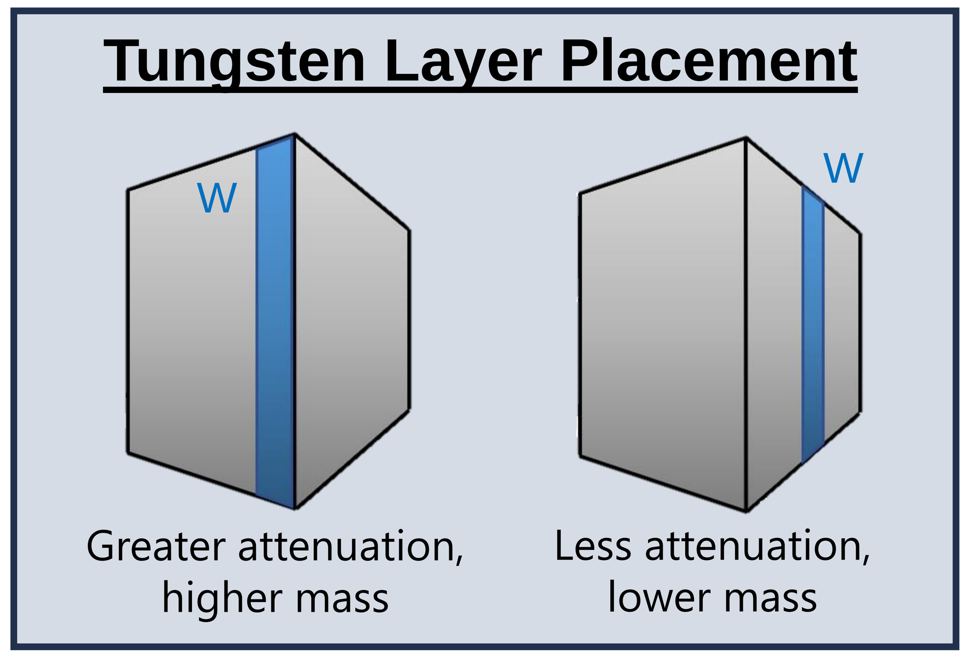

Fig. 4 – A visualization of the impact of the tungsten layer on the mass of the shield.

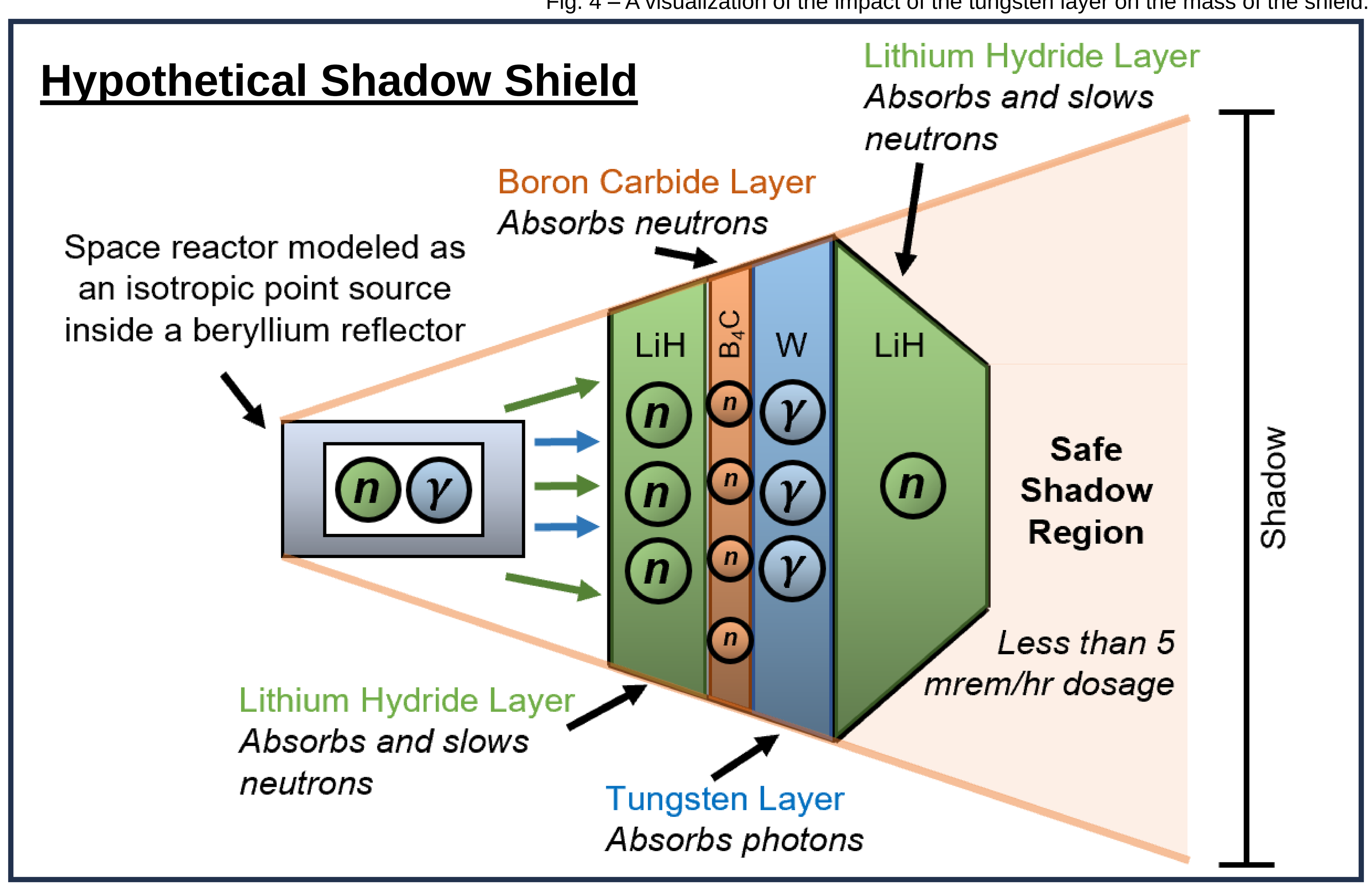

Fig. 5 – A hypothetical shield geometry designed to effectively attenuate both neutrons and gamma-rays.

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Conclusions

We anticipate a multi-layer shield comprised of tungsten, lithium hydride, and boron carbide will make an effective shadow shield for a space reactor.

- Mass may be negatively impacted by placement of tungsten layer
- Data collection will show optimum geometry and tungsten placement for mass optimization as well as dose minimization
- Variation in the layer thicknesses of each layer may allow for further mass optimization
- Variation in the rise and fall angles may allow for further mass optimization while maintaining a safe dosage in the shadow region

Future Study

- Complete current model to collect relevant data to study mass optimization and overall effectiveness of the modeled shield
- Measure dose over a mesh surface to study non-uniform dose distribution in the shadow region
- Increase complexity of the space reactor model to improve accuracy of radiation distribution
- Include optimization opportunities for overall shielding thickness in addition to mass and dose optimizations for a single thickness
- Analyze how variation in the rise and fall angles of the shield can also optimize overall mass of the shield without compromising functionality

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