Neutronics Design Optimization of a Heat Pipe Cooled Micro Modular Fast Reactor Using OpenMC

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Abstract

Very small modular nuclear reactors (vSMR), or micro-reactors, are identified as a potential means to provide reliable and cost-effective power between 1 and 10 MWe for remote installations. The paper presents a neutronic optimization study of a sodium heatpipe-cooled Micro Modular Reactor (MMR) design that has been simulated using the Monte Carlo method. As a high-fidelity open-source Monte Carlo code, OpenMC has been used to simulate the neutron flux distribution, power and burnup of the reactor core using the ENDF-B/VII.1 data library.This Micro Modular Reactor is a 30KWe power reactor with a 20-year lifetime without refuelling, designed to operate in a fast spectrum with TRISO fuel. TRISO particles are the leading-edge nuclear fuel form that is structurally more resistant to neutron irradiation, corrosion, oxidation and high temperature than traditional reactor fuel. TRISO fuels comprise thousands of micro-encapsulated uranium-bearing fuel kernels and are individually coated with multiple layers of pyrolytic carbon and silicon carbide that act as containment for the fuel and fission products. The paper shows the study of a hexagonal unit cell with a sodium-cooled heat pipe in the center surrounded by the TRISO particles embedded in a beryllium matrix and the effect of different absorbing materials on the full core.

1. INTRODUCTION

In the realm of nuclear engineering, the quest for innovative and efficient energy solutions continues to drive advancements in reactor design and technology. Among emerging concepts, very Small Modular Reactors (vSMRs), colloquially referred to as Micro Modular Reactors (MMRs), have garnered significant attention as a promising avenue for delivering reliable and cost-effective power to remote locations. This paper presents a comprehensive exploration of the neutronic design optimization of a heat pipe-cooled MMR, leveraging state-of-the-art simulation techniques with OpenMC. With a focus on safety, efficiency, and sustainability, our study delves into the intricacies of TRISO fuel and beryllium matrix utilization, drawing inspiration from pioneering concepts such as the Los Alamos National Laboratory (LANL) Mega-Power design[1]. TRISO particles have been used because they can be used in a very high-temperature reactor without conflicting any safety issues[2]. Through meticulous analysis of flux distributions across various energy spectrums, we aim to elucidate the viability of our proposed MMR design for operation within a fast energy spectrum. By shedding light on the potential of heat pipe-cooled MMR technology, this research contributes to the ongoing dialogue surrounding the future of nuclear energy and its role in addressing global energy challenges.

To design the reactor model, simulate, and analyse results, we used OpenMC, a community-developed Monte Carlo neutron and photon transport simulation code. It is capable of performing fixed source, k-eigenvalue, and subcritical multiplication calculations. Comparatively easy to build models using either a constructive solid geometry or CAD representation. As a high-fidelity open-source Monte Carlo code, OpenMC has been used to simulate the neutron flux distribution, power and burnup of reactor core using ENDF-B/ VII.1 data library.

2. GEOMETRY OF MICRO MODULAR REACTOR

2.1 Unit cell

The centrepiece of our research is the 30KWe Micro Modular Reactor, meticulously engineered for a remarkable 20-year lifespan without the need for refuelling. Operating within a fast spectrum, this innovative reactor harnesses the unparalleled capabilities of TRISO Fuel, representing the pinnacle of nuclear fuel technology. TRISO particles demonstrate exceptional resilience to the rigours of neutron irradiation, corrosion, oxidation, and high temperatures[3]. Each TRISO fuel pellet is a marvel of engineering, housing thousands of micro-encapsulated uranium-bearing fuel kernels. These kernels are meticulously enveloped in layers of pyrolytic carbon and silicon carbide, providing inherent containment and ensuring operational safety.

At the heart of our reactor's design lies a hexagonal unit cell, cradling a sodium-cooled heat pipe, enveloped by TRISO particles seamlessly integrated within a beryllium matrix. By harnessing the unique properties of TRISO particles, we eliminate the need for additional fuel cladding, mitigating the risk of single-point failures within the pressure vessel or fuel cladding. This design approach not only enhances operational safety but also streamlines reactor efficiency, paving the way for sustainable and resilient nuclear energy solutions.

In Figure 1, a cross-sectional view of a single fuel element, offers a glimpse into the intricate design and advanced engineering principles that underpin our innovative reactor concept. This specific unit cell pitch length(flat to flat) is 5.2cm and the edge length (side length of the hexagon) is 2.986cm.

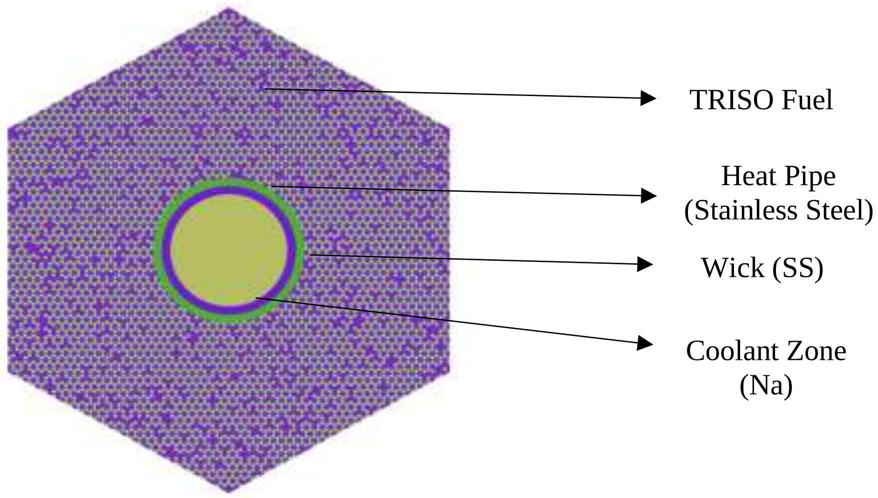

Figure 1: Cross-sectional view of a unit cell of hexagonal fuel matrix (pitch 5.2 cm).

Figure 1 depicts relevant preliminary materials associated with the fuel element of a unit cell. The heat pipe is characterized by an inner diameter of 1.575 cm and an outer diameter of 1.775 cm, with a wall thickness of 1.0 mm. All materials utilized in constructing this unit cell consist of high-temperature ceramic metals.

2.2 Full core with control drum

The core's defining feature is the heat pipe, with each heat pipe inserted into a hexagonal fuel element. As shown in Figure 1, each unit cell comprises a heat pipe working fluid surrounded by TRISO particles embedded in a beryllium matrix. The active core, illustrated in Figure 2, consists of 462 of these unit cells arranged in a hexagonal shape.

The core is encircled by an aluminum oxide (Al2O3) reflector, which contains 12 rotatable control drums surrounding the core. These control drums can face inward or outward to regulate the core's reactivity. Additionally, there is a control rod with a diameter of 19 cm at the center of the core, which can be inserted or withdrawn as needed to maintain criticality. Each control drum has a diameter of 24 cm and is placed within the reflector material that surrounds the core, with the reflector having a total diameter of 188 cm.

Furthermore, focusing on sustaining fast energy nuclear reactions, the design of a complete core without control devices has been formulated and is presented below in Figure 2.

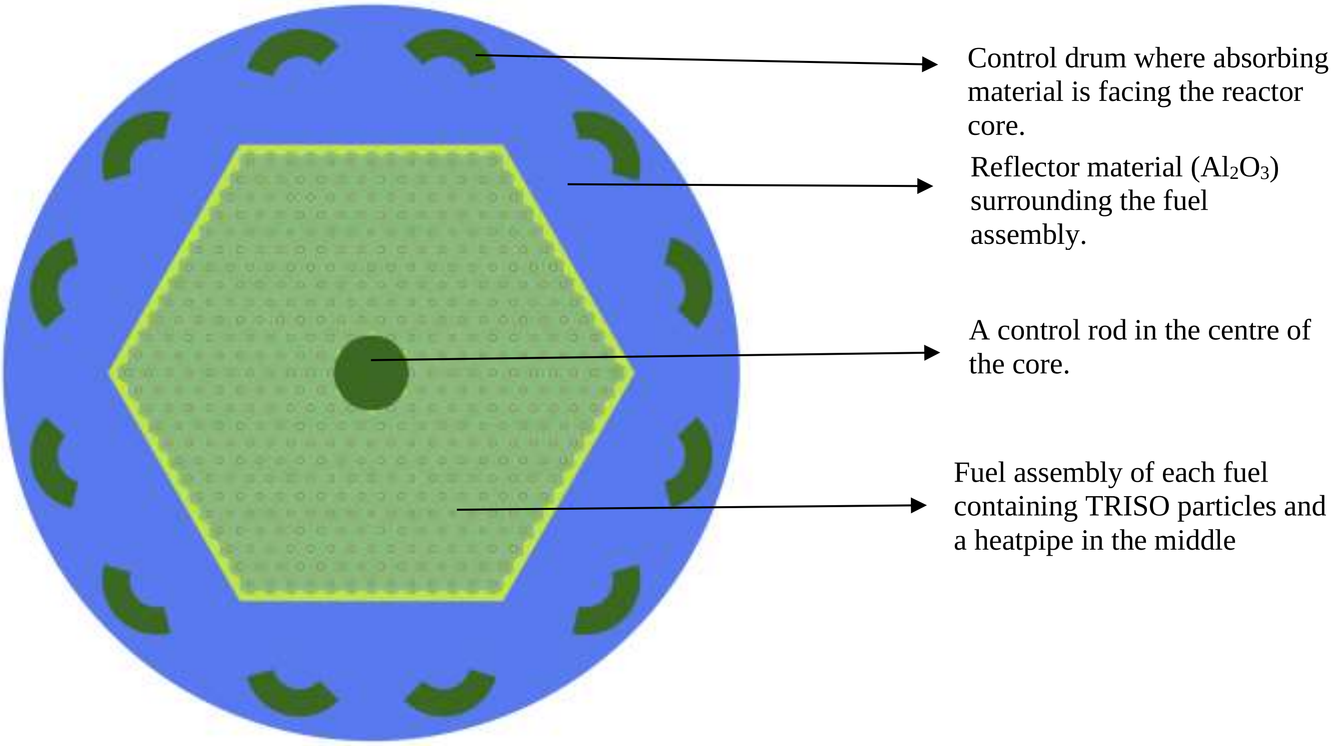

Figure 2: Design of a full core with control devices.

3. RESULT AND DISCUSSION

3.1 Unit cell

With a focus on neutronic characteristics, the optimization of the unit cell's geometry has been undertaken. Achieving criticality necessitated the calculation of various pitch sizes and exploration of different potential fuel matrices before settling on beryllium for this reactor design. Below, results obtained for different matrix materials, analyzed to understand neutron reactions within various materials containing TRISO particles, are presented. These analyses were conducted with a pitch size of 2.8 cm.

Table 1: Study of different matrix materials containing TRISO particles in the fast energy spectrum

Matrix Material	K-eff value
Stainless Steel	0.85836
Zircaloy	0.90242
HT9 alloy	0.9084
He	1.03861
Graphite	1.00119
Lead	1.01376
Beryllium (Be)	1.03161

From the analysis of the table results, it is evident that He, graphite, lead, and beryllium emerge as viable options as matrix materials. However, it should be noted that He, being a gas, lacks the capability to effectively contain TRISO particles as a matrix material. While graphite is commonly employed as a matrix material due to its favourable properties, its strong moderating effects make it unsuitable for this specific reactor design intended to operate in a fast spectrum. Similarly, lead, although a solid material, poses practical challenges in containing TRISO particles within its matrix.

On the contrary, beryllium, being in powder form, presents itself as a promising matrix material. Notably, beryllium boasts remarkable neutronic properties, characterized by neutron reflection and multiplication rather than absorption, earning it the moniker of a neutron multiplier.

To ensure the criticality of the reactor, the unit cell must attain supercriticality to allow for supporting structures not implemented in the unit cell. Consequently, various pitch sizes have been computed utilizing a beryllium matrix. The results of eigenvalue calculations for a unit cell, conducted using OpenMC, are presented in Figure 2.

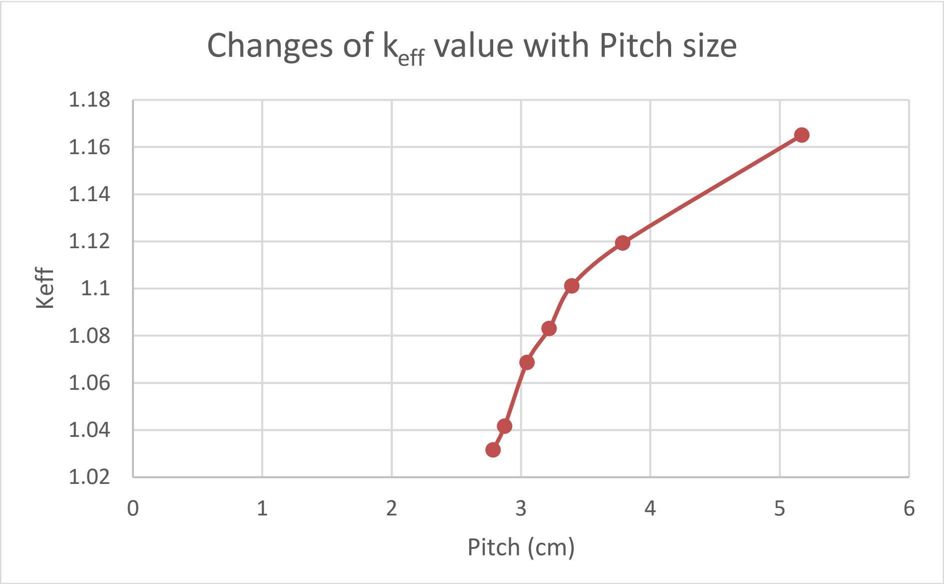

Figure 3: Calculating the pitch size of the unit cell to make the reactor supercritical.

Considering the outcomes, the pitch has been designated at 5.2 cm. Additionally, an in-depth examination of the flux distribution and normalized flux distribution within the unit cell has been conducted.

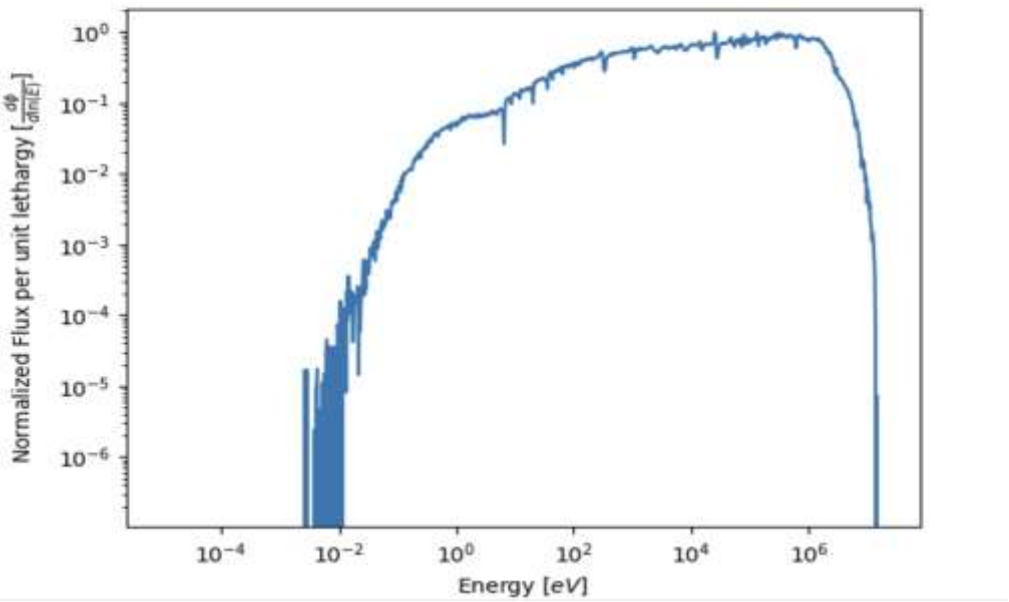

Figure 4: Normalized lethargy flux spectra

Through scrutiny of the lethargy flux spectra and normalized distribution, it becomes apparent that neutron reactions operate within a fast energy spectrum. Figure 3 illustrates the neutron spectra in terms of lethargy flux, while Figure 4 depicts the normalized lethargy flux spectra.

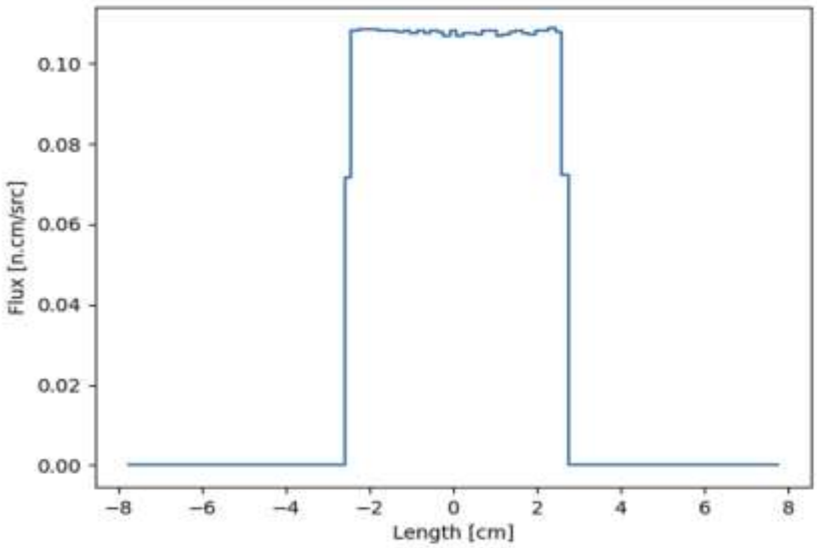

Figure 5: 1D radial flux picture for a unit cell with 5.2cm pitch.

For the visualization of this 1D radial flux depiction, a 100/100 mesh has been constructed for both the x and y axes within a unit cell. At y = 50, the 1D flux depiction is radially plotted across the x-axis for an energy limit ranging from 100 to 10^6 eV, offering insights into the fast energy flux through a 1D plot.

3.2 Full core

To make sure that the specific MMR operates in fast spectrum, a 1D plot is presented to corroborate that the majority of neutrons engage in reactions within the fast energy spectrum where neutron flux frequency verses energy plot is shown in Figure 4.

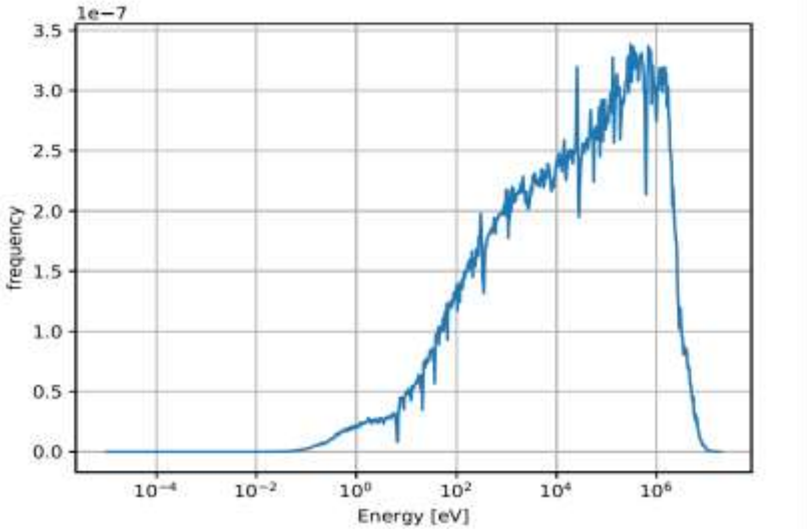

Figure 6: Neutron energy distribution in fast energy range.

This Micro Modular Reactor (MMR) features a hexagonally shaped core containing 462 fuel elements and a cylindrical control rod at its center. Surrounding the core are twelve control drums embedded within an Al_2O_3 reflector. These control drums are rotatable, with one side covered in an absorbing material. This design allows for precise control over the reactor’s operation, enabling either sustained, controlled operation or the creation of a subcritical state by positioning the absorbing material towards the core. By rotating the control drums such that the absorbing material faces the reactor, the reactor can be effectively controlled or shut down. Additionally, the control rod can be inserted into or withdrawn from the core as necessary. Following calculations have been done to determine the effectiveness (worth) of the control rod and control drums, and the results are presented in Table 2.

We performed calculations to determine the effectiveness (worth) of the control rod and control drums, and the results are presented in Table 2.

Table 2: Reactivity calculations of the core with and without absorbing material.

Absorbing Material	Without absorbing material k_{eff}	k_{eff} (k1) value Inserting the Control rod in the centre of the core	Change of reactivity ρ_1 (mk) =((k1-k)/(k1*k))*1000	k_{eff} (k2) value Rotating the Control drums inward the core	Change of reactivity ρ2(mk) =((k2-k)/(k2*k))*1000	k_{eff} (k3) value Inserting Control Rod and rotating the Control Drums inward	Change of reactivity ρ3(mk) =((k3-k)/(k3*k))
Hafnium hydride (HfH_2)	1.06304	0.96737	-93.0323	0.99621	-62.6286	0.90071	-169.537
Europium Oxide	1.06280	0.98891	-70.3036	0.99890	-60.0581	0.90739	-161.151
Ag-In-Cd	1.05011	0.99402	-53.7348	1.00953	-39.0118	0.92831	-124.945
Cd	1.06301	1.01363	-45.8284	1.02171	-39.6954	0.96887	-91.4053
Gd_2O_3	1.05835	1.00699	-48.1915	1.01632	-40.3609	0.93579	-123.749
Dysprosium Titanate ($Dy_2T_2O_7$)	1.05679	1.01280	-41.1	1.00719	-47.272	0.94276	-114.454
Boron Carbide (B_4C)	1.05949	1.00121	-54.9411	1.00876	-48.301	0.91633	-147.46

Table 2 presents a comparative analysis of different absorbing materials used to determine the effectiveness (worth) of the control drums surrounding the core and the control rod positioned at the core's center. Based on the Eigenvalue simulation results and subsequent calculations, hafnium hydride emerged as the most effective absorbing material.

To evaluate the impact of the control rod and control drums on the reactor's active flux, additional calculations were performed, with the results illustrated in Figures 7 and 8. Figure 7 displays the one-dimensional (1D) flux distribution, highlighting how the core flux is altered by the insertion of the control rod. The pronounced peak in the center of the 1D flux distribution indicates significant neutron absorption by the inserted absorbing material.

Additionally, the gradual decrease in the flux spike is attributed to the influence of the control drums surrounding the core.

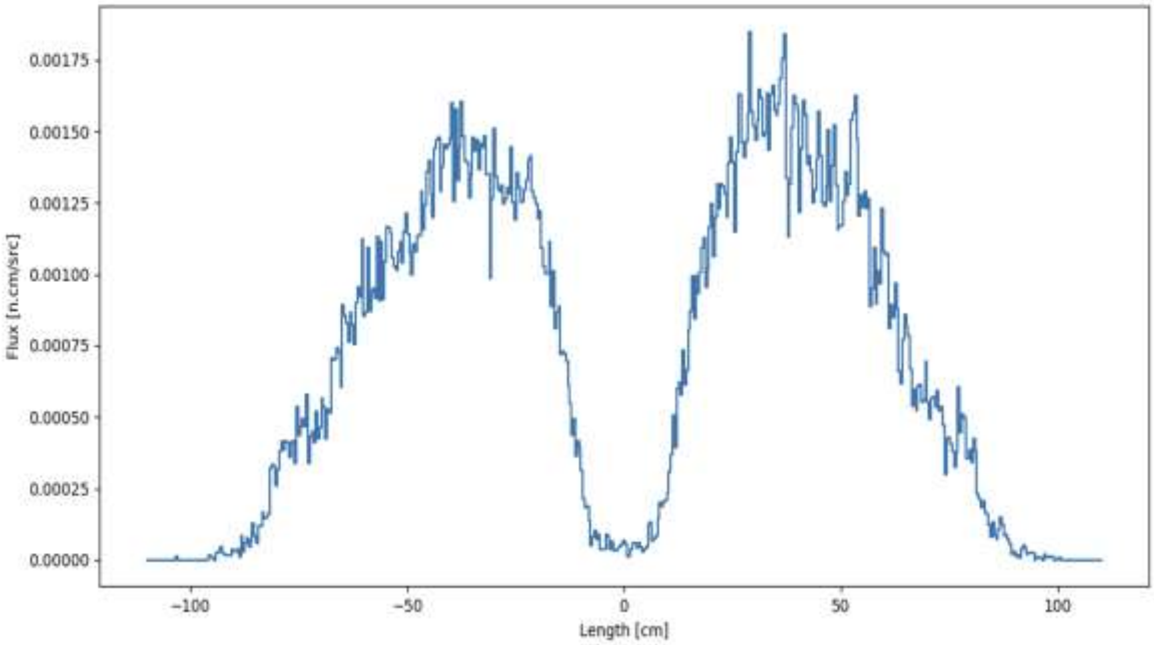

Figure 7: 1D plot of radial flux changes of full core inserting control rod in the middle of the core.

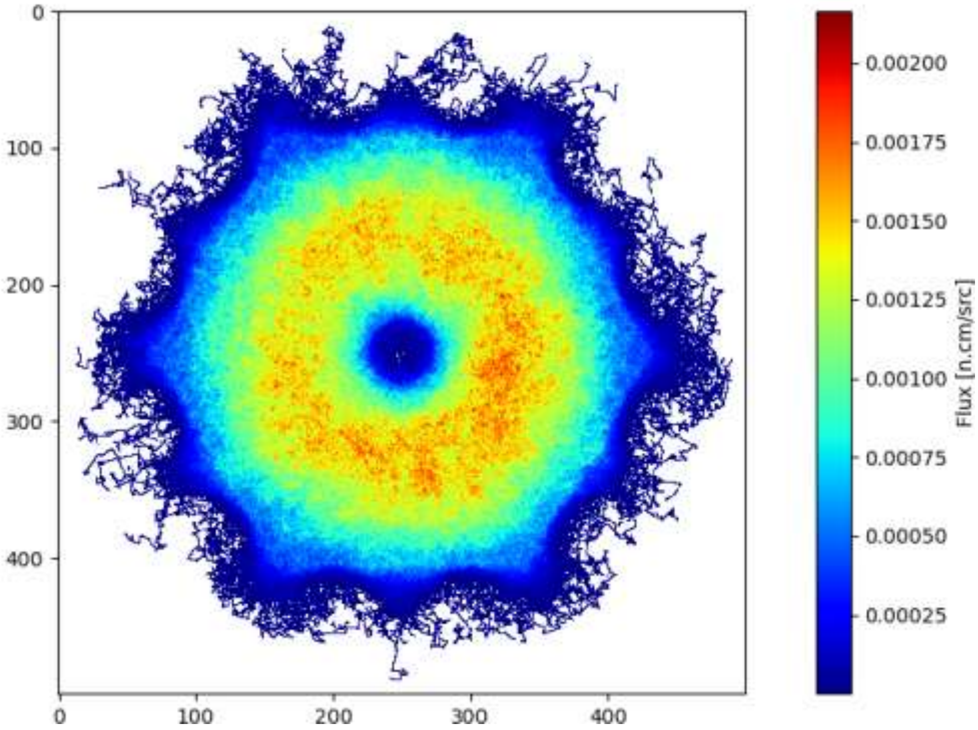

Figure 8: 2D plot of the normalized flux distribution of full core.

The phenomena observed in Figure 7 can also be illustrated in a two-dimensional (2D) plot, which provides a detailed view of the normalized flux distribution. Figure 8 depicts how the flux changes upon the insertion of a control rod in the center of the hexagonal core, as well as the effect of the control drums surrounding the core, oriented inward. This 2D representation offers a comprehensive visualization of the flux behavior within the reactor core.

4. CONCLUSION

In conclusion, the neutronic optimization study presented in this paper highlights the potential of sodium-cooled Micro Modular Reactors (MMRs) as a reliable and cost-effective power solution for remote installations. Utilizing advanced simulation techniques with OpenMC, we have demonstrated the efficacy of TRISO fuel and a beryllium matrix in enhancing reactor safety and efficiency. The detailed analysis of flux distributions across various energy spectra further substantiates the suitability of the proposed design for operation in a fast energy spectrum. These findings provide a robust foundation for the continued development and deployment of MMR technology, offering a promising pathway toward sustainable and resilient energy solutions for the future.

Future work will include power distribution and burn-up calculations, which will be integrated into subsequent iterations of this paper.

5. FURTHER INFORMATION

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