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NEUTRONIC EVALUATION OF A MICRO REACTOR BASED ON THE KRUSTY PROJECT

Gabriel B. Domingos[1], Claubia Pereira[1], Clarysson A. M. Silva[1]
[1]Departamento de Engenharia Nuclear, UFMG, Departamento de Engenharia Nuclear
(Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Campus UFMG, PCA 1, Bloco 04, Anexo Engenharia, Pampulha, 31270-90 Belo Horizonte, MG, Brazil)
gb17491@ufmg.br

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ABSTRACT

Microreactors are classified as Small Modular Reactors with a power output of up to 10 MW(e). They can operate as part of the electric grid or as part of a microgrid and have advantages such as industrial production, transportability, quick supply of demand, and requiring few personnel for operation and maintenance. The present work focuses on studying the use of different fuel types for a microreactor, using the KRUSTY project as a reference. The conventional proposal uses UMo with an enrichment of 93.1%, and the current study aims to evaluate distinct fuels while limiting the enrichment to 19.9% due to proliferation issues. The simulations were carried out using MCNP6, which calculates the neutronic parameters. Firstly, the conventional model was simulated by the code to compare the results with previous works. Then, the fuel composition and geometry were adjusted to achieve reactor criticality. In these analyses, UMo and UPuMo were evaluated using enriched U, depleted U, and Pu matrix from a typical PWR burn. Regarding the results, the conventional KRUSTY model simulated by MCNP6 presents good agreement with previous studies. The reactor with UMo enriched to 19.9% becomes subcritical, but using UPuMo it is possible to achieve reactor criticality.

1. INTRODUCTION

In recent years, Microreactors have generated significant interest in the scientific community due to the intrinsic characteristics of small nuclear systems, leading to the development of several projects. The possibility for industrial-scale production, ease of transportation, rapid response to energy demand, minimal operator requirements, and reliable energy generation make these systems attractive to the nuclear industry [1]. They could represent an advancement in nuclear technology, and several companies such as Mitsubishi Heavy Industries, Toshiba Corporation, Westinghouse Electric Company have presented Microreactor projects [2][3]. Also, NASA has performed several experiments aiming to provide a reliable and efficient energy source for future space missions. The Kilowatt Reactor Using Stirling Technology (KRUSTY) consists of the development and testing of a ground technology demonstrator of a 1 kWe fission power system [4][5]. This prototype operated as a fission power system in 2018 and can be considered the first test operation of a Microreactor. Thus, considering available data on KRUSTY, the present work focuses on neutronic analysis of this system. The MCNP6 code was used for steady-state simulations. The KRUSTY employs UMo with 93.1% of ^{235}U, but the current study aims to evaluate distinct fuels, limiting the enrichment to 19.85% due to proliferation issues. Initially, the conventional model was simulated to compare the results with previous studies. Using the data available in the reference work, the simulations compare the effective multiplication factor (k_{eff}) between the MCNP6 model (from this paper) and the MCNP5 model (from previous work). Afterwards, wasevaluated the use of UMo and UPuMo using using enriched U, depleted U, and Pu matrix. Thesefuels have a smaller concentration of fissile isotopes than the proposed NASA fuel, which leads to the reactor becoming subcritical. Thus, the fuel composition and geometry were adjusted to achieve reactor criticality. The next topics present the model simulated in MCNP6, the composition of the fuels evaluated and the neutronic results.

2. METHODOLOGY

2.1. The Simulated System

Initially, in KRUSTY projects, UMo and UZr were proposed as reactor fuel. UMo was chosen due to its experience and experimental data compared to that of UZr. Additionally, Mo has low fast neutron capture and moderate epithermal capture compared to Zr. This feature makes Mo usually better neutronically than Zr [6]. The KRUSTY fuel (UMo) consists of a cylinder with outer diameter of 11 cm and length of 25 cm. It contains a 4 cm hole for B_4C stack aiming to reactivity control. This control rod has an enrichment of 96% in ^{10}B. Fig. 1 illustrates the manufactured fuel (left) and the reactor core constructed by NASA (rigth). This core is surrounded by a neutron reflector, BeO, and is further encased in shield. Between the core and the reflector, there are multilayer insulation (Mo) and a vacuum can (SS316). The radial shield is stainless steel (SS304) and the axial shield contains layers of B_4C and SS304. The KRUSTY uses eight heat pipes (Haynes 230) around the core for coolant circulation (sodium). Tab. 1 presents the main characteristics of the KRUSTY core [3][4][7].

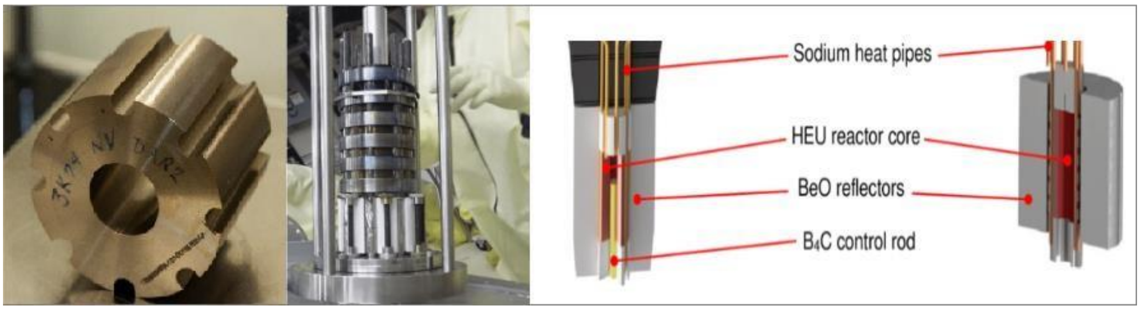

Fig. 1. KRUSTY fuel (left) and core (right).

Tab. 1. Main features of KRUSTY core.

Zone	Material	Density (g/cm^3)	Dimensions (cm)	
Fuel	UMo	17.15	Inner radius	2.0
			Outer radius	5.5
			Heigth	25.0
Control Rod	B_4C	2.15	Outer radius	1.9
			Heigth	12.7
Heat Pipes	Haynes 230	8.97	Inner radius	0.546
			Outer radius	0.635
Reflector	BeO	2.82	Inner radius	7.24
			Outer radius	19.05
			Heigth	30.48
Radial Shield	Sainless steel (SS304)	7.9	Inner radius	20.5
			Outer radius	50.9
			Heigth	63
Axial Reflector	BeO	2.82	Heigth	10.16
			Outer radius	12.7

2.2. MCNP6 Model

The simulated model presents detailed geometry according to the reference descriptions. Concentric cylinders were configured to represent core elements. Eight eccentric cylinders models the heat pipers. Also, multilayer insulation, vacuum can, radial and radial shield were configured. The Fig. 2 depicts the MCNP6 model. In the central core zone, there is a cavity with a radius of 2 cm and a height of 25 cm for inserting the control rod. The fuel region has the same height as the control rod and an outer radius of 5.5 cm. Eight heat pipes with coolant (Na), equally distributed at 45º intervals, encircle the fuel zone. These tubes are radially placed 5.2 cm from the reactor center, and they have an inner radius of 0.546 cm and an outer radius of 0.635 cm, respectively. Heat pipes are fixed by 6 ring clamps (Haynes-230) that are placed 6.06 cm from reactor center. Radial and axial reflectors surrounding the fuel zone and heat pipes. Radial reflector has inner/outer radius of 7.24/19.05 cm and height of 30.48 cm. Both the top and bottom reflectors have a radius of 10.16 cm and a height of 10.16 cm. Surrounding the reflectors is a shield (SS304) with an inner radius of 20.5 cm, an outer radius of 50.9 cm, and a height of 63 cm. Additionally, there are bottom and top plate shields (B4C) each with a thickness of 5.1 cm [3, 4].

The simulations comprise 200 active cycles with 15,000 neutrons per cycle, excluding the first 15 cycles for the convergence of the fission source distribution. With the goal of determining the profile of the radial neutron flux, a superimposed cylindrical mesh was configured in the reactor core, where the code calculates the flux for each cell within this mesh. The operational fuel temperature is (1073 K), however, as mentioned in the reference peak of (840°C), the average of (820°C) was adopted, which is equivalent to (1093 K)[7][8]. Therefore, the NJOY21 code was employed to generate the microscopic cross sections for the model. The simulations use ENDF-B/VII to ensure consistency with the database used in the previous reference.

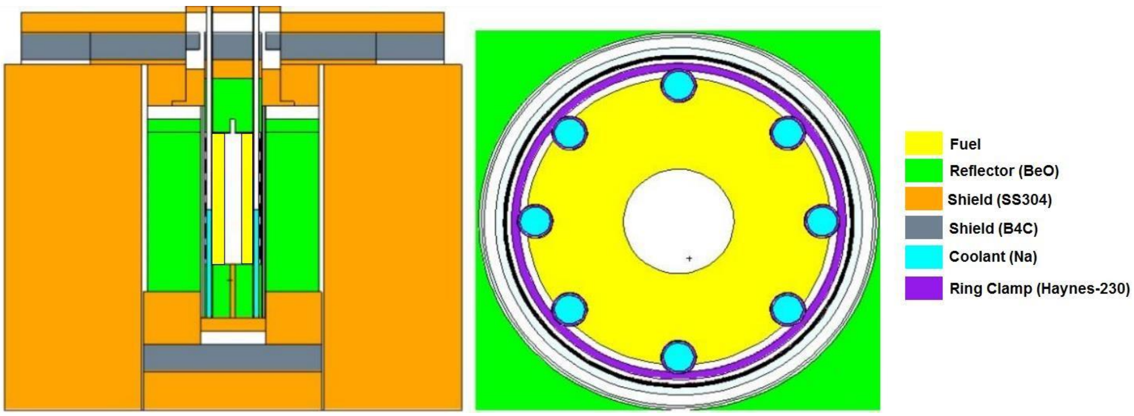

Fig. 2. Axial and radial view of MCNP6 model.

2.3. Evaluated Fuels

The Tab. 2 presents the simulated fuels for which four cases were studied. All of them uses molybdenum in order to maintaining the same metallic alloy as the NASA project fuel. The first case considers the fuel composition of the KRUSTY project, which uses highly enriched uranium (93.1%). The second employs low-enriched uranium with 19.85% of ^{235}U. The third and the forth fuels implement the use of reprocessed plutonium and uranium. The Pu matrix was derived from a spent fuel discharged from a typical Pressurized Water Reactor (PWR) with an initial enrichment of 3.1 % and a burnup of 33 Gwd/MTU. This spent fuel remained in the cooling pool for five years, and after, it was reprocessed by the PUREX technique in which U and Pu are recovery [9]. The difference between Case 3 and 4 is in the uranium enrichment. The Case 3 employ enriched uranium (5.0%) while Case 4 uses depleted uranium (0.20%) from enrichment plant [10]. Furthermore, all fuels were simulated at the operating temperature (1093K), evaluating the reactor's criticality with the control rod completely removed and under SCRAM conditions. Considering that UPuMo may be a viable fuel alternative for fast reactors [11], it was simulated in KRUSTY model.

Tab. 2. Isotopic fuel composition (in weigh percentage) of evaluated fuels.

Element	**Nuclide**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
U	^{234}U	0.93	-	-	-
	^{235}U	86.01	18.33	3.36	0.14
	^{236}U	0.36	-	-	-
	^{238}U	5.05	74.02	66.63	69.85
Pu	^{238}Pu	-	-	0.44	0.44
	^{239}Pu	-	-	10.97	10.97
	^{240}Pu	-	-	3.75	3.75
	^{241}Pu	-	-	3.52	3.52
	^{242}Pu	-	-	1.33	1.33
Mo		7.65	7.65	10.0	10.0
Fissile content in Heavy Metal		93.13	19.85	19.85	16.26
Density (g/cm^3)		17.15	16,90	16,47	16,47

3. RESULTS

The verification of MCNP6 model was performed in previous work [12], where the calculated criticality was compared with that obtained by NASA in their official KRUSTY tests. The MCNP6 presents an effective multiplication factor (k_{eff}) of 1.02374, while the NASA project shows a value of 1.0180 (difference of 574 pcm). In KRUSTY test, the control rod is located at some position at the bottom of the reactor core. This information is not clear in the technical documents, and thus, the MCNP6 model does not include the control rod. This fact may be generating the k_{eff} difference because the presence of the control rod reduces the reactivity, decreasing the discrepancy. However, considering the difference is smaller than 1.0%, the results of MCNP are reliable.

Subsequently, using the verified model, the four fuel types presented previously (Case 1 to 4) were evaluated. Tab. 3 depicts the criticality of these fuels for control rod (CR) position. As expected, the reduction in the fissile content (%) generates a reduction in the reactor reactivity and KRUSTY become subcritical. Then, aiming to achieve a k_{eff} close to that of the KRUSTY project, the conventional geometry was modified by increase of the outer fuel radius. In order to maintain the same thickness of the reflector and shield, the inner and outer radius of these media were increased by the same amount. The reactor height was not modified. Tab. 3 presents the outer radius of fuel and shield. In Cases 2, 3, and 4, the radius increased by 10.5 cm, 5.3 cm, and 6.5 cm, respectively. For these cases, the reactor becomes subcritical when the control rod is completely inserted into the core (SCRAM). However, the modified cases show a k_{eff} higher than 0.98 under SCRAM conditions. Therefore, further studies must be conducted to adjust the control rod dimensions and/or composition to ensure safety conditions.

Also, comparing the two fuel types, the UPuMo has lower delayed neutron fraction (β_{eff}) than UMo (see Tab. 3), as expected. This behavior can be attributed to the presence of fissile nuclides ^{239}Pu and ^{241}Pu, which have lower β_{eff} than ^{235}U.

Tab. 3. Evaluated fuels in weigh percentage.

Fuel Type	Fissile (%)	Case	Geometry Type	Outer Radius (cm)		*keff* for CR position		*βeff* (pcm)
				Fuel	Shield	Removed	SCRAM	
UMo	93.10	1	Conventional	5.5	50.9	1.02374	0.94907	630
	19.85	2a	Conventional	5.5	50.9	0.52482	-	-
		2b	Modified	16	61.9	1.01012	0.98206	688
UPuMo	19.85	3a	Conventional	5.5	50.9	0.62130	-	-
		3b	Modified	10.8	56.2	1.03512	0.98744	432
	16.27	4a	Conventional	5.5	50.9	0.59290	-	-
		4b	Modified	12.0	57.4	1.03532	0.99116	340

The Fig. 3 illustrates the neutron energy spectrum of evaluated fuel. All cases exhibit a hardening spectrum, with the highest neutron flux occurring around 1 MeV. Among the fuels, UMo (93.1%) presents the most hardening spectrum, while the UMo (19.85%) has the lowest one. For the same fuel type, UMo, the reduction in enrichment percentage causes a softening of the neutron spectrum. For fuels with the same enrichment (19.85%), UPuMo exhibits the highest neutron flux compared to UMo in the fast energy range. As expected, the Pu insertion generates a hardening in the energy spectrum due to neutron absorption of thermal neutrons by Pu isotopes.

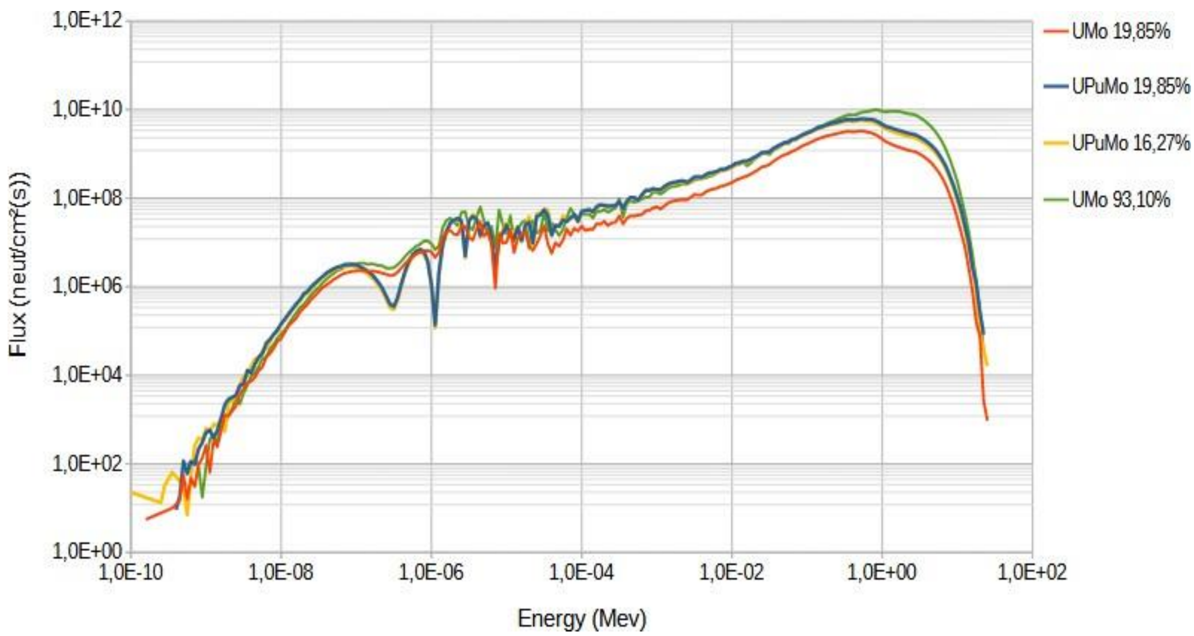

Fig. 3. Neutron energy spectrum.

The Tab. 3 presents the percentages of fissions generated by neutrons in the thermal, epithermal, and fast energy ranges. The results corroborate the behavior of the neutron energy spectrum. For different fuel types with the same fissile content (19.85%), UPuMo exhibits the highest fission percentage in the fast energy range, possibly due to the presence of Pu nuclides.

Tab. 3. Percentages of fissions in distinct neutron energy range.

Fuel Type	Fissile (%)	Case	Thermal (<0.625 eV)	Epithermal (0.625 ev - 100 kev)	Fast (>100 keV)
UMo	93.10	1	4.59%	26.26%	69.15%
	19.85	2b	7.56%	32.09%	60.35%
UPuMo	19.85	3b	6.92%	27.05%	65.02%
	16.27	4b	7.00%	26.32%	66.67%

The Fig. 4 and the Fig. 5 depict the radial and axial neutron flux profiles in the KRUSTY core for the evaluated fuels. As expected, the radial neutron flux gradually decreases from the fuel region to the outer zone of the reactor. Among the cases, the UMo (93.1%) has the highest neutron flux in fuel zone while UMo (19.85%) has the lowest one. The reduction of the fuel enrichment and the increase in the radial core dimensions for Case 2 may be causing this behavior. Comparing fuels with the same enrichment (19.85%), UPuMo exhibits a higher neutron flux than UMo in the fuel zone, which may be due to the fission reactions of Pu isotopes. This behavior may be causing a higher k_{eff} for Case 3 compared to Case 2 (see Table 3). For the same fuel type, UPuMo, the higher enrichment produces the higher neutron flux, as expected.

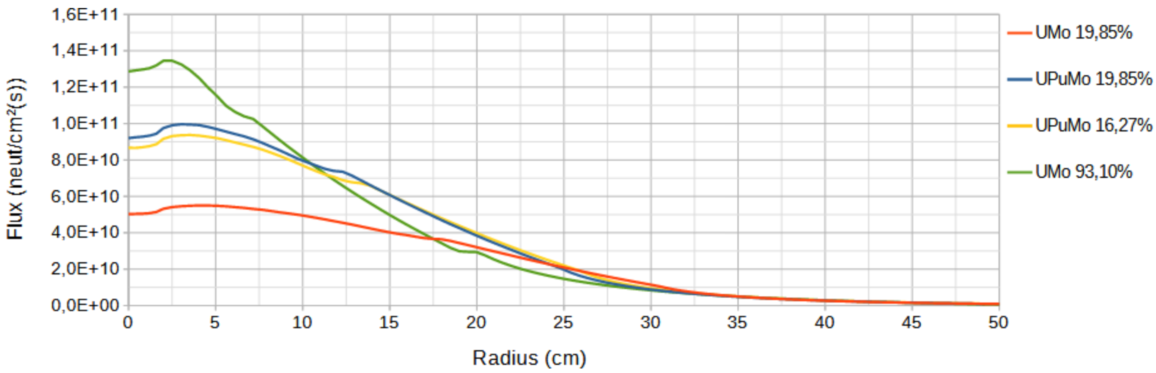

Fig. 4. Radial neutron flux profile.

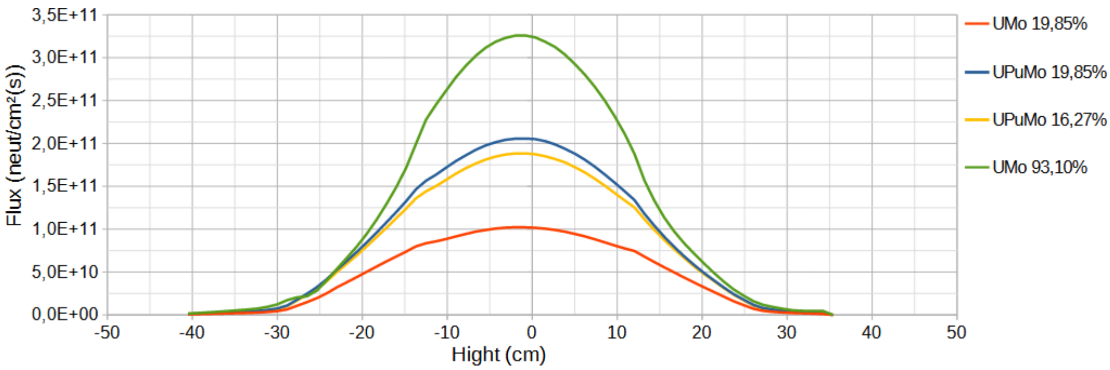

Fig. 5. Axial neutron flux profile.

4. CONCLUSIONS

The present study evaluates the use of different fuels for KRUSTY. By reducing the fuel enrichment from 93.1% to 19.85%, it is necessary to increase the reactor dimensions to achieve criticality. Among the fuel types, UMo has the highest core radius, while UPuMo has the smallest. The UPuMo presents a hardened neutron spectrum compared to UMo and the highest neutron flux in the fuel zone. Considering these aspects, UPuMo may be a promising fuel. However, this fuel type has a lower delayed neutron fraction than UMo, which may affect reactivity control. Furthermore, it is necessary to evaluate the neutronic parameters and the fuel evolution during the reactor lifetime, aiming to study the fuel transmutation and the final activity of UMo and UPuMo. Future work will simulate these fuels, considering KRUSTY's lifespan, using the developed MNCP6 model

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