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Original Article

Neutronic performance analysis of U–Mn fuel and MgO-BeO tube material in the dual fluid reactor

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ABSTRACT

This study investigates the feasibility of using a Uranium–Manganese (U–Mn) alloy as an alternative fuel for the Dual Fluid Reactor (DFR_m) concept to increase the temperature margin, along with a Magnesium Oxide–Beryllium Oxide (MgO–BeO) ceramic fuel tube. Neutronic analyses were performed using the SERPENT 1.1.7 Monte Carlo code with the ENDF/B-VII cross-section library to evaluate fuel performance, reactivity behavior, and safety margins. The results indicate that the U–Mn fuel exhibits lower k_{eff} values and shorter fuel cycle length to those of the U–Cr fuel, while providing the advantage of a lower eutectic temperature. Reactivity coefficients found to be negative for both fuel and coolant with the SiC fuel tube, ensuring inherent safety during temperature excursions. However, for the MgO–BeO configuration, the reactivity coefficients for MgO-BeO were found to be positive, which represents a critical drawback of this material; hence, further geometrical optimization is required. Consequently, although U–Mn fuel maintains negative temperature feedback under SiC-based configurations, alternative tube materials such as MgO–BeO require further optimization to ensure stable and inherently safe reactivity behavior throughout the fuel cycle. Future research could focus on optimizing reactor geometry to enhance the utilization potential of U–Mn fuel.

1. Introduction

Today, nuclear energy systems are considered one of the most important low-carbon energy sources, due to their potential to meet the energy demand and contribute to sustainable energy production [1,2]. Thus, Generation IV reactors were designed to improve sustainability, and several research were carried out to develop and optimize their design. One of the Generation IV designs, Molten Salt Reactor MSR design has been the subject of many studies due to its use of liquid fuel and its potential for transuranic burning [3].

Being one of the MSR designs, the Dual Fluid Reactor (DFR) stands out with unique core geometry [4]. The DFR is known for combining the features of Molten Salt Reactors (MSR) and Lead-Cooled Fast Reactors (LFRs), and its geometry consists of separate fuel and coolant loops. The fuel tubes separate the fuel from surrounding lead coolant. Operating at high temperatures of approximately 1000 °C, the DFR is capable of accommodating both chloride and metallic fuels, while providing a versatile platform for testing advanced material combinations aimed at enhancing safety margins and overall reactor performance [4–6]. However, as a novel concept among Generation IV reactors, DFR is open to research on various topics, especially in terms of exploring alternative fuels and structural materials. Despite its potential, very few studies have investigated alternative fuel alloys or structural materials for DFR; therefore, the DFR concept remains open for further investigation [7–9].

In previous works, alternative metallic fuels such as U–Ni and U–Fe were proposed for the DFR_m concept to reduce the fuel freezing risk and extend the operational temperature range [10–12]. Although these alloys exhibited slightly lower k_{eff} values owing to their reduced fissile content, they demonstrated neutronic behavior comparable to the reference U–Cr fuel and consistently maintained negative Doppler coefficients throughout the burnup period. Building on these findings, the present study introduces U–Mn alloy as a new fuel candidate with a lower eutectic temperature and comparable uranium density, aiming to further improve DFR_m performance [10–12].

Recognizing this gap, the present study investigates the feasibility of a uranium–manganese (U–Mn) alloy as a candidate fuel and the Magnesium Oxide–Beryllium Oxide (MgO–BeO) ceramic composite as a fuel tube material [13,14]. This work evaluates how these alternatives influence neutronic behavior, thermal characteristics, and operational safety, providing new insights into DFR_m design and expanding the

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flexibility and robustness of this emerging reactor concept.

In this context, a uranium–manganese (U–Mn) alloy is proposed as a candidate for DFR_m fuel, featuring a eutectic point of approximately 716 °C, nearly 145 °C lower than that of U–Cr. The similar uranium content of U–Mn to the reference U–Cr fuel enables the maintenance of comparable fuel cycle lengths without increasing enrichment, while providing a broader safety margin at elevated temperatures [15]. The neutronic behavior of U–Mn fuel has been analyzed using the Serpent 1.1.7 Monte Carlo simulation code to assess its feasibility in fast reactor operation [16,17].

Another focus of this study is the exploration of a high-temperature alternative fuel tube material to replace silicon carbide (SiC). The MgO–BeO ceramic composite is promising material that has suitable thermal and neutronic characteristics as a fuel tube material with its improved structural stability under high-temperature conditions. Additionally, MgO-BeO was investigated in DFRs geometry in previous studies, and results have shown that MgO–BeO maintains a fast neutron spectrum, which aligns with the fast-spectrum requirements of DFR_m fuel, making it a suitable candidate for fuel tube applications [18].

By systematically evaluating both fuel and fuel tube material alternatives, this study aims to enhance the design flexibility, operational safety, and overall performance of DFR_m reactors, contributing to the ongoing development of next-generation sustainable nuclear systems.

2. Materials and method

This section introduces the properties of the proposed materials, including the U–Mn fuel and MgO–BeO structural material, as well as the computational tools and the main design features of the DFR_m reactor system.

2.1. Properties of the proposed fuel

The aim of this study is to propose fuels with lower melting points for the DFR_m concept and to investigate their neutronic behavior. In this context, a uranium–manganese (U–Mn) alloy has been proposed. The U–Mn fuel consists of 5.9 wt% ^{55}Mn and 94.1 wt% uranium and reaches its eutectic point at 716 °C [15], which is lower than the 860 °C minimum melting point of the U–Cr fuel previously proposed for the DFR_m concept. The phase diagrams of U–Cr and U–Mn are presented in Fig. 1 (a) and (b), respectively. This lower eutectic temperature makes U–Mn an attractive candidate for extending the safe operational temperature range of the DFR_m.

However, the U–Mn fuel also has certain disadvantages compared to U–Cr. Firstly, its uranium content is slightly lower and requires slightly higher ^{235}U enrichment to maintain comparable reactivity. Secondly, ^{55}Mn has a higher neutron capture and elastic scattering cross section than chromium isotopes, which could lead to a lower reactivity in the reactor. Nevertheless, this difference is relatively small and does not affect the feasibility of U–Mn fuel in the DFR_m design [17].

In this study, the U–Mn alloy was analyzed within the DFR_m core to evaluate its impact on overall reactor behavior. The uranium enrichment ratio was kept the same as that of the reference U–Cr fuel in order to isolate and assess the effect of alloying elements on neutronic performance. The density calculation was calculated using Eqs. (1) and (2) for U-Mn and U-Cr respectively [15]. The compositions of the evaluated fuels are listed in Table 1. Additionally, the compositions and eutectic temperatures of the U-Fe and U-Ni fuels are included in the same table to allow for direct comparison with previous DFR_m studies on material properties and neutronic performance. As can be seen from the table, U-Mn has the lowest eutectic temperature among the examined candidates and provides a significant advantage in terms of thermal safety margin.

$$\rho_{U-Mn} = \frac{100}{\frac{wt.\%Mn}{\rho_{Mn}(T)} + \frac{wt.\%U}{\rho_{U}(T)}} \quad (1)$$

$$\rho_{U-Cr} = 0.985\ \frac{100}{\frac{wt.\%Cr}{\rho_{Cr}(T)} + \frac{wt.\%U}{\rho_{U}(T)}} \quad (2)$$

In addition to the eutectic point, the thermophysical properties of U–Mn, U–Cr, U–Ni, and U–Fe should also be comparatively evaluated. Unfortunately, experimentally measured thermophysical data for these metallic fuel systems are not available in the open literature. Therefore, following the computational procedure proposed by Fei et al. [19], approximate thermophysical properties for U–Cr, U–Mn, U–Fe, and U–Ni were obtained [20,21]. Based on this approach, the thermal conductivity k, specific heat capacity c_p, and density ρ values were estimated. The resulting data are presented in Table 1. Examination of Table 1 indicates that the alloys exhibit broadly similar thermophysical properties, except for U–Ni, which shows a noticeably higher thermal conductivity. From a heat-transfer standpoint alone, these characteristic positions the U–Ni alloy as a more advantageous option.

2.2. Properties of the proposed fuel tube: MgO-BeO

The MgO–BeO ceramic composite has been widely proposed as a promising moderator material for high-temperature reactors, and many studies have focused on its moderating performance. The magnesium

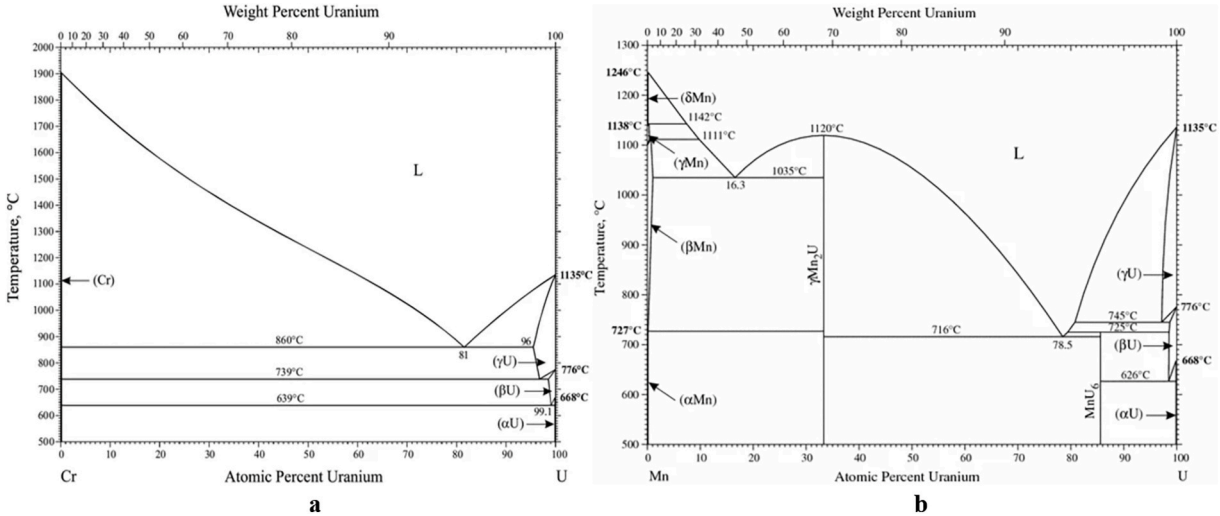

Fig. 1. Phase diagrams for a) U-Cr and b) U-Mn fuel [15].

Table 1
Fuel compositions (wt%) [10,15] and thermal properties [19–21].

Fuel	Cr	Mn	Fe	Ni	^{235}U	^{238}U	Eutectic Point (°C)	k (W/mK)	c_p (J/(kg·K)	ρ (g/cm^3)
U-Cr	4.78	–	–	–	12.80	82.42	860	14.72	226.11	17.47
U-Mn	–	5.90	–	–	12.68	81.45	716	14.19	236.04	17.30
U-Fe	–	–	10.2	–	12.07	77.73	725	15.67	255.80	16.90
U-Ni	–	–	–	11.0	11.96	77.71	740	18.79	245.79	16.91

oxide (MgO) component offers economic advantages among oxide, hydrate, and nitrate ceramics, as it is inexpensive and widely available. In addition, MgO maintains structural and chemical stability under irradiation up to approximately 1170 K. In the previous studies, MgO–BeO ceramics with varying BeO contents were examined and it was reported that the composition containing 40 vol% BeO exhibits superior moderation characteristics and excellent thermal stability at high temperatures [22].

In previous studies on DFR systems, MgO–BeO was also evaluated as a potential moderator material. However, its moderation capability in DFR cores was found to be quite limited. Considering this limitation and its favorable thermal and structural properties, MgO–BeO is proposed in this study as a potential fuel tube material for the DFR$_m$ concept. The thermophysical properties of the MgO–BeO composite containing 40 vol % BeO are listed in Table 2.

2.3. Core modelling

The neutronic and burnup behavior of the DFR$_m$ concept was investigated using the SERPENT 1.1.7 Monte Carlo transport code in conjunction with the ENDF/B-VII.0 evaluated nuclear data library [16,17]. Burnup calculations were performed using a source of 100,000 neutrons per cycle over 100 active and 50 inactive cycles to ensure statistical stability. In the Serpent model, the calculations were normalized to the reactor thermal power of 250 MW$_{th}$ to achieve accurate calculation results. Vacuum boundary conditions were applied to the outer radial and axial surfaces to simulate neutron leakage. The maximum statistical uncertainty in the results was 2.5 pcm, confirming the reliability of the simulations. The fuel tube and plenum unit cell geometry was given in Fig. 2. The full core geometry, including cross-sectional and axial views of the DFR$_m$, is shown in Fig. 3. Parameters for the analyzed DFR$_m$ reactor geometry were adopted from a previous study and listed in Table 3 [4,12].

3. Results

In this study, the main objective is to examine how the proposed U-Mn fuel affects the fuel cycle behavior within the existing DFR$_m$ geometry, without any modification to the reference configuration. According to the results shown in Fig. 4, the proposed U-Mn fuel provides a 5770-day fuel cycle length, which is 370 days shorter than that of U-Cr. The variation of k_{eff} values with effective full power day (EFPD) for both fuels follows a parallel trend. Although natural chromium was used in U-Cr fuel, the ^{52}Cr isotope, with an abundance of 83.789 %, has a lower neutron capture cross-section than the ^{55}Mn isotope, which leads to lower k_{eff} values for U-Mn fuel and shorter fuel cycle length. To provide a robust comparison with previously studied alternative fuels, the evolution of k_{eff} for U-Fe and U-Ni fuels have also been included in Fig. 4 [10–12]. The results indicate that U-Mn provides a significantly longer fuel cycle length than both U-Fe and U-Ni fuels, primarily due to its higher uranium content. Consequently, while U-Cr still offers the longest cycle, U-Mn demonstrates superior neutronic performance compared to U-Fe and U-Ni, yielding results closest to the reference U-Cr fuel. Despite exhibiting a shorter fuel cycle compared to U–Cr fuel, its lower eutectic temperature represents a significant advantage.

Table 2
Composition of MgO-BeO material (w/o) [10,18,22].

Material	Density (g/cm^3)	^{1}H	^{2}H	^{9}Be	^{16}O	^{24}Mg
MgO-BeO	3,0900	–	–	10,53	46,81	42,66

In the previous study [10], it was observed that the MgO–BeO material did not noticeably thermalize the neutron spectrum in the DFRs geometry. This result suggests that MgO–BeO is compatible with the fast reactor environment in neutronic perspective, and thus it was proposed for incorporation into the DFR$_m$ design. For this reason, the effect of using the MgO–BeO material partially in the fuel tube and as the entire fuel tube material was examined to evaluate its impact on the fuel cycle for both U–Cr and U–Mn fuels. Two different MgO–BeO thicknesses were considered. In the first case, the SiC thickness of 0.15 cm in the fuel tube was reduced by 0.05 cm and replaced with MgO–BeO moderator material. In the second case, the SiC was completely replaced with 0.15 cm MgO–BeO, and the effects of these configurations on the fuel cycle were analyzed. According to the results presented in Fig. 5 for the U–Cr fuel, when 0.05 cm MgO–BeO was used, the fuel lifetime remained unchanged, whereas when 0.15 cm was used, the fuel lifetime decreased.

As shown in Fig. 6, for the U–Mn fuel, a 0.05 cm MgO–BeO layer performs slightly better than the 0.15 cm layer; however, in both cases, the fuel cycle length is still shorter than that of the original SiC configuration.

Although a 0.05 cm MgO–BeO layer yields slightly better neutronic performance, the 0.15 cm thickness was selected due to its higher fabrication feasibility and mechanical robustness. For improved safety and structural integrity, thin SiC coating may be applied if necessary, following the hybrid design approach commonly suggested in the literature. In this study, a fully MgO–BeO fuel tube with 0.15 cm thickness was adopted, and the neutronic simulations were performed accordingly.

The fuel tube material effect on neutron energy spectrum was studied. Fig. 7 shows the neutron energy spectra obtained for U–Cr (top) and U–Mn (bottom) fuels using SiC and MgO–BeO fuel tubes. In both configurations, a fast neutron spectrum is clearly observed, indicating that the reactor operates in fast neutron spectrum regardless of the tube material. Minor deviations in specific energy regions are attributed to neutron absorption by Mn and Cr isotopes within the fuel compositions, leading to slightly reduced the number of fast neutrons in the system. In addition, small variations between the SiC and MgO–BeO cases arise from the neutron cross-sections of Mg, Be, and O isotopes. Nevertheless, these effects are limited, and both fuel-tube configurations result in a predominantly fast neutron spectrum. Additionally, in order to evaluate the spatial power behavior of the DFR$_m$ core, power distribution analysis was performed using Serpent. The obtained axial and radial power distribution is presented in Fig. 8 (a) and (b) respectively.

In the proposed fuels, an important factor is to examine the behavior of isotopes present in the fuel and produced by fission throughout the burnup. Understanding these trends helps assess the similarities and differences in fuel performance between U-Cr and U-Mn. As a result, isotopic variation of ^{235}U, ^{238}U, ^{135}Xe, ^{149}Sm, ^{239}Pu, and ^{241}Pu with EFPD was investigated and consequently, as shown in Fig. 9, the variation of these isotopes found to be following the same trend for both U-Cr and U-Mn fuels, mainly because the uranium content and neutron cross-sections in the two fuels are almost identical. While ^{135}Xe and ^{149}Sm levels behaved as expected in the studied cases, their accumulation and impact on reactivity would differ under the DFR$_m$ concept due

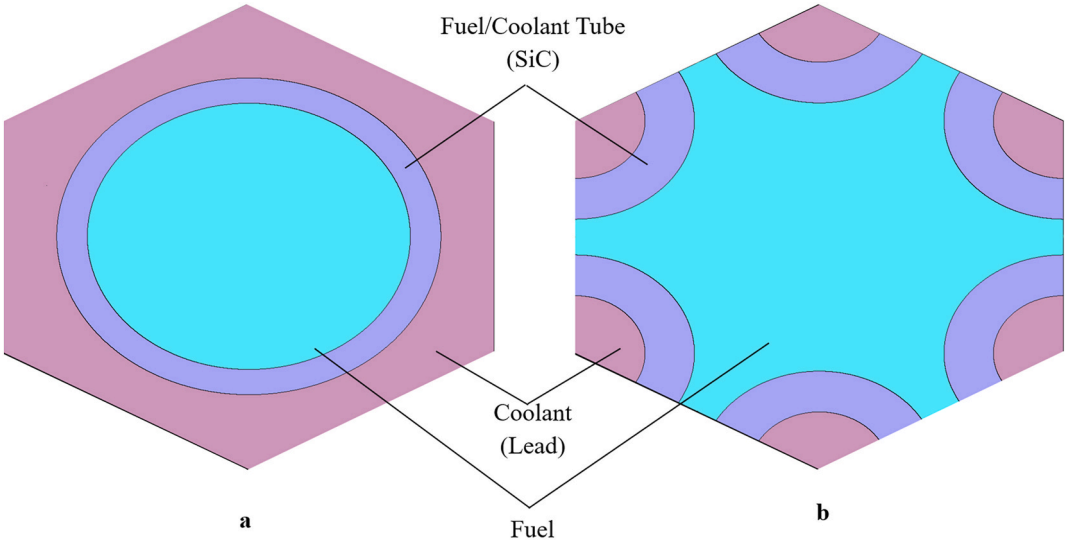

Fig. 2. Unit cell geometry of a) fuel, and b) plenum region [10,12].

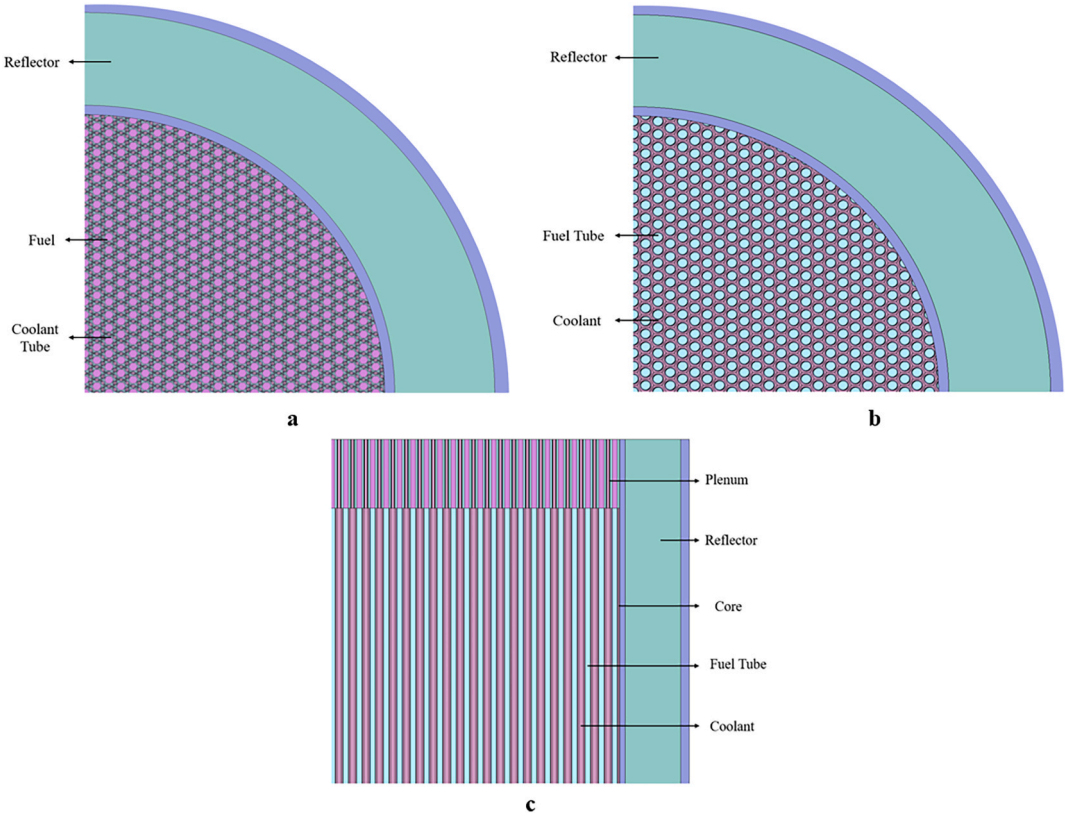

Fig. 3. Serpent model of the DFR_m core [10,12].

to the presence of online refueling.

Another important factor to analyze is the safety performance of the U-Mn fuel. Its fuel and coefficients were calculated using Eq. (3) at both the beginning and the end of the fuel cycle [23,24].

$$\alpha_T = \alpha_M = \alpha_C = \frac{1}{k_1 k_2} \times \frac{k_2 - k_1}{T_2 - T_1} \tag{3}$$

As presented in Table 4, the U–Mn fuel exhibits negative temperature coefficients, which is a favorable and expected behavior for nuclear fuels, as it contributes to the inherent safety of the reactor. The temperature range of 1000K–1400K has been used as a reference for the calculations, as literature data allows accurate determination of U–Mn fuel density within this range. All coefficients have been evaluated at both the beginning and the end of the fuel cycle to capture reactivity changes due to fuel burnup.

In the reference study, the total fuel reactivity coefficient for U–Cr with a SiC fuel tube has calculated as −2.4684 over the 1200K–1800K temperature range. According to our results in Table 4, U–Mn fuel with a SiC tube meets the required negative reactivity margins and satisfies the reactor safety criteria. However, when using an MgO–BeO fuel tube, positive reactivity has obtained at the end of the fuel cycle, indicating the direct impact of material and geometry choices on reactivity

Table 3
Geometrical parameters of DFR_m reactor (cm) [5,10,12].

Parameter	Value	Parameter	Value
$r_{fuel\ tube\ inner}$	0.95	R_{core}	60
$r_{fuel\ tube\ outer}$	1.1	Core outer wall thickness	62
L_{fuel}	120	Reflector outer wall thickness	3
Fuel tube pitch	2.8	Reflector thickness	20
Number of fuel tubes	1666	In/outer plenum height	15
$r_{coolant\ tube,\ inner}$	0.516	Plenum pitch	1.616
$r_{coolant\ tube,\ inner}$	0.667	$R_{reactor}$	85
Reactor thermal power	250 MW_{th}	Coolant	Lead
		Fuel	U-Cr

behavior. The coolant temperature coefficients have found to be particularly positive for the MgO–BeO configuration, highlighting the influence of coolant density changes on the overall reactivity.

To investigate the positive reactivity contribution introduced by the MgO–BeO material, the (n, 2n) reactions occurring in the system has analyzed for both MgO–BeO and SiC fuel tubes. This analysis was motivated by the well-known tendency of beryllium to undergo (n, 2n) reactions to high neutron energies. The results obtained expressed as the ratio of (n, 2n) reactions to the total number of reactions, are presented in Table 5. Accordingly, among all the elements in proposed tube materials, it can be inferred that the increase in reactivity observed at both the beginning of cycle (BOC) and at the end of cycle (EOC) is primarily attributable to the (n, 2n) reactions induced by beryllium.

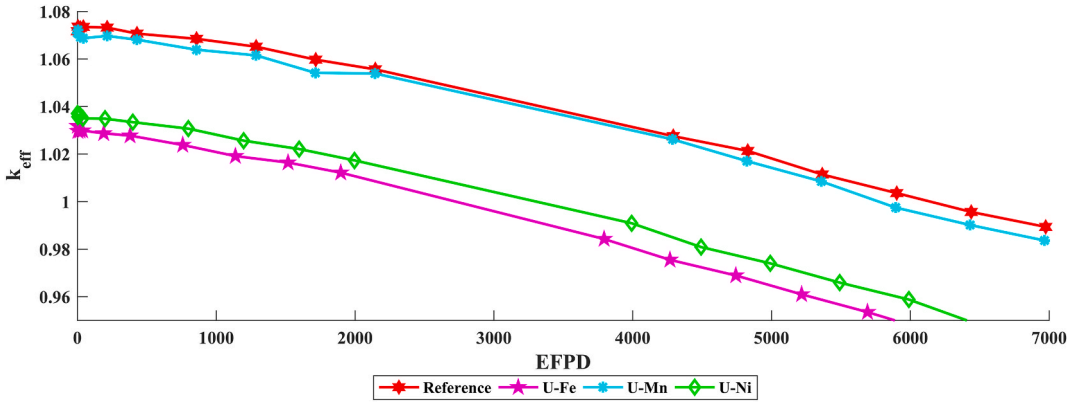

Fig. 4. Variation of k_{eff} values with EFPD.

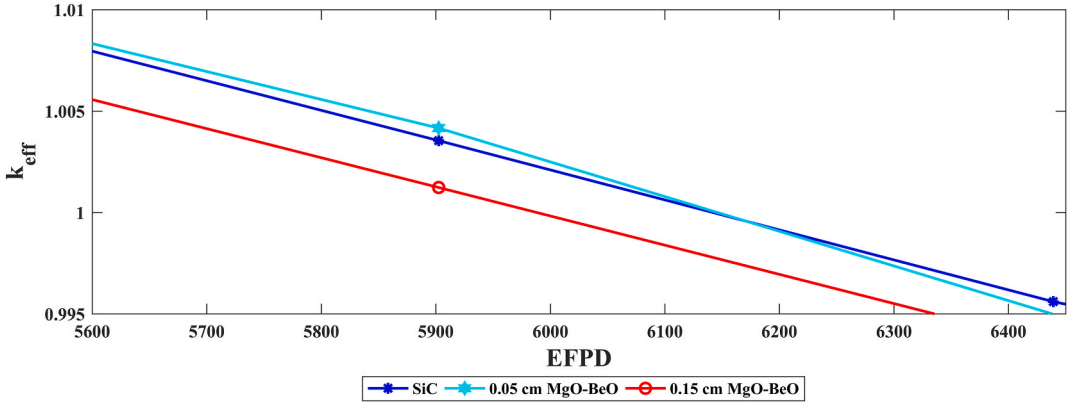

Fig. 5. Effect of MgO-BeO thickness on DFR_m fuel cycle length core with U-Cr fuel.

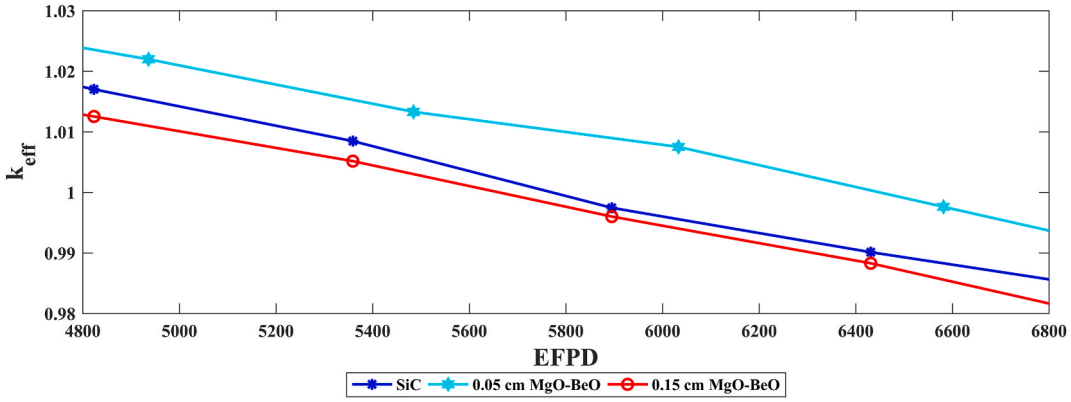

Fig. 6. Effect of MgO-BeO thickness on DFR_m fuel cycle length core with U-Mn fuel.

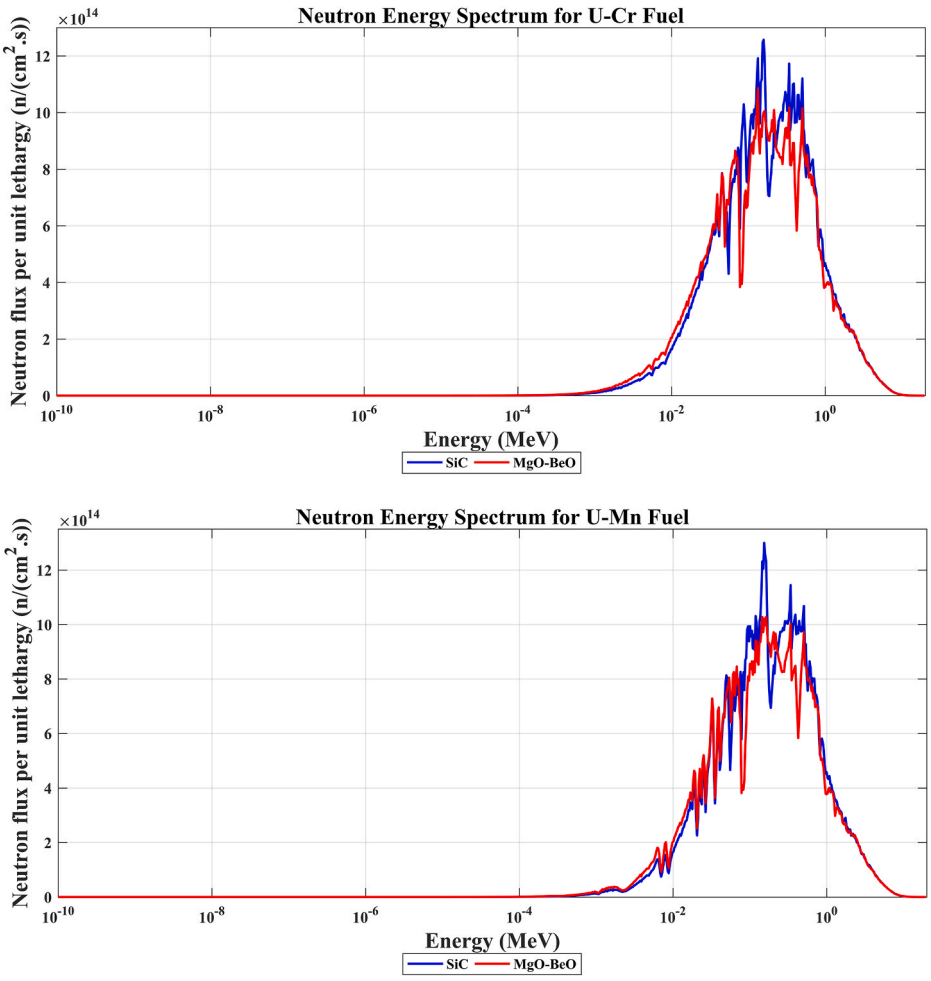

Fig. 7. Neutron energy spectra for U–Cr (up) and U–Mn (bottom) fuels in SiC and MgO–BeO fuel tubes.

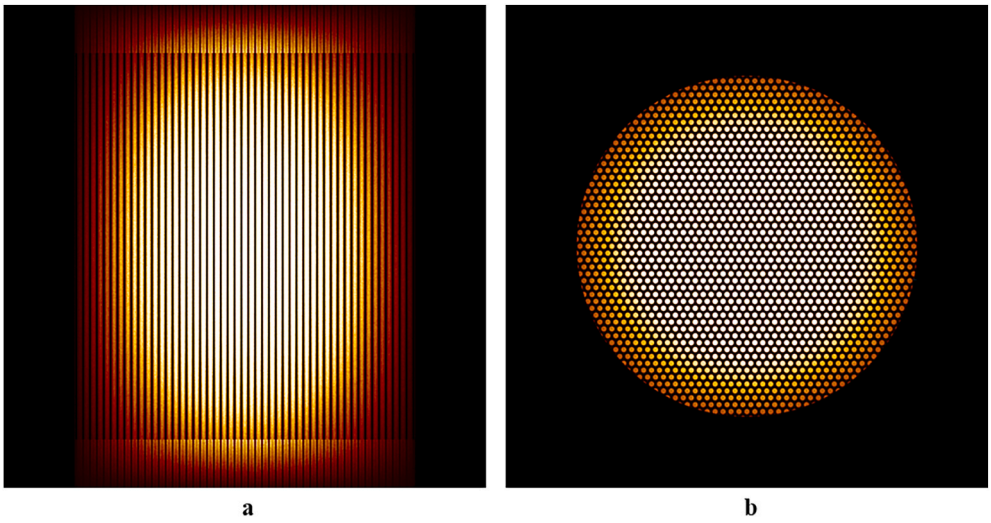

Fig. 8. Power distribution in a) axial b) radial direction in DFR_m core.

4. Conclusion

In this study, the neutronic behavior of a newly proposed U-Mn metallic fuel was evaluated within the existing DFR_m geometry, without changing the reference core configuration. The goal was to determine whether U-Mn was a viable alternative to the reference U-Cr fuel and to investigate the possible impact of MgO-BeO as a fuel-tube material on overall reactor performance. Comprehensive Monte Carlo simulations were performed throughout the fuel cycle utilizing the SERPENT 1.1.7 code and the ENDF/B-VII.0 nuclear data library to investigate criticality, spectrum features, isotopic evolution, and temperature feedback behavior.

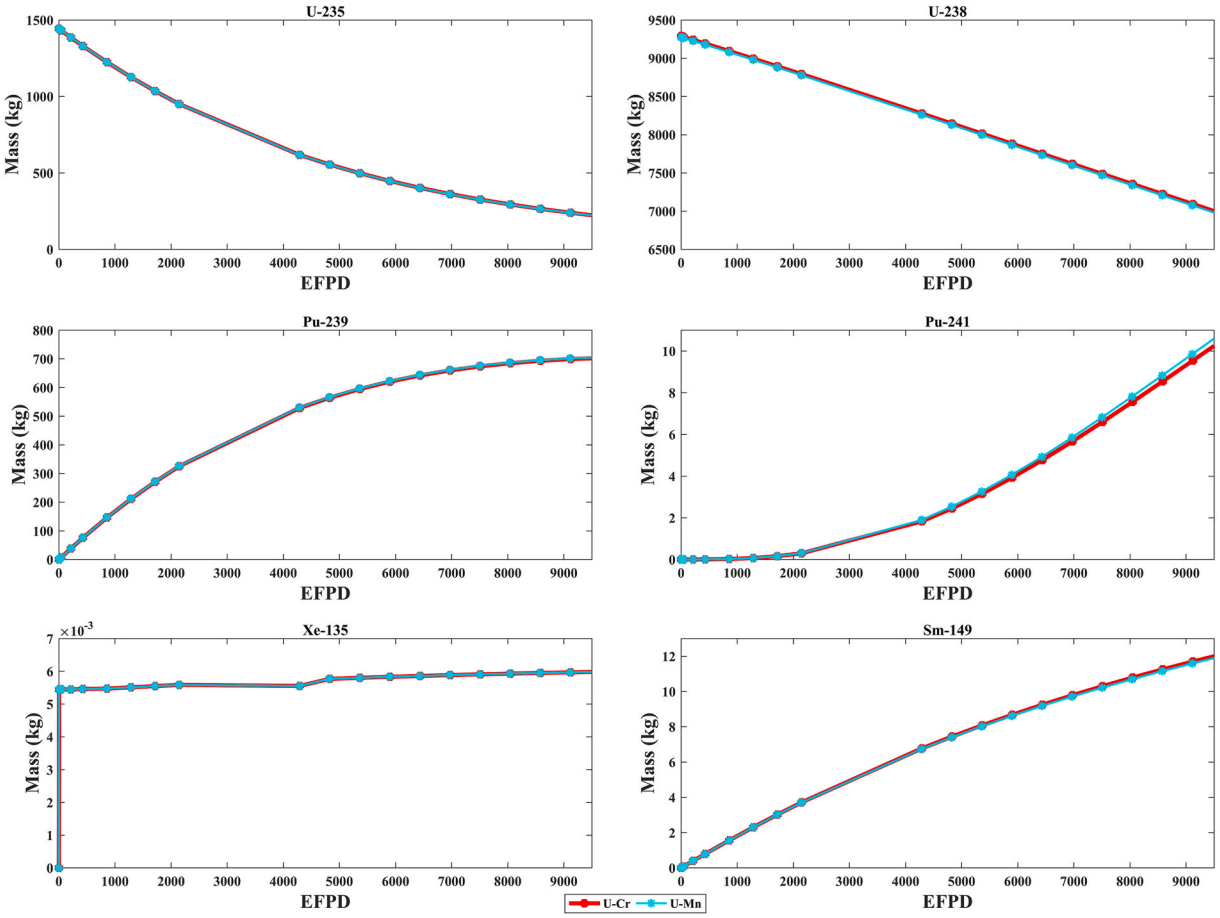

Fig. 9. Variation of the important isotopes with EFPD.

Table 4
Temperature Coefficients for U-Mn fuel (pcm/K).

Fuel	Burnup	α_T (1000K–1200K)	α_T (1200K–1400K)	α_M (900K–1200K)	α_C (900K- 1200 K)
U-Mn (SiC)	BOC	−3.135	−2.089	−0.012	−0.278
	EOC	−2.222	−2.034	−0.216	−0.344
U-Mn (MgO-BeO)	BOC	−2.466	−1.832	−0.257	−0.336
	EOC	−1.815	0.001	0.251	−0.304

Table 5
The fractions of (n,2n) reactions in fuel tube materials.

Fuel Tube Material	Burnup	(n,2n) Fraction	Fission rate 1000K	Fission rate 1400K
SiC	BOC	4.9573e-07	7.69709E+18	7.69702E+18
	EOC	6.0658e-07	7.57883E+18	7.58554E+18
MgO-BeO	BOC	0.0035	7.69732E+18	7.69759E+18
	EOC	0.0033	7.58429E+18	7.58382E+18

The results indicate that the U-Mn fuel provides lower k_{eff} values and fuel lifetime to the U-Cr fuel. Consequently, using U-Mn fuel in the DFR_m concept provides 370 days shorter fuel cycle life, while extending the reactor's operating temperature range. Compared to the U-Fe and U-Ni fuels previously examined for the DFR_m concept, the U-Mn alloy provides the longest fuel cycle length. Moreover, U–Mn retains a lower eutectic temperature than the other candidate fuels, providing a notable advantage in thermal safety margin. Overall, considering both its thermal characteristics and performance metrics, U–Mn appears to be the alloy most comparable to U–Cr among the fuels evaluated.

To verify safety requirements, temperature coefficients were examined for the performance of U-Mn fuel in the DFR_m geometry. The results show that the fuel and coolant temperature coefficients are negative. Regarding the fuel tube material, the use of MgO–BeO was explored as a potential replacement for SiC, motivated by its high melting point, radiation resistance, and minimal moderation capability. The analysis indicated that MgO–BeO inclusion influenced reactivity behavior through secondary nuclear effects—particularly due to Be-induced (n, 2n) reactions at high neutron energies (above a threshold energy of approximately 1.67 MeV). The ratio of (n, 2n) to total reactions confirmed that these reactions were responsible for the observed positive reactivity contribution at both BOC and EOC. Safety analyses confirmed that the U–Mn fuel exhibits negative temperature coefficients across the considered temperature range (1000K–1400K), fulfilling the inherent safety requirements of fast-spectrum reactors. However, when combined with MgO–BeO cladding, positive reactivity coefficients for MgO-BeO material were observed. Although the overall feedback remains negative due to the fuel Doppler effect, the presence of a positive component reduces safety margins. Therefore, to ensure a fully negative reactivity profile, MgO–BeO can be implemented as a thin layer over

SiC, allowing the reactor to maintain negative reactivity throughout the entire core lifetime.

Additionally, dissimilar-material joints represent a key technological hurdle and acknowledge that their behavior under high thermal loads and irradiation remains an active research area. To advance this technology, it is essential to investigate feasible joining concepts—such as diffusion bonding, graded interlayers, and compliant transition zones—that have been proposed in advanced reactor materials programs but still require thorough validation under high-temperature lead conditions.

In summary, the findings demonstrate that the U–Mn fuel is a promising candidate for fast reactor applications such as the DFR_m concept, offering comparable neutronic behavior to U–Cr while potentially simplifying fuel fabrication. In addition to these advantages, the U–Mn alloy offers potential benefits in terms of proliferation resistance due to its alloying characteristics, which may complicate reprocessing or isotopic separation. In future studies, the reactor geometry may be adjusted specifically to accommodate the neutronic behavior and thermal-hydraulic properties of U-Mn fuel. The MgO–BeO composite emerges as a viable cladding or structural material due to its high-temperature capability and limited moderation effect, although its (n, 2n) contribution requires careful management to avoid positive reactivity insertion during long-term operation.

CRediT authorship contribution statement

Semra Daydas: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ali Tiftikci:** Writing – review & editing, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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