NEUTRONIC EVALUATION OF U-MN ALLOY AS AN ALTERNATIVE FUEL FOR THE DUAL FLUID REACTOR

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INTRODUCTION: Today, nuclear energy plays a key role in low-carbon power generation—delivering high output from minimal fuel consumption. However, these systems must still overcome challenges such as complex safety systems, high costs, waste management and proliferation risks [1,2] Therefore, next-generation nuclear reactor designs have increasingly focused on addressing these concerns—particularly enhancing safety, improving waste handling, and increasing intrinsic proliferation resistance. In this context, Molten Salt Reactors (MSRs) stand out due to their inherently proliferation-resistant characteristics and consequently, numerous MSR designs have been proposed [3,4]. One such reactor, the Dual Fluid Reactor (DFR) is a novel fast reactor design that merges the molten salt fuel approach of MSRs with the lead coolant system of Lead Cooled Fast Reactor (LFR) [5-7]. In DFR design, the liquid fuel circulates within fuel tubes, while a separate loop contains the lead coolant. This enables DFR to have approximately 1000 ˚C operation temperature, making it suitable for utilization of both chloride and metallic fuels. As a result, DFR has two concepts, depending on the fuel type they use: molten salt used DFRs, and molten metallic fuel used DFR_m [5-9]. The DFR benefits from its use of metallic fuels, which allow higher uranium density and promote the production of proliferation-resistant plutonium isotopes, thereby enhancing the reactor's intrinsic proliferation resistance [10].

The reference DFR_m with 250 MW_{th} power output utilizes uranium-chromium (U-Cr) alloy with a eutectic point of 860 ˚C as fuel [7-12]. This alloy is well known for its high thermal conductivity and high uranium density, while the chromium element provides excellent neutron economy due to its low elastic scattering and absorption cross-sections at fast neutron energies. However, it is essential to explore alternative fuel alloys with lower melting points to extend the operational temperature range since U-Cr fuel has a relatively high melting point. Accordingly, a uranium–manganese (U–Mn) alloy is proposed for the DFR_m concept, considering its lower eutectic point, and its neutron behavior is analyzed using the Serpent 1.1.7 Monte Carlo simulation code. [12,13]. The aim of the study is to highlight the advantages of the proposed fuel in terms of reactor feasibility and provide alternative fuel to the DFR_m design.

1. OVERVIEW

This section provides the properties of the U-Mn alloy fuel, the computational tools used for neutronic analysis, and the geometrical configuration of the DFR_m reactor system.

1.1. Properties of the proposed fuel

The aim of this study is to propose fuels with lower melting points for the DFR_m concept and investigate their neutronic behavior. In this context, U-Mn fuel has been proposed. As seen in the phase diagram of the U-Mn alloy in Figure 1, U-Mn fuel, containing 5.9% ^{55}Mn and 94.1% uranium, reaches its eutectic point at 716 ˚C [12]. This temperature is lower than the 860 ˚C minimum melting point of the

U-Cr fuel proposed for the DFR_m concept, making the U-Mn fuel an attractive option for increasing the safe operating temperature range of the DFR_m concept.

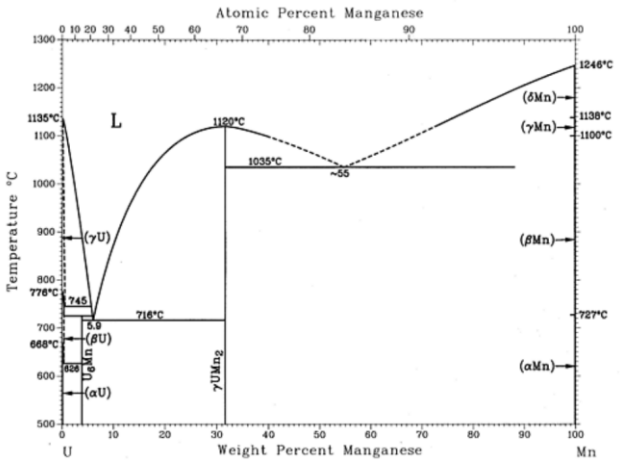

FIG. 1. Phase diagram of Mn-U fuel [12]

However, U-Mn fuel has some disadvantages compared to U-Cr fuel. Firstly, the uranium content of U-Mn fuel is slightly lower than that of U-Cr fuel. Therefore, fuel with higher enrichment of ^{235}U must be used in U-Mn fuel. The second disadvantage is that ^{55}Mn has a higher capture and elastic scattering cross-section compared to chromium isotopes. However, this difference is relatively small and does not prevent the use of U-Mn fuel in the DFR_m design.

The study investigates the U-Mn fuel by using the same enrichment ratio used for the U-Cr fuel in order to reliably assess the effect of alloying elements in selected metallic fuels on the fuel cycle. The compositions of the evaluated fuels are presented in Table 1.

TABLE 1 FUEL COMPOSITIONS [12]

Yakıt	^{235}U	^{238}U	Cr	Mn	Fe
U-Cr	12.80	82.42	4.78	–	–
U-Mn	12.68	81.45	–	5.9	–

1.2. Modelling

DFR_m geometry was modelled using the SERPENT 1.1.7 code with the ENDF/B-VII.0 neutron cross-section library for the neutronic and burnup simulations [13,14]. Burnup carried out with a source of 100,000 neutrons over 100 active cycles and 50 passive cycles, with vacuum boundary conditions applied at all edges. The maximum statistical uncertainty in the results was 2.5 pcm. The cross-sectional and axial full core geometry of the DFR_m is given in Figure 2. Parameters for the examined DFR_m reactor geometry were taken from the previous study [15].

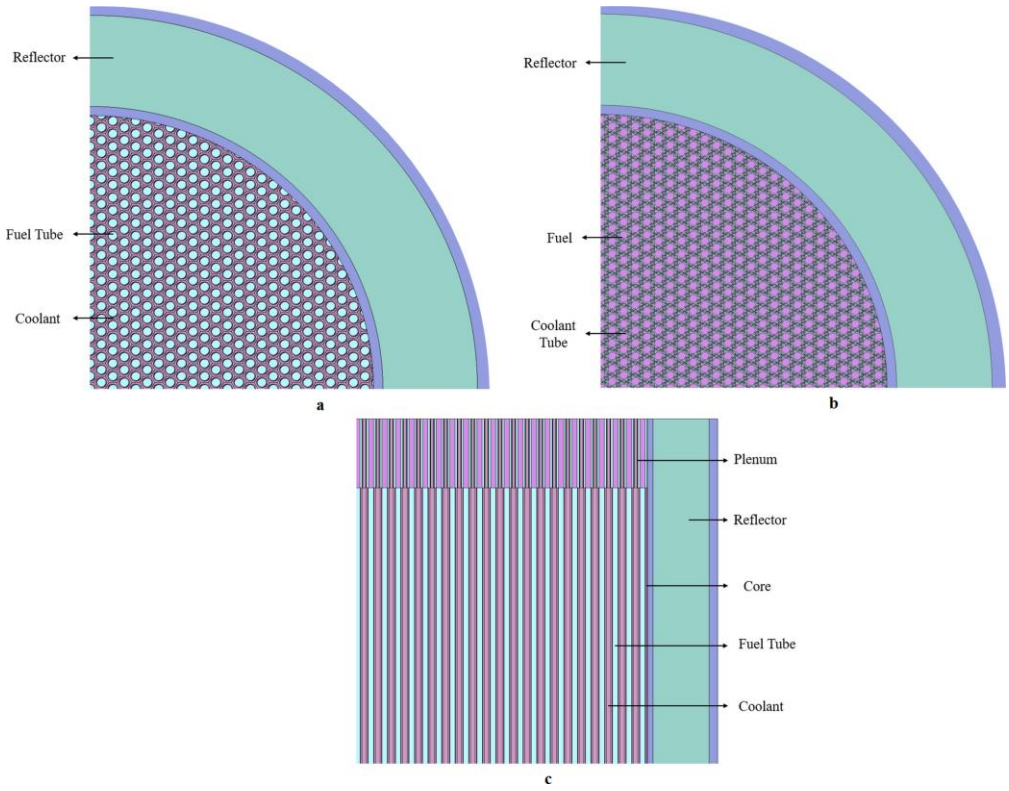

FIG. 2. DFR_m core geometry [15]

2. RESULTS

Burnup calculations were carried out for the selected U-Mn fuel, and the variation of the effective multiplication factor (k_{eff}) over the burnup period is illustrated in Figure 3.

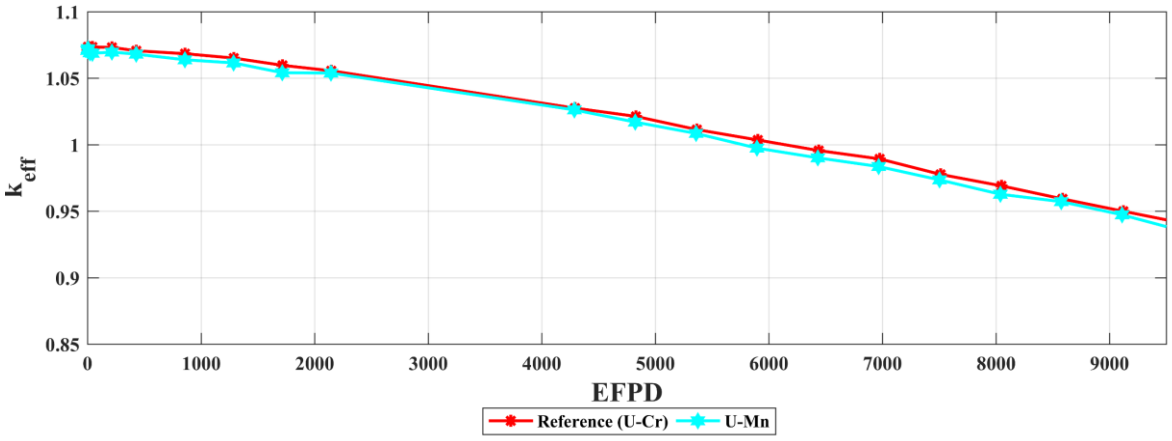

FIG. 3. k_{eff} vs. EFPD

According to the results, the U-Mn fuel exhibits slightly lower k_{eff} values compared to the U-Cr fuel. However, both fuels demonstrate a similar trend in k_{eff} evolution throughout the burnup period. Although natural chromium composition was used in the U-Cr fuel, the dominant isotope, 52Cr (with a natural abundance of 83.789%), has a lower neutron capture cross-section than ^{55}Mn[16]. This contributes to the slightly reduced k_{eff} values observed in the U-Mn fuel.

To assess the safety performance of the U-Mn fuel, its Doppler and coolant coefficient was calculated using Eq. 1 for at the beginning and at the end of the fuel cycle [17-18].

$$\alpha_F = \alpha_C = \frac{1}{k_1 k_2} \times \frac{k_2 - k_1}{T_2 - T_1} \quad (1)$$

As presented in Table 2, the U-Mn fuel exhibits negative temperature coefficients, which is a favourable and expected behaviour for nuclear fuels, as it contributes to the inherent safety of the reactor.

TABLE 2 TEMPERATURE COEFFICIENTS FOR U-MN FUEL (PCM/K)

Burnup	α_F (1000 K – 1400 K)	α_C (900 K – 1200 K)
BOC	-2,92	-0.46
EOC	-1.75	-0.72

3. CONCLUSION

The results indicate that the U-Mn fuel provides k_{eff} values and fuel lifetime very similar to those of the U-Cr fuel. Consequently, using U-Mn fuel in the DFR_m concept enables achieving the same fuel cycle length as with U-Cr, while extending the reactor's operating temperature range. Temperature coefficients examined to assess the safety of U-Mn fuel in the DFR_m geometry show that the Doppler and coolant temperature coefficients are negative. Accordingly, it is concluded that U-Mn fuel ensures safety in the event of any temperature increase. 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 optimized specifically for the neutronic behaviour of U-Mn fuel, aiming to improve the effective multiplication factor and enhance fuel utilization. Such optimization could involve adjustments in fuel volume fraction, core dimensions, or reflector configurations to better align with the characteristics of the proposed alloy.

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