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CERMET MATERIALS FOR HYBRID FISSION-FUSION NUCLEAR REACTOR

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Abstract

Recent advancements in energy generation are increasingly driven by the pursuit of higher efficiency and more sustainable resource utilization. In this context, several innovative nuclear reactor concepts are under active investigation, including Generation IV systems, fusion power plants, Accelerator-Driven Subcritical Reactors (ADS), and Hybrid Fusion-Fission Reactors (FFHR).

The cermet alloys analysed in this study demonstrate favourable thermophysical properties that position them as promising candidates for certain hybrid reactor configurations. Nonetheless, critical challenges persist—particularly regarding the complex interactions between the reactor coolant and the cermet materials.

1. INTRODUCTION

One of the most contentious challenges in the field of nuclear energy is the management of spent fuel elements from nuclear power plants—commonly referred to as nuclear waste. Among the various radioactive by-products, the isotopes of greatest concern to the industry are the minor actinides, due to their long-lived radiotoxicity, and plutonium, which poses significant risks related to nuclear weapons proliferation [1,2].

In response to these concerns, emerging nuclear reactor designs are increasingly focused on improving energy efficiency and maximizing resource utilization, while simultaneously addressing the issue of nuclear waste. Among the most promising innovations are Fission-Fusion Hybrid Reactors (FFHRs), which integrate a nuclear fusion device with a subcritical fission assembly [3,5,6]. In this configuration, the fusion device serves as a neutron source, supplying high-energy neutrons to sustain fission reactions in the subcritical core. The fusion process typically employs deuterium-tritium (D-T) fuel, producing 14 MeV neutrons that enable the reactor to operate within a fast neutron spectrum—an essential feature for transmuting and burning long-lived radioactive isotopes [7].

Despite the conceptual advantages of FFHRs, including their potential to reduce nuclear waste and enhance fuel utilization, all proposed designs to date have been hindered by the absence of a sufficiently efficient and sustained neutron source [1–8].

A critical engineering challenge in FFHRs lies in their dependence on thermal-to-electric energy conversion. Since the fusion device requires electrical power to operate, the overall system efficiency is tightly coupled to the thermal performance of the reactor. Enhancing this efficiency necessitates raising the operating temperature of the conversion unit and, consequently, the reactor core. However, increasing core temperatures is constrained by the thermal and mechanical limits of the materials used in fuel elements, which must endure extreme conditions without compromising structural integrity.

Research into high-temperature nuclear materials dates back to the 1960s and 1970s, particularly within the context of the space race. Among the materials tested, cermets—composite materials composed of uranium oxide embedded in a tungsten matrix—demonstrated exceptional thermal resilience, maintaining structural stability at temperatures approaching 3000 K. Tungsten's reflective and neutron-multiplicative properties are expected to enhance the performance of cermets in fast-spectrum reactors. Moreover, the interaction of fast neutrons with tungsten initiates a transmutation cycle that produces osmium, rhenium, and trace amounts of other valuable metals such as platinum and gold. Importantly, these transmutation products do not adversely affect the mechanical integrity of the cermet, as confirmed in previous studies [8].

2. CONCENTRIC MODEL

The most promising model for FFHR follows the three-layer arrangement. This model establishes that fusion device should be placed at the centre, surrounded by the fuel elements and finally by the lithium breeding blanket [9].

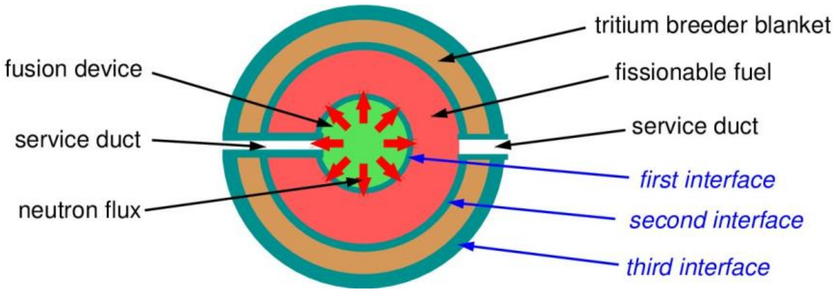

FIG. 1. The concentric model showing an FFHR arrangement.

Although this simplified model appears to enable full utilization of the neutrons generated by the fusion device, in practice, the quantity of high-energy neutrons (14 MeV) produced remains insufficient to sustain the desired level of fission activity. This limitation raises the need for a mechanism to convert a small number of fast neutrons into a larger population of lower-energy neutrons. One such approach is the use of a multiplicative cascade system.

A multiplicative cascade consists of concentric shells of fissile material, separated by substantial void regions. The geometry, composition, and spacing of these shells critically influence the neutron multiplication factor and overall system performance. *FIG.1* illustrates a conceptual FFHR design based on these principles: two concentric shells of 8% enriched uranium—chosen for its metallic behavior—serve as the fissile fuel; lithium silicate is employed as the tritium breeding blanket (TBB); and a tungsten layer functions as both a neutron reflector and radiation shield.

Building upon the capabilities of an operational fusion device, it is theoretically feasible to achieve both energy self-sufficiency and tritium breeding self-sufficiency through the implementation of a multiplicative cascade system in combination with lithium silicates.

Each region and interface within this configuration possess distinct nuclear characteristics that collectively shape the neutron flux spectrum as it propagates outward from the fusion source. These spectral transformations are crucial for evaluating the reactor's transmutation capabilities and overall energy conversion efficiency.

As demonstrated in reference [11], the energy spectrum of neutrons transmitted through tungsten under 14 MeV incident flux reveals a series of nuclear reactions that initiate a transmutation cycle. This cycle results in the gradual conversion of tungsten into osmium and rhenium, along with trace amounts of other heavy metals such as platinum and gold. Importantly, these transmutation products do not compromise the structural integrity of the tungsten matrix. Previous studies under fission-spectrum conditions have confirmed that the presence of these elements does not adversely affect the mechanical or thermal stability of the material, as also shown in reference [11].

3. RESULTS AND DISCUSSION

To enhance the yield and retention of fission products, an alternative hybrid reactor model has been proposed based on the concept of concentric shells. These shells are constructed using a specialized tungsten-based alloy known as cermet, which enables the reactor to operate at temperatures approaching 3000 K.

Cermets—composite materials combining ceramic and metallic phases—were originally developed for nuclear reactors intended for aerospace propulsion applications, as detailed in reference [12]. In this conceptual design (see *FIG. 2*), the reactor consists of a nuclear fusion device that produces 14 MeV neutrons, which in turn drive a subcritical fission assembly. The fuel configuration employs cermet shells composed of tungsten and uranium dioxide enriched to 50%, denoted as W/[U (50%) O_2].

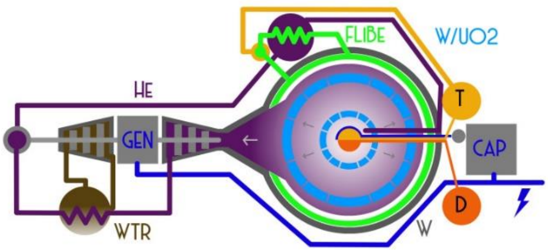

FIG. 2. Scheme of the conceptual design given by ref [12].

The introduction of cermet materials into the fission layers significantly elevates the core temperature, rendering lithium silicates unsuitable due to their thermal instability and tendency to decompose under such conditions. A viable solution is to replace these silicates with molten salts containing lithium, which offer superior thermal resilience. One of the most promising candidates is FLiBe—a eutectic mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2)—known for its high-temperature stability, favorable neutronic properties, and compatibility with fast-spectrum reactors.

As presented in reference [13] and illustrated in FIG. 3, the resulting neutron spectrum closely resembles that of conventional fast fission reactors. Under these conditions, water cannot be used as a coolant due to its strong moderating effect, which would shift the neutron energy distribution toward thermal levels and compromise the fast-spectrum environment. Instead, inert gases such as helium are required to preserve the fast neutron flux essential for efficient transmutation and sustained fission reactions.

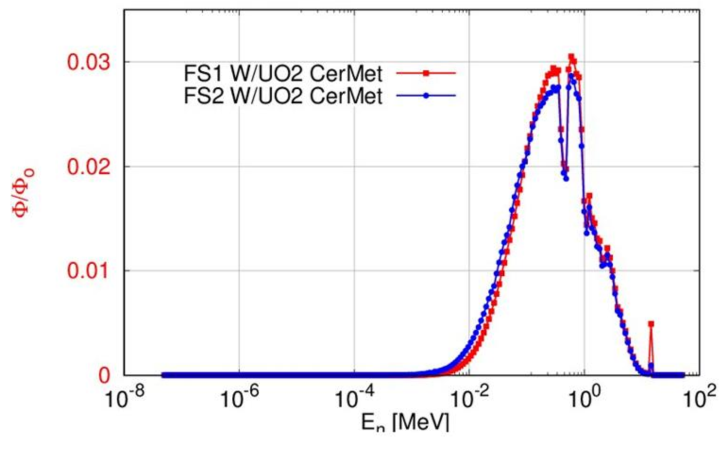

FIG. 3. Neutron spectra in the two fuel layers, showing that the FFHR behaves like a fast neutron reactor [13].

To evaluate the structural stability of cermet materials under irradiation, FIG.4 presents a damage distribution obtained using the IMPC5 Monte Carlo simulation. The simulated target consists of a tungsten prism measuring $30 \times 30 \times 40$ nm^3, with the 40 nm dimension aligned along the z-axis—the average direction of the incident beam. Embedded at the center of the prism is a 15 nm uranium dioxide (UO_2) sphere.

The irradiation scenario involves a 150 keV proton beam with a Gaussian angular distribution. This setup simulates realistic beam divergence, where most protons strike the surface at near-normal incidence, while a fraction enters at oblique angles. As illustrated in the figure, at 150 keV, the protons lack sufficient energy to displace tungsten atoms; atomic displacements are confined to the UO_2 sphere.

At higher proton energies, additional mechanisms such as electronic sputtering become significant contributors to surface erosion. In these cases, a substantial portion of the ion energy is transferred to the electronic subsystem along the ion track, leading to localized excitation and potential degradation of material properties.

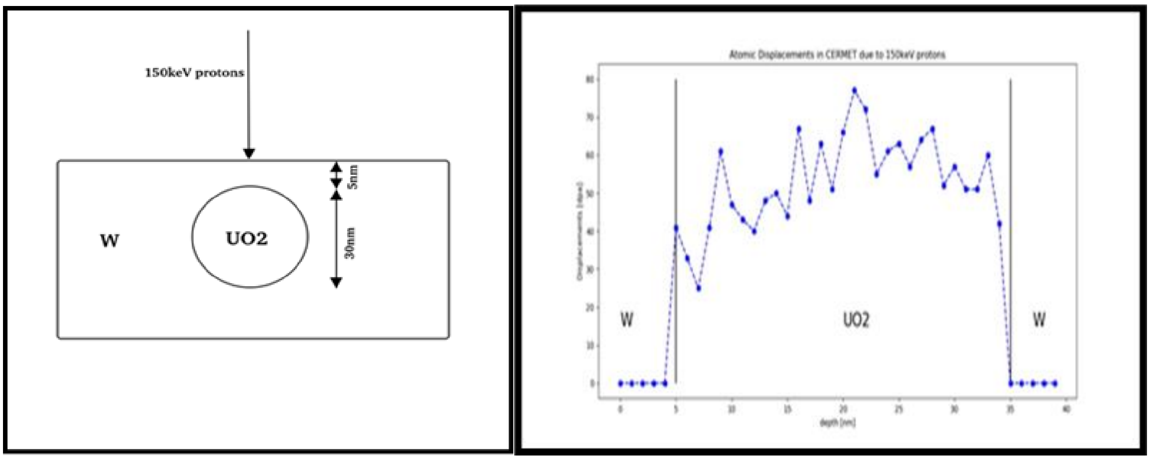

FIG. 4: Scheme (left) and damage in the Cermet (right), using IMPC5 simulation.

4. CONCLUSIONS

The cermet alloys investigated in this study exhibit robust thermophysical properties and, based on irradiation data from fast reactors exceeding 100 displacements per atom (dpa), demonstrate notable resistance to swelling and high-temperature embrittlement. From the perspective of their interaction with gaseous coolants, simulations indicate that at the studied proton energies, atomic displacements within the cermet matrix do not occur. Moreover, tungsten-based cermets show good compatibility with helium, reinforcing their suitability for fast-spectrum reactor environments.

However, several unresolved challenges remain regarding the long-term behavior of the coolant in contact with cermet materials. In particular, at these energy levels, corrosion mechanisms must be thoroughly examined to understand the chemical and structural effects induced by helium interaction.

Further research should focus on the detailed thermal and mechanical characterization of the fuel region, especially the temperature-dependent properties of tungsten. Key parameters such as phonon dynamics, elastic moduli, hardness, and thermal conductivity must be evaluated to ensure material integrity and reactor performance under extreme operating conditions.

5. REFERENCES

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