Preliminary Design and Thermal-Burnup Analysis of HANARO Irradiation Test for UCO TRISO Fuel

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1. Introduction

KAERI has been developing TRISO-coated particle fuel for High-Temperature Gas-cooled Reactor (HTGR) applications [1, 2]. Through prior research, KAERI acquired TRISO fabrication technology and successfully conducted an irradiation test in the HANARO research reactor [3]. However, the fuel currently under development utilizes a UCO fuel kernel, features a significantly higher enrichment of 14.5% compared to previous designs, and has different compact dimensions and geometry. Once the development of this fuel is completed, an in-pile irradiation test is planned in HANARO to evaluate its irradiation and thermal performance.

This paper presents the in-pile irradiation test plan and preliminary rig design for the UCO TRISO fuel under development. Based on the preliminary design of the test rig, analysis results assuming irradiation in the HANARO OR6 irradiation hole are described. Because fuel with relatively high enrichment is loaded, a hafnium (Hf) shroud is applied to control the test section power, similar to previous irradiation tests [4]. A one-dimensional thermal analysis was conducted based on the preliminary fuel rod design to predict the fuel centerline temperature according to linear power. Based on these results, conservative test conditions were established by incorporating the HTGR conceptual design criteria. The results of this study will be utilized as basic data for preliminary performance and safety assessments of future HANARO irradiation tests.

2. Test Rig and Rod Design

The test rig to be utilized in this irradiation test adopts the proven rig structure previously used for Light Water Reactor (LWR) fuel irradiation tests. The existing rig consists of upper and lower clusters that can be independently inserted and discharged, allowing distinct irradiation environments to be realized in each cluster.

The lower cluster directly adopts the specifications and enrichment (14.5%) of the HTGR fuel to perform a standard burnup test, whereas the upper cluster is designed for an accelerated irradiation test by adjusting the enrichment or TRISO packing fraction. The fuel rod dimensions were determined based on the specifications of HTGR fuel rods. A stainless-steel-based cladding is applied to ensure structural integrity, and the fuel rod interior is backfilled with helium gas to enhance heat transfer.

Fig. 1 shows the cross-sectional arrangement of fuel rods within the lower cluster in the HANARO OR6 irradiation hole. Four fuel rods are symmetrically arranged within a single cluster. In the lower cluster, all rods have the same high enrichment and standard packing fraction, resulting in high power generation; therefore, an Hf shroud is placed around the test section to attenuate the thermal neutron flux and suppress excessive linear power. Conversely, the upper cluster will control total cluster power by adjusting the enrichment or packing fraction, while maximizing the power per TRISO particle to enable performance evaluation under accelerated burnup conditions.

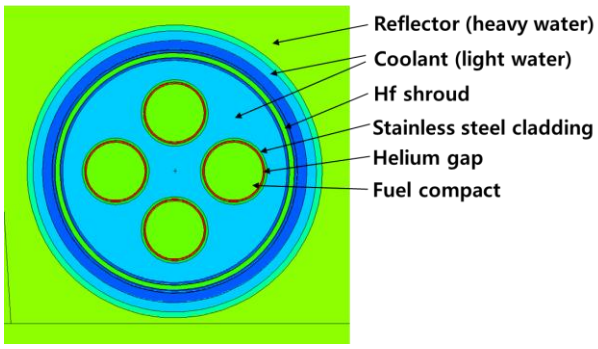


Fig. 1. Horizontal schematic diagram (MCNP model) of test rig structure in OR6 irradiation hole

3. Thermal and Neutronic Estimation for Test

3.1 Thermal Analysis

The fuel compact-to-cladding gap was set to 0.08 mm based on LWR fuel irradiation test experience and manufacturing tolerances. Fig. 2 shows the calculated fuel centerline temperature as a function of the linear heat generation rate (LHGR) under this gap condition.

According to the HTGR conceptual design criteria, the maximum fuel centerline temperature during normal operation is evaluated to reach approximately 1250°C. However, because an HTGR uses helium gas as a

coolant, its cooling performance is lower than that of the water-cooled HANARO environment. Therefore, for conservative evaluation in this test, the test conditions are designed such that the average centerline temperature throughout the entire irradiation cycle (EOL) satisfies 1250°C. These analysis data will be used to predict temperature changes within the fuel rod and determine operating parameters.

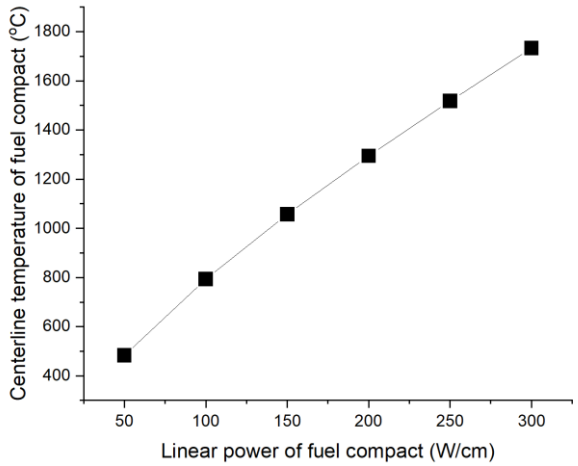


Fig. 2. Calculation result of centerline temperature by linear power of fuel compact

3.2 Neutronic Analysis

Fig. 3 shows the variation in the average linear power of the fuel compact as a function of the Hf shroud thickness in the lower cluster. As the Hf shroud thickness increases, the linear power decreases due to enhanced thermal neutron absorption. Without the Hf shroud, the average linear power reaches nearly 600 W/cm, whereas applying an Hf shroud with a maximum thickness of 1.0 mm can effectively reduce the linear power to approximately 240 W/cm.

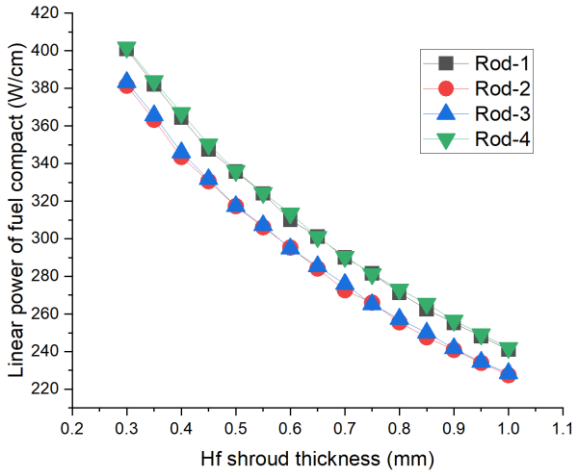


Fig. 3. Linear power of fuel compact by Hf shroud thickness

Fig. 4 presents the axial linear power distribution of a representative fuel rod (Rod-1), assuming an Hf shroud thickness of 0.5 mm. Owing to 3D core neutron behavior and boundary leakage/reflection effects, relatively higher local linear power occurs at the axial extremities compared to the central region. Consequently, some axial burnup gradient is expected to develop within the fuel rod during long-term irradiation.

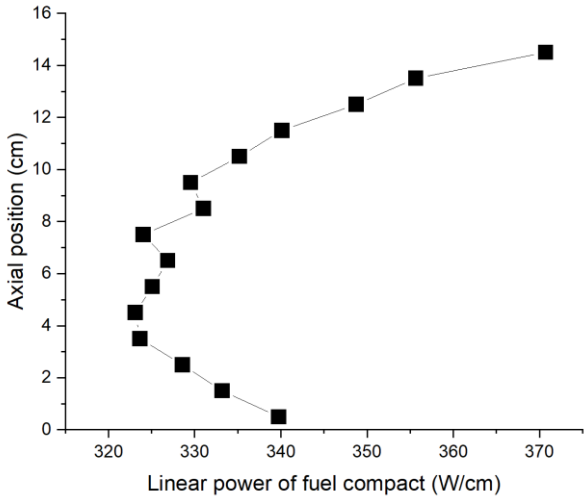
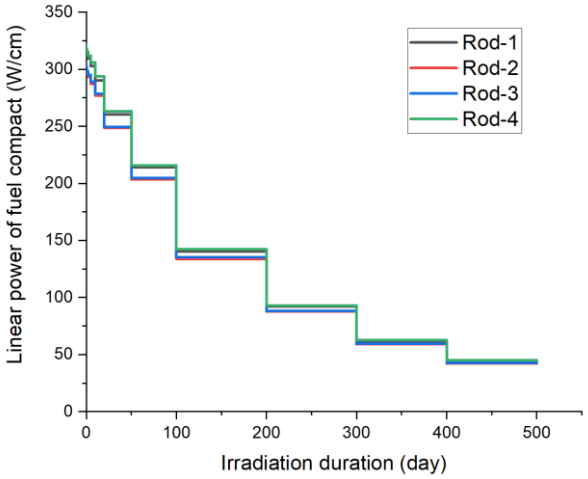
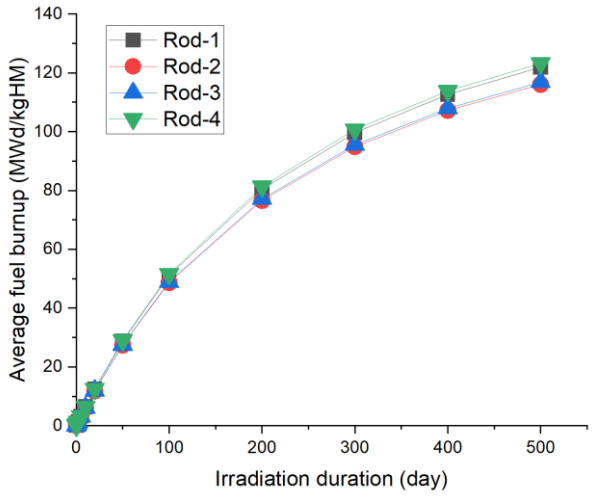


Fig. 4. Linear power of fuel compact at each axial position of Rod-1

Fig. 5 shows the linear power variation and cumulative burnup of the fuel during irradiation. Although a fixed-core model was utilized, which has limitations in absolute precision, the overall burnup trends can be clearly observed. As shown in Fig. 5(a), the linear power decreases rapidly as irradiation progresses. This is attributed to the relatively high initial enrichment (14.5%), which causes a higher initial consumption rate of U-235 compared to lower-enriched fuels. The cumulative burnup accumulation with irradiation time is shown in Fig. 5(b). During the initial period of approximately 150 days, a burnup of about 70 MWd/kgHM is expected to be achieved smoothly. However, beyond this point, the burnup accumulation rate decreases significantly due to the rapid decline in linear power. To achieve higher burnup more efficiently during long-term testing, it is considered necessary to gradually reduce the Hf shroud thickness or implement additional rig design optimization methods.



(a)



(b)

Fig. 5. (a) Linear power decrease by depletion and (b) burnup increase of fuel compact

4. Conclusions

In this study, the preliminary design of an irradiation test for the newly developing UCO TRISO fuel in the HANARO OR6 hole was established, and preliminary neutronic, burnup, and thermal analyses were performed.

(1) A two-stage upper/lower cluster structure was adopted to establish independent environments for standard and accelerated burnup testing.

(2) An Hf shroud was applied to control excessive linear power from the high-enrichment fuel, and the linear power attenuation characteristics according to shroud thickness were evaluated.

(3) Conservative test conditions satisfying the HTGR design criterion (1250°C) were determined through 1D thermal analysis.

(4) The burnup accumulation characteristics and the necessity of optimizing shroud thickness during irradiation were identified through burnup analysis.

The preliminary design and analysis results presented in this paper will serve as essential foundational data for the detailed rig design and safety analysis report (SAR) for future HANARO irradiation tests of UCO TRISO fuel.

ACKNOWLEDGEMENTS

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