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Accelerated Irradiation Test Design for Performance Assessment of LEU+ Fuel in HANARO

Seongwoo Yang[a*], Junesic Park[a], Sung-Jae Park[a], Dong-Joo Kim[b]
[a]HANARO Utilization Division and [b]LWR Fuel Technology Research Division,
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beongil, Yuseong-gu, Daejeon, 34057
[*]Corresponding author: swyang@kaeri.re.kr

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1. Introduction

As the global energy transition accelerates in response to climate change and the pursuit of carbon neutrality, nuclear energy is being re-evaluated as a stable and efficient carbon-free power source. Small Modular Reactors (SMRs), in particular, are emerging as a leading next-generation nuclear technology, offering enhanced safety, flexible power control, and reduced construction times and costs through modular fabrication[1]. However, the widespread adoption and long-term sustainability of SMRs hinge on resolving the fundamental challenge of spent nuclear fuel (SNF) management. The high radioactivity and heat of SNF necessitate long-term, secure storage and disposal, which incurs significant social and economic costs. Therefore, enhancing the competitiveness and public acceptance of SMRs requires the development of innovative fuel technologies that minimize SNF generation per unit of electricity produced.

A primary strategy for reducing SNF volume is to increase the fuel's discharge burnup, thereby extending its operational lifetime within the reactor. Achieving higher burnup not only lengthens the refueling cycle and improves the reactor's capacity factor but also reduces the total amount of fuel required, leading to a direct decrease in SNF generation. In this context, research has commenced on LEU+ fuel[2], which features a higher uranium-235 enrichment than conventional low-enriched uranium (LEU) to maximize performance. The objective of LEU+ fuel is to enable long-cycle SMR operation for improved economics while simultaneously reducing SNF accumulation to enhance the overall sustainability of nuclear power.

However, the conventional path to commercializing a new fuel design involves in-reactor demonstration tests that can span several years to decades, posing a significant bottleneck to technological advancement. To overcome this temporal constraint and expedite performance evaluation, accelerated irradiation testing presents a viable alternative. This paper details the design of an accelerated test for LEU+ fuel within the High-flux Advanced Neutron Application Reactor (HANARO). The successful execution of this test is expected to enable the rapid accumulation of high-burnup data, facilitating a timely assessment of the fuel's performance under extended operational conditions.

2. Nuclear fuel test in HANARO

2.1 Test capability for nuclear fuel test

Fig. 1 illustrates the MCNP evaluation model of the HANARO core. The core is operated with driver fuel consisting of twenty 36-pin hexagonal fuel assemblies and twelve 18-pin circular fuel assemblies. The positions not occupied by driver fuel—designated CT, IR 1-2, and OR 3-6—are utilized as test holes for irradiation experiments. The central test (CT) and inner region (IR) holes are surrounded by driver fuel, resulting in a high fast-neutron flux suitable for nuclear material tests requiring significant displacement damage. Conversely, the outer region (OR) holes exhibit a relatively high thermal neutron flux, making them ideal for fuel and instrumentation tests. Due to the diagonally symmetric positioning of the control rod absorbers, the thermal neutron flux generally varies across the test holes in the following order: OR4, 5 < OR 3, 6 < IR 1, 2 < CT.

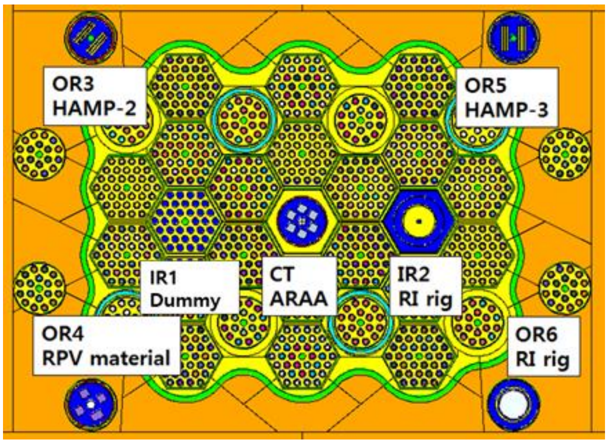

Fig. 1. MCNP model example of HANARO core

Fig. 2 shows a typical static rig used for nuclear fuel irradiation tests. This type of rig is utilized for non-instrumented tests where sensors are not required to measure specific fuel characteristics. The test rig generally consists of upper and lower clusters, which can be replaced (i.e., inserted and withdrawn) after reaching a target burnup. Each cluster can accommodate four test rods, with each rod having an independent coolant flow channel; the number of rods can be increased if the flow channels are shared. Because the rig is fixed within the test hole, the neutronic conditions experienced by the test rods vary with changes in the overall core environment. In HANARO, these variations can be quite significant even within a single operational cycle, primarily due to the large reactivity worth of the control rod absorbers.

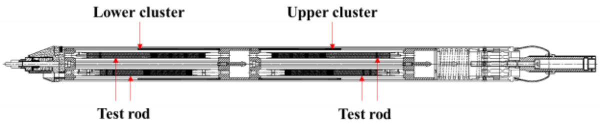

Fig. 2. Schematic drawing of fuel test rig in HANARO

Nuclear fuel tests at the HANARO facility are typically performed in the OR test holes. The thermal neutron flux in these OR holes is significantly higher than in commercial reactors, which necessitates precise control of the linear heat generation rate (LHGR). In HANARO, the LHGR of the test rods has been primarily controlled by using a hafnium (Hf) shroud to moderate the neutron flux. Fig. 3 shows the heat generation of CSBA pellets, currently under testing in the OR4 position, as a function of the Hf shroud's thickness[3]. For this particular fuel, with a U-235 enrichment of 4.5 wt%, the local maximum LHGR reached approximately 95 kW/m without the application of the Hf shroud. Considering that the typical local maximum LHGR for fuel in a commercial reactor is around 40 kW/m, it is evident that very high power conditions can be achieved. Therefore, the sufficient thermal neutron flux in HANARO enables a wide variety of fuel irradiation tests.

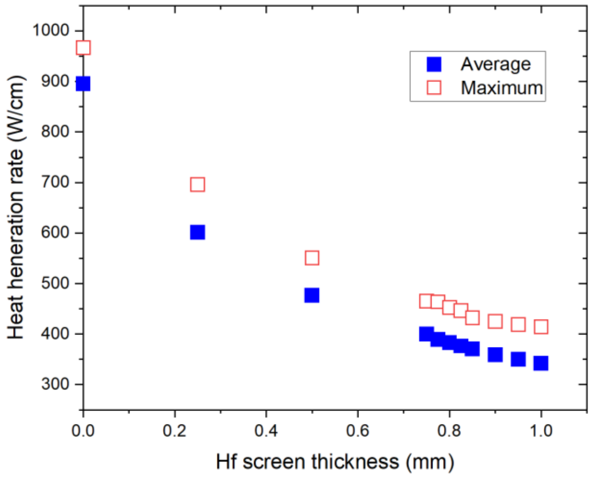

Fig. 3. Linear heat generation rate of CSBA-loaded pellets according to the Hf shroud thickness in OR4 irradiation hole

2.2 LEU+ fuel test

A performance evaluation for LEU+ fuel with enrichments of 5 wt% or higher has been planned at the HANARO reactor. While tests on CSBA pellets and KAERI's Accident Tolerant Fuel (ATF) are ongoing, one of their clusters will be withdrawn to initiate the LEU+ fuel irradiation test [3]. As shown in Fig. 4, the test cluster is configured with fuel rods of varying enrichments (4.5, 6, 7, and 9 wt%), pellets with a high Gd_2O_3 content (up to 24 wt%), and KAERI ATF test rods.

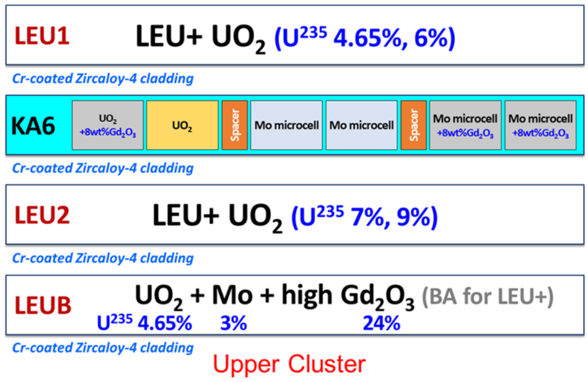

Fig. 4. Test rods configuration of LEU+ fuel test cluster

To support the design and evaluation of this experiment, a neutronic analysis was performed using MCNP6[4], simulating an equilibrium core state for HANARO. Fig. 5 displays the MCNP models of the test rig in both horizontal and axial views. In this configuration, test rods with lower enrichment levels were positioned adjacent to the reactor core, while the higher-enrichment LEU+ fuel rods were placed on the periphery. The Hf shroud was not applied in this test due to significant procurement challenges and its high cost. Consequently, the cluster's structural material was changed from aluminum alloy to stainless steel, and the active fuel section of the test rods was relocated to the top of the cluster.

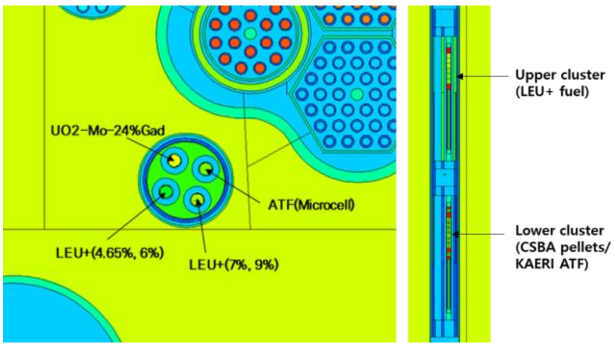

Fig. 5. MCNP model for LEU+ fuel test

Table I presents the results of the neutronic analysis for the planned test at the beginning, middle, and end of the cycle at the first operation cycle of HANARO. The coolant temperature in HANARO is only 40°C, which is considerably lower than that of a commercial reactor. This lower operating temperature allows the test rods to be subjected to a higher LHGR. Typically, the LHGR in

HANARO is controlled up to a maximum of 50 kW/m, and to ensure a conservative safety margin, the local maximum LHGR is limited to approximately 60 kW/m.

Table I: LHGR evaluation results for LEU+ fuel test cluster at the beginning of test

Material	LHGR (kW/m)			
	BOC	MOC	EOC-1	EOC-2
H-LEU_1-1(7%)	63.81	71.96	82.63	83.32
H-LEU_1-2(7%)	56.25	62.19	72.23	74.40
H-LEU_1-3(7%)	52.99	59.74	69.19	72.22
H-LEU_1-4(9%)	61.65	69.86	80.25	84.24
H-LEU_1-5(9%)	59.93	66.58	79.56	82.97
H-LEU_1-6(9%)	68.69	77.60	89.10	94.99
H-LEU_2-1(4.65%)	44.23	51.03	58.26	57.70
H-LEU_2-2(4.65%)	39.35	43.38	51.13	51.21
H-LEU_2-3(4.65%)	36.51	41.30	47.81	50.08
H-LEU_2-4(6%)	43.79	48.82	55.51	59.51
H-LEU_2-5(6%)	43.15	47.87	55.76	59.23
H-LEU_2-6(6%)	49.30	53.71	63.33	67.07
H-LEU_3-1(24%Gad)	2.11	2.45	2.97	2.91
H-LEU_3-2(24%Gad)	1.85	2.22	2.66	2.88
H-LEU_3-3(24%Gad)	1.85	2.22	2.65	2.76
H-LEU_3-4(24%Gad)	1.79	2.11	2.67	2.74
H-LEU_3-5(24%Gad)	1.70	2.10	2.54	2.66
H-LEU_3-6(24%Gad)	1.80	2.03	2.61	2.75
H-ATF-1(Microcell+8%Gad)	3.83	4.76	5.45	5.49
H-ATF-2(Microcell+8%Gad)	3.68	4.24	5.20	5.28
H-ATF-3(Microcell)	36.47	42.28	55.06	56.49
H-ATF-4(Microcell)	36.15	43.28	55.09	58.66
H-ATF-5(UO2)	33.14	37.58	48.65	52.23
H-ATF-6(UO2+8%Gad)	3.55	4.07	5.07	5.55

The analysis revealed that while the most of test rods of LEU+ fuel with enrichments of 6% or less, the KAERI ATF, and the high-content Gd_2O_3 remained within the 60 kW/m limit, the 7% and 9% LEU+ fuel rods exhibited an LHGR exceeding 70 kW/m. Therefore, the current design configuration is unsuitable for testing the 7% and 9% LEU+ fuel. Although applying the Hf shroud is a conventional method for LHGR control, its procurement is currently very difficult. Moreover, applying the Hf shroud to the entire cluster would excessively suppress the LHGR of the other test rods, unacceptably slowing their burnup accumulation. To resolve these challenges, a new approach must be devised.

3. Fuel dimension reducing for acceleration test

As discussed in Section 2, the HANARO reactor possesses a sufficient neutron flux to conduct nuclear fuel tests. However, using test rods with the same specifications as those in commercial reactors leads to an excessively high fuel centerline temperature, which has traditionally been controlled with the Hf shroud. Since HANARO is not equipped with a loop facility to simulate a commercial reactor environment, its capabilities are better suited for evaluating burnup-dependent characteristics rather than observing integral test effects. Therefore, an accelerated test methodology was adopted to maximize these advantages for the LEU+ fuel experiment. This approach offers the distinct benefit of enabling the observation of fuel behavior in the high-burnup region—the primary area of interest—within a relatively short timeframe.

The accelerated test method involves modifying the fuel's dimensions. Reducing the fuel size decreases heat generation; specifically, reducing the pellet diameter is highly effective in lowering the centerline temperature due to the inherently low thermal conductivity of ceramic fuel. Table II presents a conservative evaluation of the LHGR at the end of operation cycle for the LEU+ fuel with reduced pellet diameters. When the pellet diameter was reduced by 10%, 20%, and 30%, the average LHGR of the test rods decreased to 87.1%, 64.0%, and 56.7% of the original value, respectively. For the LEU+ fuel test, a 20% reduction in diameter is sufficient to bring the LHGR for most of the rods within the 60 kW/m limit, making the test feasible.

Table II: LHGR evaluation by reducing pellet dimension of 7 and 9% LEU+ fuel

Material	LHGR (kw/m) @ EOC-2			
	Normal	10% red	20% red	30% red
H-LEU_1-1(7%)	83.32	70.44	53.36	45.84
H-LEU_1-2(7%)	74.40	66.20	47.65	42.42
H-LEU_1-3(7%)	72.22	63.74	46.25	41.37
H-LEU_1-4(9%)	84.24	73.22	53.95	49.37
H-LEU_1-5(9%)	82.97	74.55	53.13	48.25
H-LEU_1-6(9%)	94.99	80.68	60.84	51.83

This 20% reduction in diameter corresponds to a fuel volume that is 64% of the original. Since burnup is calculated by the heat generation rate per unit mass of uranium, the burnup accumulation rate is inversely proportional to the fuel mass and can thus be significantly increased. For example, the KAERI ATF currently under testing in HANARO has reached a burnup of approximately 14,000 MWD/tU in one year. Assuming the same irradiation period and similar LHGR, the LEU+ fuel in an accelerated test could achieve a burnup of approximately 21,875 MWD/tU. Consequently, this method allows for rapid verification of fuel performance at high burnups through post-irradiation examination.

4. Conclusions and Future works

An irradiation test for LEU+ fuel is planned for the HANARO reactor. However, the high linear heat generation rate of the higher-enrichment fuel poses significant limitations, and the conventional use of the Hf shroud for power control is not a feasible option. To overcome this challenge, an accelerated test concept has been applied.

It was confirmed that by reducing the fuel pellet diameter by approximately 20%, the fuel rods can meet the required safety margins for the test. This modification is also expected to increase the burnup accumulation rate by about 1.5 times compared to the standard design, enabling faster results. However, the reduced fuel dimensions necessitate more complex analysis, evaluation, and simulation to study its performance.

The accelerated test will be conducted using LEU+ fuel pellets fabricated to a diameter of 6.27 mm. This experiment is scheduled to begin at the end of 2025, and it will serve to validate the effectiveness of the accelerated testing methodology.

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