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Original Article

# Analysis on the post-irradiation examination of the HANARO miniplate-1 irradiation test for kijang research reactor

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ABSTRACT

The construction project of the Kijang research reactor (KJRR), which is the second research reactor in Korea, has been launched. The KJRR was designed to use, for the first time, U–Mo fuel. Plate-type U–7 wt.% Mo/Al–5 wt.% Si, referred to as U–7Mo/Al–5Si, dispersion fuel with a uranium loading of 8.0 gU/cm$^3$, was selected to achieve higher fuel efficiency and performance than are possible when using $U_3Si_2$/Al dispersion fuel. To qualify the U–Mo fuel in terms of plate geometry, the first miniplates [HANARO Miniplate (HAMP-1)], containing U–7Mo/Al–5Si dispersion fuel (8 gU/cm$^3$), were fabricated at the Korea Atomic Energy Research Institute and recently irradiated at HANARO. The PIE (Post-irradiation Examination) results of the HAMP-1 irradiation test were analyzed in depth in order to verify the safe in-pile performance of the U–7Mo/Al–5Si dispersion fuel under the KJRR irradiation conditions. Nondestructive analyses included visual inspection, gamma spectrometric mapping, and two-dimensional measurements of the plate thickness and oxide thickness. Destructive PIE work was also carried out, focusing on characterization of the microstructural behavior using optical microscopy and scanning electron microscopy. Electron probe microanalysis was also used to measure the elemental concentrations in the interaction layer formed between the U–Mo kernels and the matrix. A blistering threshold test and a bending test were performed on the irradiated HAMP-1 miniplates that were saved from the destructive tests. Swelling evaluation of the U–Mo fuel was also conducted using two methods: plate thickness measurement and meat thickness measurement.



## 1. Introduction

U–Mo alloy, in a U–Mo/Al dispersion fuel form, one of the most promising new fuel candidates owing to its high uranium density as well as excellent irradiation performance, is being developed extensively to convert from highly enriched uranium fuel to low enriched uranium fuel for high-performance research and test reactors [1]. However, the formation of an interaction layer (IL) between U–Mo particles and the Al matrix, and the associated pore formation, under high heat flux and high burnup conditions, degrade the irradiation performance of the U–Mo/Al dispersion fuel [2–9]. One remedy to overcome the interaction problem in U–Mo/Al dispersion fuel has focused mostly on Si addition to the Al matrix. Because Si has a higher chemical affinity for U than Al does, an Si-rich layer formed at the interface between the U–Mo particles and the Al matrix can act as a diffusion barrier and reduce the rate of interaction between the U–Mo and the Al during irradiation [10,11]. Because a Si addition to the Al matrix to suppress IL growth in the U–Mo/Al dispersion fuel was proposed to stabilize the ILs, there have been numerous out-of-pile [12–25] and in-pile tests [26–55] conducted to examine the Si effect. It has been commonly accepted that Si addition to Al in U–Mo dispersion fuel, even in small amounts (e.g., 2–5 wt.% Si), effectively reduces IL growth and further delays pore formation and growth in ILs under moderate heat flux conditions (e.g., <~250 W/cm$^2$). However, there is still uncertainty regarding the bounding conditions of the fission rate and burnup for the onset of breakaway swelling, below which U–Mo dispersion fuel shows safe and predictable in-pile performance behavior.

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In April 2012, the Korea Atomic Energy Research Institute (KAERI) launched the construction of the Kijang research reactor (KJRR), as a major national project for nuclear science and engineering, aiming at (1) satisfying domestic and global needs for medical and industrial radioisotopes including Mo-99, (2) providing sufficient industrial demand for neutron transmutation doping, and (3) facilitating the utilization of radioisotopes related research [56]. It is worth noting that U–Mo fuel will be loaded in the KJRR as part of the world's first commercialized use of such fuel. Plate-type U–7 wt.% Mo/Al–5 wt.% Si dispersion fuel, U–7Mo/Al–5Si hereafter, with a uranium loading of 8.0 gU/cm$^3$, was selected to achieve greater efficiency and higher performance than are possible when using $U_3Si_2$/Al fuel; this reactor will as a result be able to operate with a longer fuel cycle (~50 days/cycle). It was also confirmed, through previous in-pile and out-of-pile experiments using U–Mo fuel, that the KJRR fuel will exhibit safe and sound irradiation behavior under the Kijang operation conditions of heat flux (average ~40 W/cm$^2$ and local peak ~120 W/cm$^2$), and burnups (average ~65 at.% U-235 and local peak >~80 at.% U-235), respectively [57]. Although adding 2 wt.% silicon to the Al matrix can effectively suppress the IL growth in U–Mo/Al dispersion fuel, the addition of 5 wt.% Si was decided on to obtain a sufficient margin of fuel swelling owing to irradiation-induced IL growth. The fission rate of the KJRR is much lower than the fission rates that the European and US U–Mo fuel development programs are interested in for high-performance research reactors. However, qualification of the fuel by demonstrating the mechanical integrity, geometric stability, acceptable dimensional changes, and assurance that the performance of the fuel is stable and predictable during the irradiation period will be necessary.

In addition to the LTA (Lead Test Assembly) that was built and is now being irradiated at the ATR (advanced test reactor) at INL (Idaho National Laboratory), USA, the HANARO miniplate irradiation tests (HAMP-1, 2, and 3) were planned for the sake of a comprehensive fuel qualification of the fuel design, manufacturing, and in-pile performance. Table 1 provides a list of the important parameters for the HAMP and LTA irradiation tests, by which a series of fuel performance data with different plate sizes, heat fluxes, and burnups will be obtained to verify the stable in-pile performance behavior of the KJRR fuel. The HAMP-1 miniplate irradiation test was designed to provide basic irradiation data including the fuel behavior up to a fuel burnup of about 60% to 65% U-235 depletion under heat flux of ~220 W/cm$^2$ on average. In this study, a postirradiation analysis of plate-type U–7Mo/Al–5Si dispersion fuel from the HAMP-1 miniplates was performed in-depth in order to verify the safe in-pile performance behavior of the U–Mo fuel under the KJRR irradiation conditions.

The significance of the HAMP-1 test is twofold. One aspect is that this is the first test of plate-type U–Mo/Al or U–Mo/Al–Si dispersion fuels fabricated at KAERI. The other aspect is that this test will demonstrate the viability of the fuel design planned for use as the driver fuel for KJRR. Therefore, a good in-pile performance of the fuel was considered a stepping stone for the world's first use of this fuel in a commercial reactor; the future contribution by KAERI to the global research and test reactor community in high-density fuel development also hinges on this experiment.

## 2. Experiment description

The HAMP-1 test, utilizing atomized U–7Mo particles dispersed in Al–5Si, consists of six miniplates with a U loading of 8.0 gU/cm$^3$ and two plates with a loading of 6.5 gU/cm$^3$. The irradiation capsule, called 13F-05K, consists of two clusters (upper and lower), each of which contains four miniplates, as shown in Figs. 1 and 2. Each plate is inserted into the slots inside the cluster, and its axial movement is restrained by the upper and lower stoppers. The HAMP-1 test plates were irradiated at the OR3 hole in the HANARO for four cycles (#92–#95), with a 111.4-EFPD (effective full power day) residence time from January 27, 2014 to June 18, 2014, while nearly facing the core center. The fission rate for the HAMP-1 irradiation, a crucial irradiation parameter, was designed to be high enough, compared to the KJRR irradiation condition in terms of the fuel qualification in which the irradiation performance of U–7Mo/Al–5Si dispersion fuel under the HAMP-1 condition was evaluated, to be safe and predictable even after ~60% burnup.

For the safety assessment of the HAMP-1 irradiation test, nuclear calculations were performed using the McCARD (Monte Carlo Code for Advanced Reactor Design and analysis) code, which is one of the Monte Carlo codes [58]. McCARD is capable of performing burnup calculation using the built-in depletion equation solver module. To calculate the heat flux and burnup, the fuel meat zone of each miniplate was divided into 7 × 4 segments. The calculated results agree well with the calculation uncertainties. The current as-run analysis assumed a uniform fuel loading in the fuel meat.

**Table 1**
List of important parameters for the HAMPs and LTA irradiation tests.

| Parameters | HAMP-1 and -2 | HAMP-3 | FA irradiation (KJRR-LTA) |
|---|---|---|---|
| U-235 enrichment | 19.75 ± 0.2% | | |
| Number of plates | 10 (8.0 gU/cm$^3$)<br>2 (6.5 gU/cm$^3$) | 4 (8.0 gU/cm$^3$) | 19 (8.0 gU/cm$^3$)<br>2 (6.5 gU/cm$^3$) |
| Fuel meat dimension (mm) | 0.51 ± 0.03 (*T*)<br>25 ± 1.8 (*W*)<br>70 ± 5 (*L*) | 0.51 ± 0.03 (*T*)<br>25 ± 1.8 (*W*)<br>600 ± 5 (*L*) | 0.51 ± 0.03 (*T*)<br>62 ± 1.8 (*W*)<br>600 ± 5 (*L*) |
| Fuel plate dimension (mm) | 1.27 ± 0.05 (*T*)<br>35 ± 0.2 (*W*)<br>130 ± 0.5 (*L*) | 1.27 ± 0.05 (*T*)<br>35 ± 0.2 (*W*)<br>640 ± 0.5 (*L*) | 1.27 ± 0.05 (*T*)<br>70.7 ± 0.2 (*W*)<br>640 ± 0.5 (*L*) |
| Achieved/target BU ($U^{235}$ depletion %) | Ave. 62.4% (HAMP-1)<br>Ave. 70–75% (HAMP-2) | 70–75% (ave.)<br>85–90% (local peak) | ~85% (local peak) |
| Average heat flux at BOC, (W/cm$^2$) | 225 (HAMP-1)<br>140–150 (HAMP-2) | | 160 |
| Local peak heat flux at BOC, (W/cm$^2$) | 257 (HAMP-1)<br>170–180 (HAMP-2) | 135–145 | 188 |
| Flow rate in fuel channel (m/s) | 13.2 | 13.2 | 7.2 |
| Water gap in fuel channel (mm) | 2.13–2.20 | 2.13–2.20 | 2.35 |
| Irradiation hole | OR-3 (HANARO) | OR-5 (HANARO) | NEFT (ATR) |
| Irradiation Schedule | Jan. 27, 2014–June 14, 2014 (HAMP-1)<br>2017– (HAMP-2) | 2017– | Nov. 10, 2015–Feb. 2017 |

ATR, advanced test reactor; BOC, beginning of cycle; BU, burnup; FA, fuel assembly; HAMP-1, HANARO miniplate irradiation test; KJRR, Kijang research reactor; LTA, Lead Test Assembly; NEFT, North East Flux Trap.