Microstructure Evolution of Atomized U_3Si_2 Dispersion Fuel under Irradiation

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***Keywords : Research Reactor, Atomized, U_3Si_2, Irradiation, PIEs, Fuel Performance**

1. Introduction

The development of U_3Si_2 dispersion fuel has facilitated the transition of many commercial research reactors to low-enriched uranium (LEU) fuel. However, several high-power research reactors still rely on highly enriched uranium (HEU) fuels. Due to the anticipated long lead time for the commercial availability of U-Mo fuel, some European countries have opted to develop high-density U_3Si_2 dispersion fuel as an alternative for their high-power research reactors [1].

To qualify high-density atomized U_3Si_2 dispersion fuel, KAERI and SCK CEN initiated the KAERI high-density atoMized silicide fuel Qualification Irradiation (KIMQI) project to evaluate fuel performances under severe conditions. Recently, the KIMQI-FUTURE irradiation test and subsequent post-irradiation examinations were successfully completed. This study presents the microstructural characteristics of atomized U_3Si_2 dispersion fuel irradiated under different irradiation conditions and analyzes its performance.

2. Irradiation Summary of KIMQI-FUTURE test

The KIMQI-FUTURE irradiation test was conducted to satisfy the standard fuel requirements of HPRRs, targeting a local peak heat flux of 470 W/cm² at the beginning of cycle (BOC) and a local peak burnup of 70% U-235 at the end of cycle (EOC). KAERI fabricated full-size fuel plates with a uranium density of 5.3 gU/cm³ and successfully irradiated them in the BR2 reactor, achieving the target heat flux and burnup.

As summarized in Table 1, the KIMQI-004 plate reached a local peak burnup of 72.6% U-235 at the end of irradiation, with an average burnup of 48.6% U-235. It also exhibited a local peak heat flux of 473 W/cm² at BOC and an average heat flux of 281 W/cm². The other plates showed similar heat flux and burnup values, indicating comparable irradiation behavior [2].

Table 1. Key irradiation results of high-density U_3Si_2 fuel plate in BR2 [2]

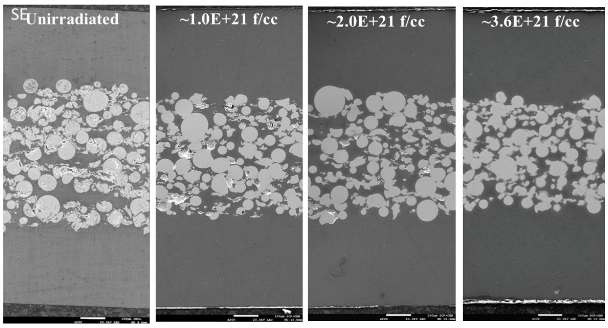
Plate ID	Avg. Heat Flux (W/cm²)	Peak Heat Flux (W/cm²)	Avg. ^{235}U Burnup EOC (%)	Peak ^{235}U Burnup EOC (%)
P002	280	464	48.9	72.5
P003	272	450	48.6	72.3
P004	281	473	48.6	72.6
P013	288	460	48.9	70.8

3. Results of Post-irradiation Examinations

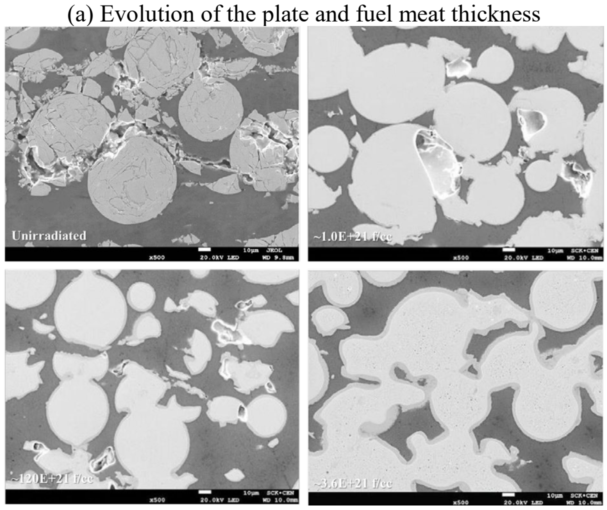
3.1. Microstructure Characteristics of Atomized U_3Si_2 Dispersion Fuel Irradiated in BR2

Fig. 1 shows the microstructural evolution of atomized U_3Si_2 dispersion fuel as a function of burnup. In the fresh fuel, most U_3Si_2 particles exhibited cracks due to their inherent brittleness. However, these cracks and as-fabricated pores progressively diminished with burnup, likely due to irradiation-induced annealing.

Fission gas bubbles became discernible at a fission density of approximately 1.5 × 10^{21} f/cc. The size and spatial distribution of these bubbles within the fuel kernel were non-uniform, and this inhomogeneity became more pronounced at higher burnup levels. At the highest burnup, both micro-sized bubbles and regions containing uniformly distributed nano-sized bubbles were observed.



(a) Evolution of the plate and fuel meat thickness



(b) Evolution of fuel meat microstructures

Fig. 1. Microstructure images of 5.3 gU/cm³ of high-density U_3Si_2 dispersion fuel plates as a function of burnup

As observed in the microstructural evolution, the formation of interaction layer (IL) between the fuel and the matrix was observed. As expected, the thickness of this layer increases with increasing burnup.

Fig. 2 shows the quantitative analysis for the IL and irradiated U_3Si_2 particle. From the linescan, it can be deduced that the layer consists of ~30.7 wt% Al, ~5.9 wt% Si and ~60.3 wt% U, which results in a composition of $U(Al,Si)_{5.4}$ with an Al/Si ratio of 5. In addition, it was confirmed that Si enriched phase distributed partially in the U_3Si_2 particle. This is consistent with other known results [3].

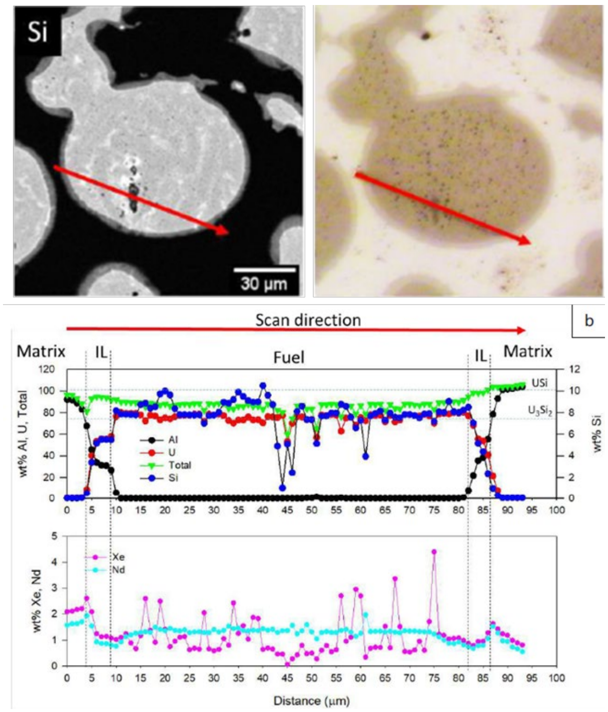


Fig. 2. Quantitative analysis for the irradiated high-density U_3Si_2 dispersion fuel

3.2. Fuel Performances Evaluation

The fuel performance of high-density atomized U_3Si_2 dispersion fuel was evaluated based on microstructural analysis. The volume fractions of the fuel, matrix, interaction layers (ILs), and pores were quantified, as shown in Fig. 3. The formation of ILs was confirmed by the gradual consumption of the Al matrix. Notably, a reduction in porosity was observed at a burnup of approximately 1.5×10^{21} f/cc, suggesting that as-fabricated pores may mitigate early-stage plate swelling during irradiation. However, once these pores are annihilated, further plate swelling is expected to occur. The as-fabricated pores were fully eliminated at a burnup of approximately 3.1×10^{21} f/cc.

The fuel swelling was evaluated based on microstructural analysis and compared with the results from non-destructive testing (NDT), as shown in Fig. 4. This indicates the swelling measurements obtained from NDT and destructive testing (DT) exhibited a consistent and linear increase in fuel swelling with increasing burnup.

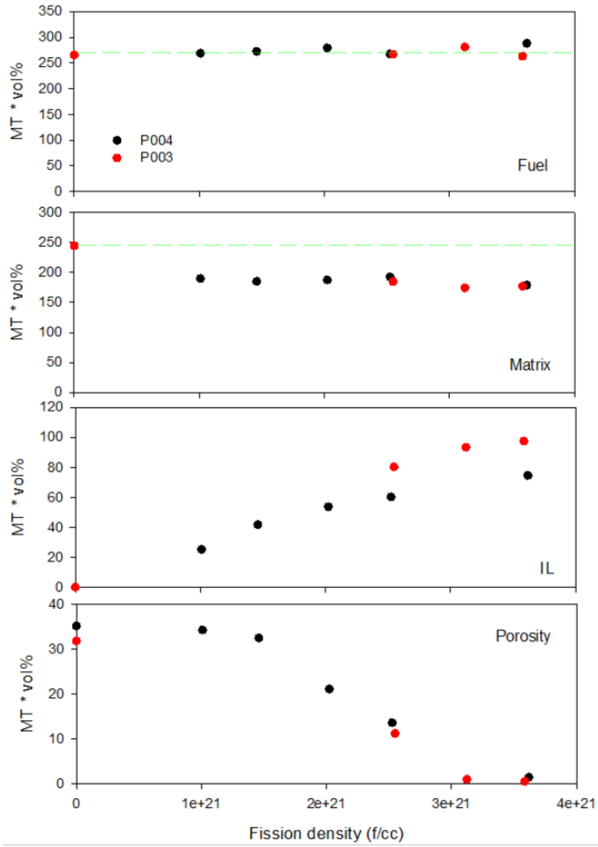


Fig. 3 Composition changes of high-density U_3Si_2 dispersion fuel as a function of burnup

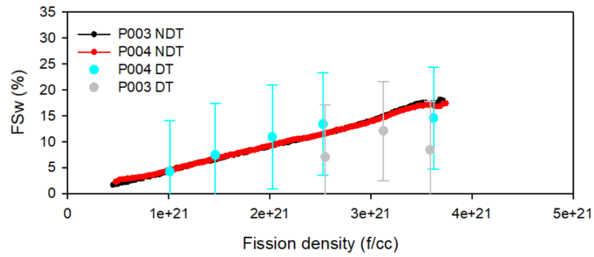


Fig. 4. Fuel swelling as a function of burnup

3. Conclusions

The KIMQI-FUTURE irradiation test successfully demonstrated the performance of high-density atomized U_3Si_2 dispersion fuel under HPRR conditions. The fuel plates, with a uranium density of 5.3 gU/cm³, achieved the target local peak heat flux (470 W/cm²) and burnup (70% U-235), confirming their suitability for high-power research reactors.

Microstructural analysis revealed that irradiation-induced annealing reduced cracks and as-fabricated pores, which disappeared entirely at a burnup of approximately 3.1×10^{21} f/cc. Fission gas bubbles appeared at approximately 1.5×10^{21} f/cc, becoming more heterogeneous with increasing burnup. The growth of the interaction layer (IL) between the U_3Si_2 particles and Al matrix was confirmed, with a composition of $U(Al,Si)_{5.4}$.

These findings indicate that atomized U_3Si_2 dispersion fuel exhibits favorable irradiation behavior and could serve as a viable alternative for the conversion of high-power research reactors to LEU fuel.

Acknowledgment

This research was supported by a grant from the Nuclear Energy and Safety Program of the National Research Foundation of Korea (NRF) funded by the Korean government (MSIT) (No. NRF-2021M2E5A1044519). We would like to express our sincere gratitude to Dr. S.H. Kim on behalf of the fabrication team at KAERI for their invaluable contribution to the fabrication of high-density U_3Si_2 fuel.

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