

Qualification Progress of Atomized U_3Si_2/Al Dispersion Fuel in KAERI

Tae Won Cho^{a,*}, Dong Jun Park^a, Jong Man Park^a, Yong Jin Jeong^a, Ann Leenaers^b, Jared Wight^b, Beatriz Acevedo^b
a: Research Reactor Fuel Division, KAERI, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Korea
b: SCK CEN, Boeretang 200, BE-2400 MOL, Belgium

*Corresponding author: twcho@kaeri.re.kr

***Keywords** : U_3Si_2 , Atomization, Research Reactor Fuel, High-density, Irradiation Test, Qualification

1. Introduction

The global initiative to minimize the use of highly enriched uranium (HEU) in research and test reactors (RRs) has driven a sustained demand for high-density, low-enriched uranium (LEU) fuels. Although U-Mo dispersion fuels were initially prioritized as a long-term solution, their qualification has been hampered by technical complexities, most notably the excessive growth of an amorphous interaction layer (IL) between the fuel and matrix.

As a reliable mid-to-long-term solution, KAERI has developed atomized U_3Si_2/Al dispersion fuel with a uranium density of 5.3 gU/cm^3 [1]. This study summarizes the comprehensive technical milestones achieved in the qualification of this fuel, with a focus on its in-pile performance and microstructural stability under high-power operating conditions.

2. Irradiation Tests of Atomized U_3Si_2/Al Fuel

As KAERI is currently the sole provider of atomized U_3Si_2 powder for dispersion fuels, the establishment of an independent irradiation database is critical, as existing literature is predominantly based on comminuted (crushed) powders. KAERI's qualification strategy involved a two-tier approach: preliminary validation through the HAMP irradiation test series in the HANARO reactor, followed by international generic qualification through the KIMQI (KAERI high-density atomized silicide fuel Qualification Irradiation) project in collaboration with SCK CEN in Belgium.

2.1 HAMP-2 Irradiation Test

The HAMP-2 campaign utilized U_3Si_2/Al mini-plates (4.8 gU/cm^3) to evaluate the fundamental irradiation behavior of atomized U_3Si_2 particles. These plates were irradiated in the OR-3 hole of the HANARO reactor for ten cycles (152.19 effective full power days). The as-run physics-thermal-hydraulic analysis confirmed that the USM09 plate achieved a highest peak burnup of 69.3% U-235 with a corresponding peak heat flux of 142.1 W/cm^2 . These results provided the first benchmark for the stability of atomized silicide fuel at high burnup levels.

2.2 KIMQI Irradiation Tests

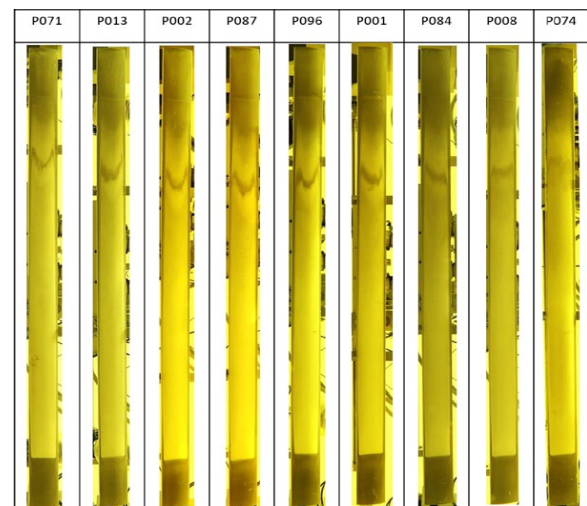
The KIMQI project was designed to validate fuel performance under the extreme conditions characteristic of high-flux Material Testing Reactors (MTRs). This project consists of two irradiation campaigns as follows. Both campaigns were conducted in the BR2 reactor, successfully reaching a peak burnup exceeding 70% U-235 and a peak heat flux of approximately 470 W/cm^2 .

- KIMQI-FUTURE: Performance verification program using flat plates to establish fundamental irradiation data.
- KIMQI-GTA: Generic qualification program utilizing curved plates and full-scale assemblies to demonstrate safety and mechanical integrity.

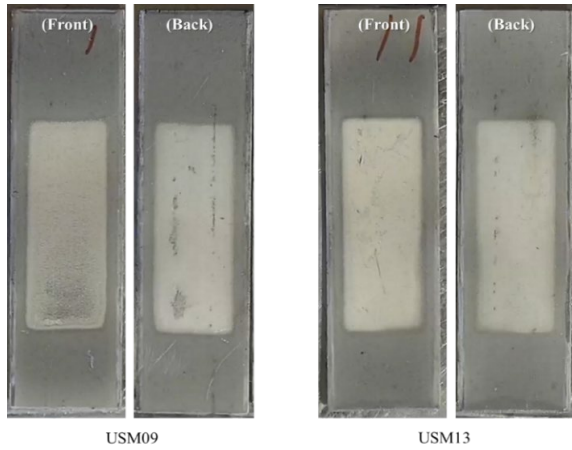
3. PIE Results of Atomized U_3Si_2/Al Dispersion Fuels

This section details the post-irradiation examinations (PIEs) of irradiated U_3Si_2 dispersion fuel plates from KIMQI-FUTURE, KIMQI-GTA, and HAMP-2 tests, providing overall fuel behaviors of atomized U_3Si_2/Al dispersion fuel under extreme condition of MTRs.

As seen in Fig. 1, visual examinations of the KIMQI-GTA and HAMP-2 plates revealed no signs of structural failure, such as blistering or debonding. While KIMQI-GTA plates exhibited a characteristic grainy surface with wavy patterns, this was identified as a normal morphological evolution of the oxide layer. HAMP-2 mini-plates remained in excellent condition, showing only localized oxide spallation attributable to post-irradiation handling rather than fuel instability.



(a) KIMQI-GTA plates



(b) HAMP-2 mini-plates

Fig. 1. Visual Appearance of Irradiated U_3Si_2/Al dispersion fuel plates

Fig. 2 and Fig. 3 show the microstructural evolution of the KIMQI-FUTURE and KIMQI-GTA plates. Their overall microstructural characteristics are similar, and no remarkable differences between them were observed. Several key observations confirm the integrity of the fuel system. First, as-fabricated pores progressively decreased with increasing burnup, consistent with pore annihilation behavior. Second, no excessive fuel–matrix interaction layer (IL) growth was observed; the IL remained thin and uniform around the particles. Third, fuel particles maintained their structural integrity without evidence of fragmentation. Similarly, no fission-gas bubble networks or coalescence features were identified within the fuel particles, indicating effective retention of fission gases and stable fuel-particle morphology.

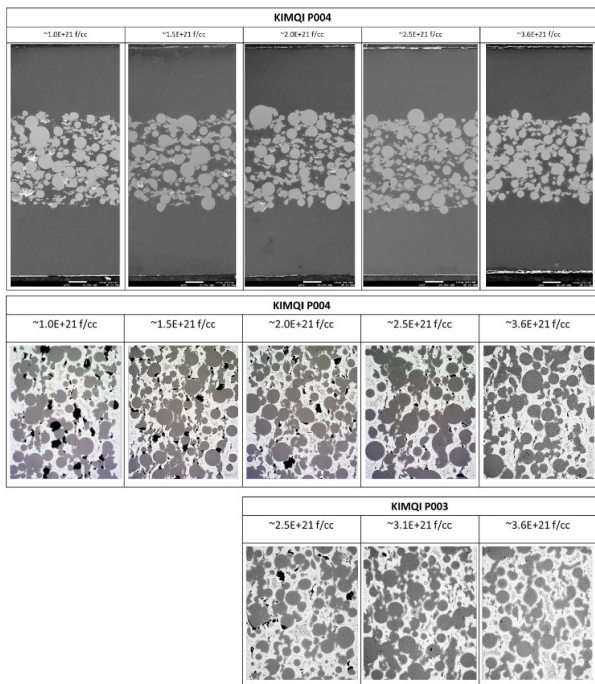


Fig. 2. Microstructure Evolution of Fuel Meat as a Function of Burnup (KIMQI-FUTURE)

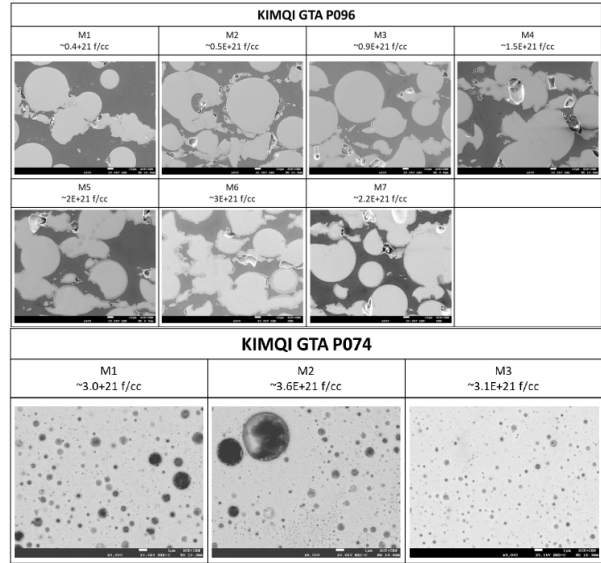


Fig. 3. Microstructure Evolution of Fuel Meat and Fission-Gas Bubble inside U_3Si_2 kernel as a Function of Burnup (KIMQI-GTA)

Fig. 4 shows the EPMA results of an irradiated U_3Si_2 particle at the highest burnup region. This reveals clear evidence of Xe precipitation into relatively large bubbles within the fuel kernel, a behavior commonly observed in irradiated silicide fuels. The Nd X-ray map exhibits a grainy appearance, suggesting that Nd may also have precipitated locally, whereas the Mo X-ray map shows no detectable precipitation, indicating that Mo remains largely in solid solution within the fuel. Within the Al matrix, no significant accumulation of fission products was observed, except in narrow regions between closely spaced fuel particles or near the IL, where a sweeping effect can locally concentrate fission products. Overall, the microstructural examinations clearly demonstrate that the fuels maintain exceptional structural and chemical stability over the investigated burnup range.

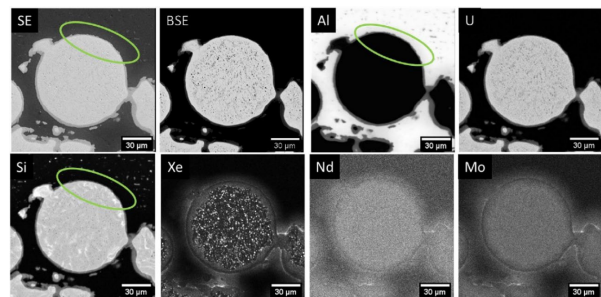


Fig. 4. EPMA X-Ray Maps (U, Si, Nd, Xe) for irradiated U_3Si_2 Particle at Highest Burnup Area

Fig. 5 shows the microstructure of a HAMP-2 mini-plate after irradiation. Overall, the appearance is similar to that of the irradiated KIMQI plates; however, a key distinction is that it contains far fewer fragmented particles and stringered regions, resulting in fuel particles that remain predominantly spherical with less particle contiguity. Furthermore, no signs of irradiation-induced microcracking were detected, and the fuel

particles remained homogeneously dispersed within the matrix. These observations demonstrate that the structural and mechanical integrity of the fuel meat was fully preserved throughout irradiation

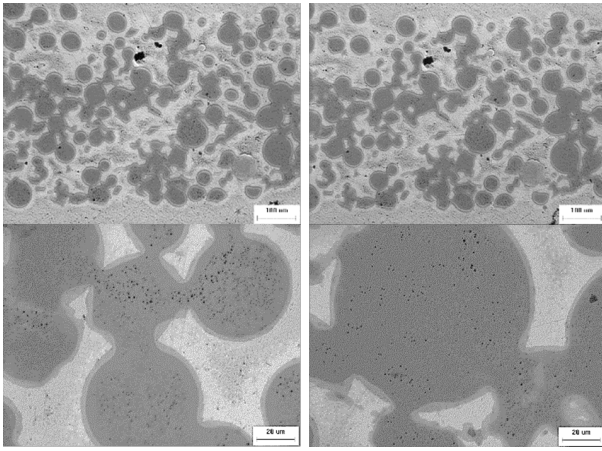


Fig. 5. Microstructure of HAMP-2 mini-plate (USM09)

4. Fuel Performance Evaluation

Fig. 6 presents the average fuel swelling curves for the KIMQI-FUTURE and KIMQI-GTA plates, together with the estimated fuel swelling from the HAMP-2 irradiation. Good agreement between the Finlay model prediction [4] and the experimentally derived swelling data was observed in all cases. This agreement indicates that the overall swelling behavior of the atomized U_3Si_2 dispersion fuel is governed by well-established microstructural mechanisms associated with fission-product accumulation, without evidence of abnormal or accelerated volume expansion.

Notably, the fuel swelling observed in the HAMP-2 and KIMQI campaigns is significantly lower than the swelling values referenced in NUREG-1313 [5], which are largely based on historical data obtained from comminuted-powder U_3Si_2 fuels. This difference highlights the beneficial effect of atomized U_3Si_2 powder in restraining fuel swelling.

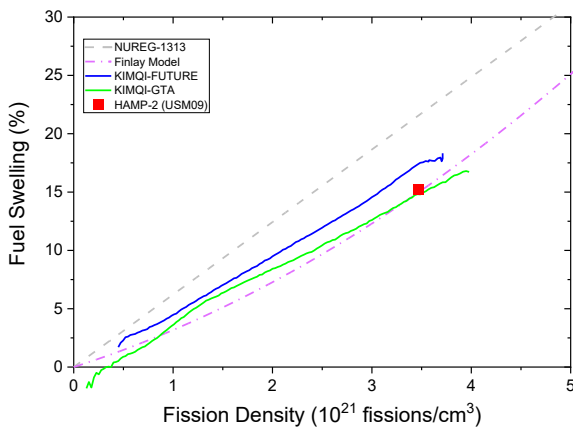


Fig. 6. Fuel Swelling Comparison: KIMQI-FUTURE/GTA vs NUREG-1313 and Empirical Model

5. Conclusions

KAERI has successfully established a full-cycle technical basis for high-density atomized U_3Si_2 fuel. The irradiation results in the HANARO and BR2 reactors have proven that KAERI's fuel is highly reliable and meets the international performance requirements for LEU conversion. Following this success, KAERI has been recognized as a qualified supplier for international research reactors. This progress is expected to facilitate the export of KAERI's RR fuel technology to global RR fuel markets, contributing significantly to the global nuclear non-proliferation and research reactor safety.

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

REFERENCES

- [1] Y. J. Jeong et al., "Development of High-density LEU U_3Si_2 Plate-type Fuel with Atomized Powder", RRFM 2019, JORDAN, 2019
- [2] T. W. Cho et al., "Irradiation Results of High-density Atomized U_3Si_2 Fuel Plates", Transaction of the Korean Nuclear Society Autumn Meeting, KOREA, Oct. 20-21, 2022
- [3] T. W. Cho et al., "Microstructure Evolution of Atomized U_3Si_2 Dispersion Fuel under Irradiation", Transaction of the Korean Nuclear Society Spring Meeting, KOREA, May 22-23, 2025
- [4] M. R. Finlay, G. L. Hofman, J. L. Snelgrove, "Irradiation behaviour of uranium silicide compounds," Journal of Nuclear Materials, vol. 325, pp. 118–128, 2004.
- [5] NUREG-1313, Qualification of U_3Si_2 Dispersion Fuel, U.S. Nuclear Regulatory Commission.