Effect of the U-Mo Particle Size on the Irradiation Performance of U-Mo/Al Dispersion Fuel

Ho Jin Ryu*, Jong Man Park, Seok Jin Oh, Se Jung Jang, Byoung Ok Yoo, Yang Hong Jung, Choong Sung Lee,
Chul Gyo Seo, Hee Taek Chae, Chang Kyu Kim
Advanced Research Reactor Fuel Development, Korea Atomic Energy Research Institute,
150, Deokjin-dong,Yuseong Gu, Deajeon, 305-353, Republic of Korea
Corresponding author: hjryu@kaeri.re.kr

1. Introduction

Dispersion fuel such as U-Mo/Al is being developed as advanced fuel for research reactors to replace the highly enriched uranium (HEU) fuel by the low-enriched uranium (LEU) fuel, because U-Mo alloys have a high uranium density and excellent irradiation stability when compared with existing fuels such as U_3Si and U_3Si_2[1]. Irradiation tests of U-Mo/Al dispersion fuel in HANARO have been carried out to investigate its fuel performance during irradiation[2]. The fuel performance behavior of U-Mo/Al dispersion fuel was estimated by using empirical models formulated based on the microstructural analyses of the post-irradiation examination (PIE) on U-Mo/Al dispersion fuel[3]. Temperature histories of U-Mo/Al dispersion fuel during irradiation tests were estimated by considering the effect of an interaction layer growth on the thermal conductivity of the fuel meat.

Because one of the performance limiting factors is a chemical interaction between the U-Mo particle and the Al matrix[4], large-sized U-Mo particles were fabricated by controlling the centrifugal atomization conditions in order to the specific interfacial area where the chemical interaction can occur. The fuel performances of the dispersion fuel rods containing U-Mo particles with various sizes were compared.

2. Irradiation Tests

In the KOMO-2 irradiation test, fine U-Mo powder and coarse U-Mo powder were separately used in order to investigate the effect of the U-Mo particle size on the irradiation behavior. The particle size of fine U-Mo powder was ranging from 38-63 μm and coarse U-Mo powder was ranging from 53-106 μm.

In the KOMO-3 irradiation test, large-sized U-Mo powders ranging from 200-300 μm were used. The average burn-up was calculated as ~54 at.% of U-235 and the peak burn-up was estimated to be ~68 at.% of U-235.

3. Performance evaluation

It is difficult to estimate the temperature history of a fuel rod during an irradiation test due to the interdependency of the fuel temperature and the thermal conductivity which are changed by the interaction layer growth, although the temperature distribution at the beginning-of-life (BOL) can be calculated based on the initial condition of irradiation and the as-fabricated microstructure of a fuel rod.

Fuel temperature of a U-Mo/Al dispersion fuel rod was calculated by solving a cylindrical heat transfer equation using the thermal conductivities of the dispersion fuel meat, Al clad, and oxide film. An empirical correlation for an interaction layer growth was developed from the results of the RERTR irradiation tests as follows:

$$Y^2 = A \cdot \dot{f}^{1/2} \cdot \Delta t \cdot \exp\left(\frac{-Q}{RT}\right) \qquad (1)$$

where Y is the interaction layer thickness (cm), $\dot{f}$ is the effective fission rate density (fissions/cm^3-s), Δt is the time interval (s), R is the ideal gas constant, and T is the absolute temperature (K). Pre-exponential constant, A (cm$^{7/2}$/fissions$^{1/2}$-s$^{1/2}$), and the activation energy, Q (kJ/mol), can be obtained by comparing the interaction layer thicknesses with the calculation results and PIE microstructures.

Fig. 1 shows the effect of the U-Mo particle size on the centerline temperature and on the interaction layer thickness when the average diameter of the U-Mo fuel particles in the 4.5 gU/cm^3 dispersion fuel is varied from 40 μm to 100 μm. Centerline temperatures were decreased by an increase in the average diameter of the fuel particles because the specific interfacial area necessary for the interaction decreases, thus the volume fraction of this less-conducting interaction layer increases slower. Interaction layer thicknesses of the center zone were also decreased by an increase in the average diameter of the fuel particles due to the lower fuel temperature in a larger particle dispersion fuel.

The effect of the U-Mo particle size has been experimentally confirmed by the KOMO-2 irradiation test as presented in Fig. 2. When the end-of-life microstructures of the U-Mo/Al dispersion fuel with fine U-Mo powder (38-63 μm) and coarse U-Mo powder (53-106 μm) were compared, the dispersion fuel with the large-sized particles exhibited a lesser volume fraction of the interaction layer. Completely reacted zone was expanded to 3/4 of the radius for the dispersion fuel with the small-sized particle, whereas only the center to 1/4 of the radius area was converted in the dispersion fuel with the large-sized particle. To overcome the limitation of a uranium loading density in U-Mo/Al dispersion fuel, coarse U-Mo particles up to 760 μm in diameter were fabricated by a centrifugal atomization process. Centerline temperature of U-Mo/Al dispersion fuel with 8 gU/cm^3 was calculated by varying the average fuel particle size from 60 μm to 200 μm. Dispersion of coarse U-Mo fuel particles larger than 200 μm is expected to be a remedy for the interaction-related problems in a rod-type dispersion fuel with a high uranium loading density.

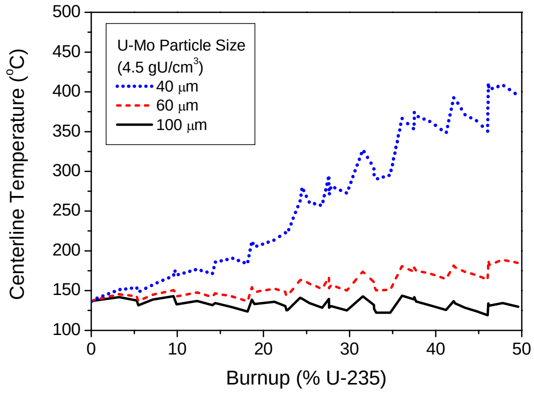
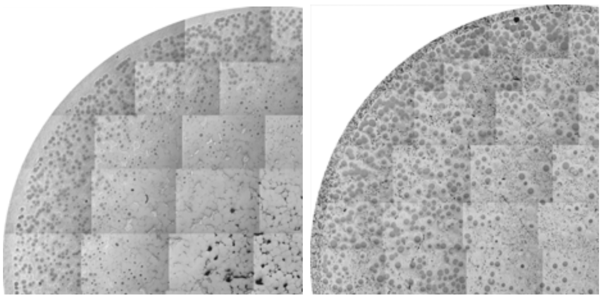


Figure. 1. Variation of the centerline temperature in the center zone of the 4.5 gU/cm^3 dispersion fuel with a varying U-Mo particle size.



(a) (b)

Figure. 2. End-of-life microstructures of the dispersion fuel with (a) fine U-Mo powder (38~63 μm) and (b) coarse U-Mo powder (53~106 μm) in the KOMO-2 irradiation test.

The calculation of the fuel temperature history during irradiation for the U-7Mo/Al (63.2% BU) of the KOMO-3 irradiation test was carried out. This model iteratively calculates fuel temperature to match the extent of IL growth at EOL. In order to modify the interaction layer growth correlation for KOMO-3 test conditions, the volume fractions of each phase of the U-7Mo/Al, e.g. U-Mo, IL, and Al matrix as a function of radial distance from fuel rod center, at the end-of-life were compared to the calculation results. The modification of the interaction layer growth correlation is thought to be required due to an uncertainty of the linear power estimation of the KOMO-3 irradiation test.

Fig. 3 shows the predicted temperature histories of centerline and periphery temperatures in the U-7Mo/Al dispersion fuel rod (557-MD1) irradiated to 63.2% BU. The centerline temperature reached a peak temperature around 204°C after 37% BU. The temperature at the EOL was 177°C. The prediction for the similar fuel (494-H2, 4.5 g-U/cc) from the KOMO-2 test showed that the peak temperature was ~480°C. Since the use of large-sized U-Mo particles was only the difference for the KOMO-3 from the KOMO-2 case, the much lower fuel temperature is attributed to the fuel particle size. Therefore, the use of large-sized fuel particles may be one of promising methods to avoid the interaction problem in U-Mo/Al.

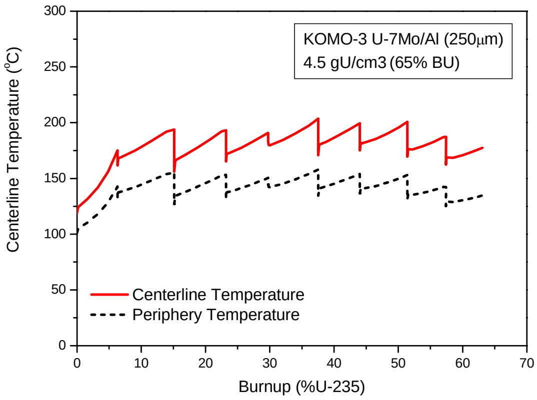


Figure 3. Centerline and periphery temperature histories with burnup in a U-Mo/Al fuel rod of the KOMO-3 irradiation test.

4. Conclusions

Fuel temperature histories of U-Mo/Al dispersion fuel containing large-sized U-Mo particles were esitimated. Estimated fuel temperature was decreased with the U-Mo particle size. It was found that a dispersion of larger U-Mo particles was effective in mitigating the thermal degradation by the interaction layer growth during irradiation.

Acknowledgment

This study was supported by the National Nuclear R&D Program of the Ministry of Education, Science and Technology (MEST).

REFERENCES

[1] M.K. Meyer, G.L. Hofman, S.L. Hayes, C.R. Clark, T.C. Wiencek, J. L. Snelgrove, R. V. Strain and K. -H. Kim, Low-temperature Irradiation Behavior of Uranium–molybdenum Alloy Dispersion Fuel, J. Nucl. Mater., Vol.304, p.221, 2002.

[2] C.K.Kim, J.M.Park, and H.J.Ryu, Use of a Centrifugal Atomization Process in the Development of Research Reactor Fuel, Nucl. Eng. Technol., Vol.39, p.617, 2007.

[3] H.J.Ryu, Y.S. Kim, J.M. Park, H.T. Chae, and C.K. Kim, Performance Evaluation of U-Mo/Al Dispersion Fuel by Considering a Fuel-Matrix Interaction, Nucl. Eng. Technol., Vol.40, p.409, 2008.

[4] A. Leenaers, S. Van den Berghe, E. Koonen, C. Jarousse, F. Huet, M. Trotabas, M. Boyard, S. Guillot, L. Sannen and M. Verwerft, Post-irradiation Examination of Uranium–7 wt% Molybdenum Atomized Dispersion Fuel, J. Nucl. Mater., Vol.335, p.39, 2004.