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Performance Evaluation of Metallic Dispersion Fuel for Advanced Research Reactors

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1. Introduction

Uranium alloys with a high uranium density has been developed for high power research reactor fuel using low-enriched uranium (LEU). U-Mo alloys have been developed as candidate fuel material because of excellent irradiation behavior.

Irradiation behavior of U-Mo/Al dispersion fuel has been investigated to develop high performance research reactor fuel as RERTR international research program [1]. While plate-type and rod-type dispersion fuel elements are used for research reactors, HANARO uses rod-type dispersion fuel elements. PLATE code is developed by Argonne National Laboratory for the performance evaluation of plate-type dispersion fuel[2], but there is no counterpart for rod-type dispersion fuel.

Especially, thermal conductivity of fuel meat decreases during the irradiation mainly because of interaction layer formation at the interface between the U-Mo fuel particle and Al matrix. The thermal conductivity of the interaction layer is not as high as the Al matrix. The growth of interaction layer is interactively affected by the temperature of fuel because it is associated with a diffusion reaction which is a thermally activated process. It is difficult to estimate the temperature profile during irradiation test due to the interdependency of fuel temperature and thermal conductivity changed by interaction layer growth. In this study, fuel performance of rod-type U-Mo/Al dispersion fuels during irradiation tests were estimated by considering the effect of interaction layer growth on the thermal conductivity of fuel meat.

2. Methods and Results

2.1 Calculation Methods

The temperature histories of the second irradiation tests (KOMO-2) in HANARO were analyzed by using reactor operation histories, fuel fabrication specifications and post-irradiation examination (PIE) results[3]. KOMO-2 tested a U-7Mo/Al dispersion fuel of 6.35 mm in diameter with 4.5 g-U/cc and a U-7Mo/Al dispersion fuel of 5.49 mm in diameter with 4.5 gU/cc in 2003 and KOMO-2 was irradiated up to 71.2 at% U-235 burn-up without the break-away swelling. PIE was carried out in the Irradiation Material Examination Facility (IMEF) facility in KAERI in 2004.

Thermal conductivity of fuel meat was calculated based on the modified Hashin and Shtrikman relation developed by CEA and employed in the PLATE code as shown in Eq.(1)[2].

$$k = \frac{-k_f + 3V_f + 2k_m - 3V_f k_m}{4} + \frac{\sqrt{8k_f k_m + (k_f - 3V_f k_f - 2k_m + 3V_f k_m)^2}}{4} \quad (1)$$

Interaction layer thickness was calculated based on a well known correlation used in the PLATE code as shown in Eq. (2),

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

where Y is the interaction layer thickness (cm), $\dot{f}$ is the fission rate density (f/cm^3-sec), Δt is time (sec), R is the ideal gas constant (1.987 cal/mole-K), and T is absolute temperature (K). Thermal conductivity of U-Mo alloys used in the calculation is a function of temperature as shown in Eq.(3).

$$k_{U-Mo} = 0.034T - 0.56 \text{ (W/mK)} \quad (3)$$

Figure 1 shows a flow chart for fuel temperature calculation procedures of this study. First, interaction layer thickness corresponding to each fission density was calculated according to the PLATE correlation for interaction layer growth. After considering the swelling from fission gas bubble, fission product, and interaction layer, thermal conductivity of the dispersion fuel meat was calculated by considering volume fraction of interaction layer, U-Mo fuel and Al matrix at each fission density. Fuel temperature was obtained from a cylindrical heat transfer equation by using the estimated thermal conductivity of the dispersion fuel meat, Al clad, and oxide film. Oxide film thickness outside of the clad was obtained from the Griess model [4].

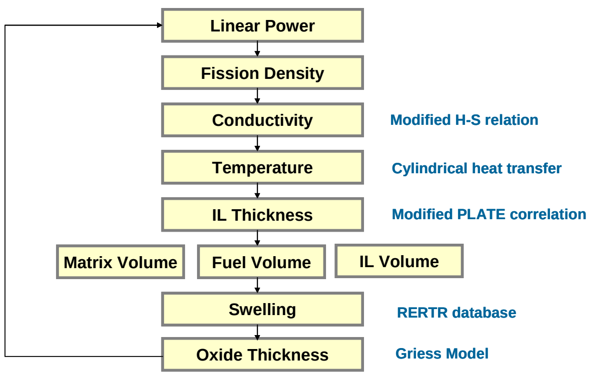

Figure 1. Fuel performance evaluation procedures.

2.2 Calculation Results

HANARO irradiation test condition for rod-type U-Mo/Al dispersion fuel was quite different from RERTR irradiation test. Fuel temperature of rod-type dispersion fuel was higher than plate-type fuel, and then the volume fraction of interaction layer can be increased up to 100%. Therefore the PLATE correlation for interaction layer growth developed from the results of RERTR irradiation test needs a modification. A pre-exponential constant in the interaction layer growth correlation was adjusted by comparing the end-of-life microstructures. This constant can be corrected after in-detail verification study by using interaction layer thickness, swelling, and oxide thickness of irradiated dispersion fuel.

Fuel temperature histories with increasing burnup were calculated for each fuel rod by using the modified correlation. The variation of normalized volume of U-Mo, interaction layer and Al matrix with increasing interaction layer thickness were also calculated. Swelling of fuel meat was calculated according to the RERTR irradiation test results [2].

To overcome the limitation of uranium loading density in U-Mo/Al dispersion fuel, very large U-Mo particle with 100-500 μm in diameter were fabricated by centrifugal atomization process. Centerline temperature of U-Mo/Al dispersion fuel with 8 gU/cc was calculated with varying average fuel particle size from 40 μm to 200 μm as plotted in Fig. 2. When the average fuel particle size is ranging from 40 to 100 μm, undesirable temperature rises were predicted due to the active interaction layer growth, while stable fuel temperature history was calculated when the average fuel particle size is larger than 150 μm. Dispersion of U-Mo fuel particle larger than 150 μm is expected to be a remedy to release temperature-related problems in rod-type dispersion fuel with a high uranium loading density.

Verification and validation of the fuel temperature calculation program developed in this study will be carried out further by using various post-irradiation examination results obtained from the HANARO irradiation tests. This performance analysis procedure for rod-type dispersion fuel was used for a safety analysis of the KOMO-3 irradiation test focusing on the dispersion fuel with very large fuel particles up to 500 μm. Fuel performance evaluation code for advanced research reactors can be established based on the calculation procedures developed in this study.

3. Conclusion

Fuel performance parameters of rod-type U-Mo/Al dispersion fuel were calculated. Fuel temperature of rod-type dispersion fuel showed strong feedback behavior due to the lower thermal conductivity of the interaction layer. It was found that dispersion of large fuel particle was effective in mitigating thermal degradation associated with the interaction layer growth. Fuel performance evaluation code for advanced research reactors can be developed based on the calculation procedure studied in this study.

References

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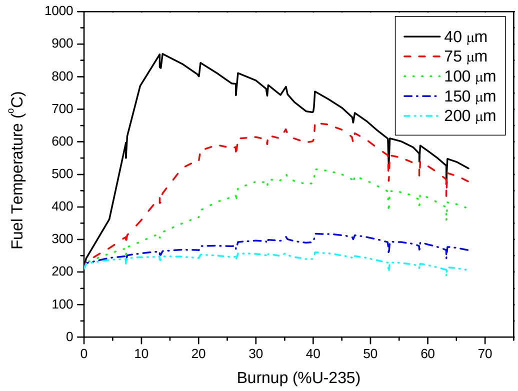

Figure 2. Fuel temperature histories with varying U-Mo fuel particle size.