Swelling Estimation of Multi-wire U-Mo Monolithic Fuel for HANARO Research Reactor

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1. Introduction

In order to use low-enriched uranium (LEU) instead of highly enriched uranium (HEU) for high performance research reactors, the reduced enrichment for research and test reactors (RERTR) program is developing high uranium density fuel such as U-Mo/Al dispersion fuel. U-Mo alloys have an excellent irradiation performance when compared to other uranium alloys or compounds [1]. But the results from the post-irradiation examination of the U-Mo/Al dispersion fuels indicate that an interaction between the U-Mo alloy fuel and the Al matrix phases occurs readily during an irradiation and it is sensitively dependent on the temperature [2, 3].

In order to lessen these severe interactions, a concept of a multi-wire type fuel was proposed. The fuel configuration is that three to six U-Mo fuel wires (1.5 mm ~ 2 mm in diameter) are symmetrically arranged at the periphery side in the Al matrix as shown in Fig. 1. In this study temperature calculations and a swelling estimation of a multi-wire monolithic fuel were carried out. Also the results of a post irradiation analysis of this fuel will be introduced.

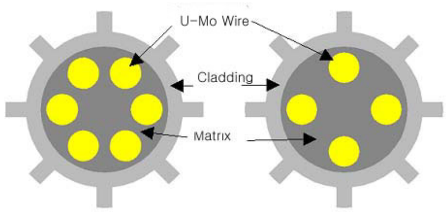


Fig. 1 The configuration of the multi-wire fuels with sixfold wires(left) and fourfold wires(right).

2. Design of the multi-wire monolithic fuel and a calculation of its temperature

The design of a multi-wire monolithic fuel started with a goal to fabricate high density U-Mo fuels for irradiation tests which is part of a program for developing high density U-Mo/Al dispersion fuel at KAERI. The target uranium density was set at 6 gU/cm^3.

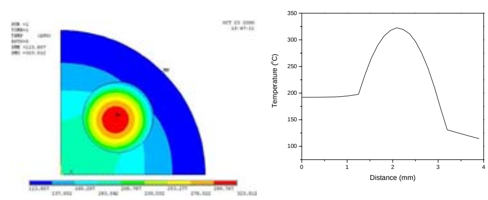
As a monolithic type fuel has a much smaller specific interface area when compared to a dispersion type fuel, it could be expected to be one of the alternatives for avoiding the U-Mo/Al interaction problems. If the wire diameter of the fourfold monolithic multi-wire is assumed as 1.93mm and the average diameter of the powder in the dispersion fuel is assumed as 50 μm, respectively, the specific interface area of the monolithic multi-wire fuel is 58 times less than that of the dispersion fuel. Therefore, it was expected that the interaction between the U-Mo powder and the Al matrix would be dramatically reduced.

To calculate the temperature profiles of the multi-wire fuel for the HANARO research reactor, a finite element analysis code, ANSYS^{TM}, was used.

The fuel meat diameter and cladding thickness were assumed to be 6.35 mm and 0.76 mm, respectively. The maximum linear power of the fuel was assumed to be 120 kW/m. Temperature calculations were implemented for 4 kinds of 6 gU/cm^3 fuel meats, which were a single wire of 3.85 mm U-Mo wire, three 2.22 mm U-Mo wires, four 1.93 mm U-Mo wires and six 1.57 mm U-Mo wires. For the material properties and boundary conditions, the cooling water temperature was taken as 40 ^{o}C, the heat transfer coefficient was 65000 W/m^2-^{o}C, the U-Mo heat conductivity was 15 W/m-^{o}C and the Al matrix heat conductivity was 220 W/m-^{o}C.

The calculation results revealed the maximum temperatures and the interface temperatures as shown in Fig. 2. The maximum temperature and the interface temperature decreased with the numbers of monolithic wires in a fuel rod. The position corresponding to the maximum temperature was found near the center of a monolithic U-Mo wire. (It moves toward the center of a fuel meat due to the heat transfer to coolant outside.) The temperature of the interface toward the inside is higher than that toward outside.

In the case of a single wire, the maximum temperature was so high that it would not be good for fuel because of a considerable fission gas swelling of U-Mo at a high temperature above 500 ^{o}C. Incorporating the more wires results in the more stable fuel, but the smaller the diameter of wire is, the more difficult it is to be considered for fabrication.



(a) (b)

Fig. 2 Temperature profile of the four-wire monolithic fuel. (a) Temperature distribution of a quarter cross-section of a fuel rod. (b) Temperature profile of temperature along a radial direction.

3. Swelling Estimation

A fuel swelling could be attributed to the interaction of the U-Mo with the aluminum matrix, a solid fission product formation, and a fission gas bubble nucleation and growth [4]. Swelling estimation is necessary to evaluate the fuel irradiation performance. In this study, the interaction thickness induced from the interaction between the U-Mo and the Al matrix for the fourfold-wire monolithic fuel during the irritation test for the conditions of HANARO was calculated based on a correlation used in the PLATE Code [4] as shown in Eq. (1).

$$y^2 = 2.2442\times10^{-19}\cdot(1.625-6.25W_{Mo})\cdot \dot{f}\cdot\Delta t\cdot\exp\left(\frac{-10000}{RT}\right) \quad (1)$$

Where y is the interaction layer thickness (cm), W_{Mo} is the weight fraction of Mo in the U-Mo fuel, $\dot{f}$ is the fission rate density (f/cm^3-sec), t is the time (sec), R is the ideal gas constant (1.987 cal/mole-K), and T is the absolute temperature (K).

The fission density of U-7Mo fuel for the HANARO irradiation test condition of ~ 70% burn-up and 168 effective full power days is assumed to be 4.64x 10^{21} f/cm^3 and the fission density rate of U-7Mo fuel is 3.2 x 10^{14} f/sec-cm^3.

According to the results of the calculation, the interaction thickness for the inside interface temperature 195 ^oC of the fourfold multi-wire fuel meats was 25 μ m, and it for the outside interface temperature 135 ^oC of it was 11 μ m.

It is assumed that the interaction product between the U-7 Mo and Al is (U, Mo)Al_4 whose density is about 5.46 g/cc because postirradiation examination of the FUTURE test irradiated at temperatures ranging 180 ~ 220 ^oC showed the Al/(U+Mo) ratio of 3.3 to 4.7 [5] .

The volume will be increased by 12.5 % of the interaction volume fraction. To conservatively estimate it, if the interaction thickness is 25 μ m around the wires, the total interaction volume will be about 3.8% of the total volume. The swelling amount due to the interaction was estimated to be less than 0.48 % of the total volume.

Calculation of the fission product swelling in the U-Mo fuel alloy used an empirical equation as shown in Eq. (2) suggested by S.L. Hayes [4].

$$\frac{\Delta V}{V} = 5.8336\times10^{-23}\cdot(1.25-2.5W_{Mo})\cdot f$$

for $f \le 2.0\times10^{21}$

$$\frac{\Delta V}{V} = (1.25-2.5W_{Mo})\cdot\left[0.1167+1.1667\times10^{-22}\cdot(f-2.0\times10^{21})\right]$$

for $f > 2.0\times10^{21}$ (2)

The fission product swelling in the U-Mo fuel alloy is about 46 %. The ratio of the fourfold U-Mo wire volume to total volume of the fuel rod with fuel meat and Al cladding whose diameter is 7.87 mm is about 24 %. Therefore swelling of the fission product of the fourfold-wire fuel rod was estimated to be about 11 %.

Therefore the total swelling of the multi-wire fuel due to the fission product swelling and interaction swelling was estimated to be less than 11.5 %.

4. Conclusion

A multi-wire type monolithic fuel was proposed in this paper to improve and solve the interaction problem in U-Mo/Al dispersion fuels. The specific area of the fourfold wire U-7Mo fuel was 58 times less than that of the conventional dispersion fuel, and the maximum temperature and the interface temperature of the fourfold U-Mo wire fuel meats by a calculation using a finite element analysis were estimated as 323 ^oC and 195 ^oC, respectively, when the uranium density of the fuel meat is 6 gU/cm^3 and the average linear power of the fuel meat is 120 kW/m.

A swelling due to the interaction between the U-Mo and the Al matrix was estimated to be less than 0.5 %. Therefore a multi-wire type monolithic fuel could be another alternative for overcoming the interaction problem of U-Mo/Al dispersion fuels.

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