PROGRESS OF THE KOMO-3 IRRADIATION TEST FOR VARIOUS U-MO DISPERSION AND MONOLITHIC FUELS TO OVERCOME THE INTERACTION PROBLEM IN U-MO/AL DISPERSION FUEL

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ABSTRACT

The next irradiation test (KOMO-3) has been planned from the aspect of overcoming the problems which were revealed in the latest irradiation tests (KOMO-2). The main reason for the problems was found to be an interaction between the U-Mo particles and the Al matrix. The interaction problem could be solved by a smaller interface area such as a monolithic fuel and a reaction retardation by a third element addition into the Al matrix or U-Mo fuel particles. In the KOMO-3 test, multi-core fuel meat and larger U-Mo particles are applied for smaller interface area. In addition, U-7Mo-X (X=0.2Si and 1.0 Zr) fuel particles and Al-X alloys (X=0.5%Si and 2.0%Si) are chosen for an interaction retardation. Multi-core fuel meat consists of 4 U-Mo rods of 2.0 mm in diameter in aluminum matrix. The equivalent U density corresponds to 6.0 g-U/cc and the highest temperature in the irradiation was estimated to be about 322 °C. Three kinds of larger U-Mo particles, which are 100-212 μm, 212-300 μm, and 300-425 μm, were prepared by atomization methods. The U densities of the larger U-Mo particle dispersion fuel meats were selected as 4.5 g-U/cc from the safety aspect.

1. Introduction

U-Mo dispersion fuel with a high uranium density has been developed for a research reactor by the RERTR program under the non-proliferation policy [1]. The irradiation tests for the preliminarily fabricated U-Mo dispersion fuels have appeared as unacceptable until now. The main reason has been revealed due to the severe interaction between the fuel particles and aluminum matrix[2].

As an alternative approach to the above problem, monolithic U-Mo fuel arose as a solution because the irradiation test for a monolithic U-Mo micro-fuel showed a very good performance during the RERTR-4 test[3]. Since that time the fabrication technology for the monolithic U-Mo plate fuel has been developed by ANL. Among the proposed various methods a friction stir welding method was evaluated to be suitable. The 2nd irradiation test for a monolithic U-Mo plate

fuel is scheduled to be done in the RERTR-7 test at ANL[4]. However, the commercial fabrication process for a monolithic U-Mo fuel plate has not been established yet.

At the previous RERTR meeting, another alternative method was proposed to solve the severe interaction problem in the U-Mo dispersion fuel, which was adding a little silicon to the matrix of aluminum. The addition of silicon into the aluminum matrix as well as some other elements such as Zr, Sn and Ge into the uranium-aluminum inter-metallic compounds was reported to have an effect of stabilizing the interaction product phase [5].

Related with the interaction problem, using the large U-Mo particle powder could be beneficial. As the particle size increases, the inter particles space increases. The impinging time of the interaction layers of the neighboring particles could be retarded. Also the temperature would rise up even slower. A calculation by using the computer code of a fuel modeling developed by ANL showed that the volume fraction of interaction product and the temperature of the fuel meat decrease much with the fuel particle size[6].

In KAERI, an effort for developing U-Mo fuel with a higher uranium density has been made to upgrade the reactor performance of HANARO and to diversify the back end option of fuel. In the 2nd irradiation test (KOMO-2), rod-type U-Mo dispersion fuels with 4 g-U/cc and 4.5 g-U/cc were irradiated in HANARO. Post-irradiation examination showed that a whole range of the fuel particles were interacted with the Al matrix in the central area the of rod-type U-Mo dispersion fuels with a high linear power after a 60% U-235 burnup[7]. Large pores were observed in the central area of the fuel rods consisting of small and standard sized fuel powders but a fairly sound structure was observed in the fuel rod with large particle-sized fuel powders. The tubular monolithic U-Mo fuel showed lots of bubbles and a large swelling in some regions due to a Si contamination from the quartz tube used for casting the mold. However, no occurrence of bubbles in the other Si-poor regions is considered to be promising.

The next irradiation test of the KOMO-3 test has been prepared by reflecting the KOMO-2 test results. In order to avoid the severe interaction problem, multi-core fuel meat has been adapted instead of a tube type for the U-Mo fuel. The fabrication of a U-Mo ring was found to be very difficulty. The U-Mo rod of the fuel core with about a 2 mm in diameter could be produced by a vacuum injection casting method. Another alternation could be alloying elements for retarding the interaction in the Al matrix as well as U-Mo fuel particles. In this paper not only the activities for overcoming the severe interaction problem but also the progress for preparing KOMO-3 test are described.

2. Plan of Irradiation Fuels

The fuels to be irradiated in the KOMO-3 test were selected as shown in Table 1. The diameters of all the fuel meats are the same as the HANARO standard type fuel of 6.35 mm.

In the previous study as presented at the last RRFM meeting, it was found that the multi-core fuel meat had a relatively high uranium density from the viewpoints of the fuel centerline and fuel surface temperatures [8]. When the uranium density is fixed, in order to have a lower centerline and interface temperature more fuel rods with a smaller diameter of the U-Mo rod should be applied. From experiments for producing U-Mo rods by a vacuum injection casting method the minimum diameter of the U-Mo rod was found to be as about 2.0 mm. In the case of assuming 6.0 g-U/cc, a multi-core fuel with 4 U-Mo rods of about 1.92 mm in diameter was estimated to have the highest centerline temperature and interface temperature of 322°C and 190

°C, respectively, which are presumed to be available from the aspects of an interaction and fission bubble.

Generally a larger diameter of the U-Mo rod is easier for a fabrication. If the addition of a third alloying element such as Si into the U-Mo was to be effective, then a larger diameter of the U-Mo rod could be achieved. From the results of the U-Mo tube fuel in the KOMO-2 test U-7Mo-0.2Si was applied to the multi-core fuel.

Table 1. Candidate fuels for the KOMO-3 test

No	Type	Material	Size	U-density	Cladding	Surface	Fuel Meat(mm)
1	Multi-core	U-7Mo	ϕ 2.0 mm×4 ea	6.0 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×100
2	Multi-core	U-7Mo-0.2Si	ϕ 2.0 mm×4 ea	6.0 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×100
3	Dispersion	U-7Mo	100-212 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
4	Dispersion	U-7Mo	212-300 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
5	Dispersion	U-7Mo	212-300 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
6	Dispersion	U-7Mo	212-300 μm	4.5 g-U/cc	Al-0.5%Si	Pre-ox.	ϕ 6.35 ×250
7	Dispersion	U-7Mo	212-300 μm	4.5 g-U/cc	Al-2.0%Si	Pre-ox.	ϕ 6.35 ×250
8	Dispersion	U-7Mo	300-425 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
9	Dispersion	U-7Mo-1.0Zr	212-300 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
10	Dispersion	U-7Mo-0.2Si	212-300 μm	4.5 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250
11	Dispersion	U3Si2	Under 150 μm	4.0 g-U/cc	Al 1060	Pre-ox.	ϕ 6.35 ×250

The interaction problem could be solved by using larger U-Mo particles. When the fuel particles in the fuel meat become larger, the inter-particle space in the dispersion fuel meat increases and the volume fraction of interacted product decreases due to a smaller specific interface area. The inter-particle space was calculated that the mono-size of the U-Mo particles was 150 μm and that they configured in closed packing way with a 27 Vol%, which are equivalent to about 4.5 g-U/cc and also required for upgrading the HANARO reactor performance. The calculated space was calculated to be about 60 μm.

The interaction layer thickness for the U-10wt%Mo dispersion in the RERTR-3 test was measured to be less than 10 μm. The heat flux, cladding temperature, and average burnup were 390 W/cm^2, 150 °C, and 40 at% respectively. A correlation of the interaction layer growth with respect to the fission rate density and temperature was developed by ANL. Supposing that the burnup is extended by up to 70 at% with the same conditions as in the RERTR-3 test, the outward thickness growth of the interaction layer was estimated to be 13.2 μm [9].

In the 4.5 g-U/cc fuel meat dispersed with the U-Mo particles of 150 μm in diameter, any impingement of the interaction layers is presumed not to occur frequently because the inter-particle space of 60 μm in the 4.5 g-U/cc fuel meat is larger than two times that of the outward thickness growth of 13.2 μm.

By supposing that the U-Mo powder with 150 μm particle size is dispersed uniformly with a close-packing manner, the growth of the interaction product layer for various parts with respect to the burn-up were investigated by dividing the fuel meat rod into 4 parts in the radial direction. The result is shown in Fig. 1. The maximum thickness of the interaction product layer is about 14 μm so that the fuel meat is presumed to be able to maintain a continuous aluminum phase.

Temperature and thermal conductivity for each part with respect to a burn-up were calculated and shown Fig. 2. Temperatures of all the parts were represented as the maximum peak at the first fuel cycle. The thermal conductivities for all the parts were degraded gradually with a burn-up. It could be attributed to the reason why the interaction product layers did not impinge with each other.

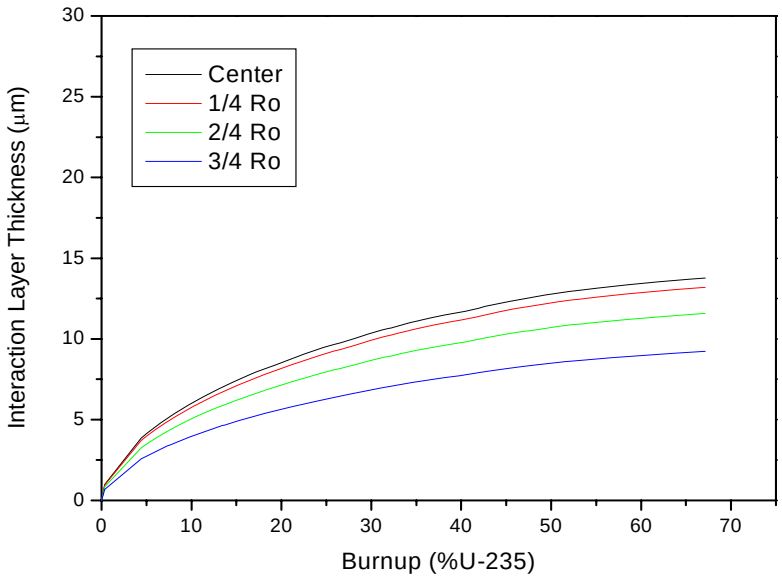


Fig. 1. Interaction layer growths for 4 parts with a burnup (%, U-235)

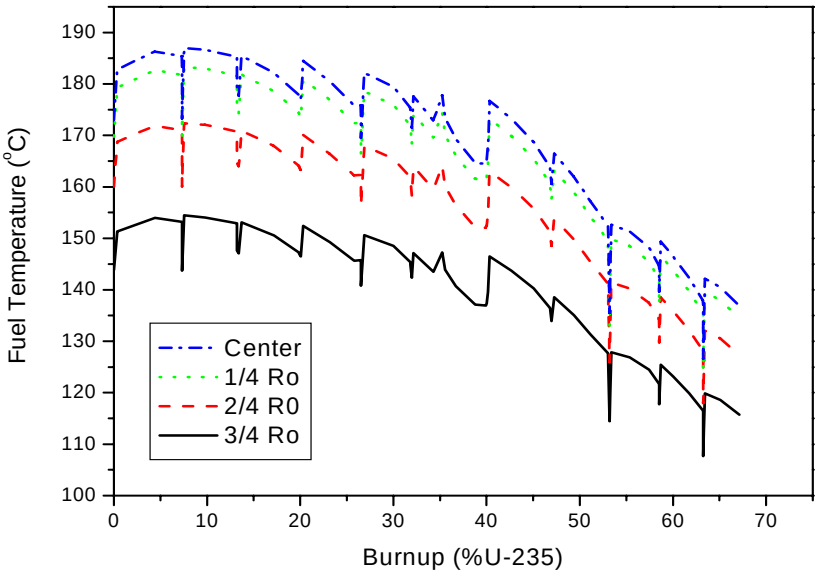


Fig. 2. Temperatures at 4 parts of the fuel meat with a burnup (%, U-235)

The inter spaces among the particles increase with the particle diameter linearly. Accordingly a larger particle dispersion fuel could be available for an increased uranium density and the higher power rate condition.

It is known that these group IV elements will promote the formation of $(U\text{-}Mo)(Al,Si)_3$. Especially from an experiment of a diffusion couple test with U-Mo and Al-Si, it was reported that the extra Si bonds would reduce the free volume of the amorphous interaction product and have an efficacy in stabilizing the interaction product against a large pore formation [5]. From the above investigations two kind of Al-Si alloys with 0.5 wt% and 2.0 wt% Si contents were taken as the matrix material.

Reportedly a small addition of Si or Al into U-Mo has a positive effect on stabilizing the irradiation behavior. In the KOMO-2 test at KAERI, a tube type U-Mo fuel contaminated with Si from a quartz tube showed that the U-Mo-Si phase containing 0.2 wt% Si was stably irradiated without any bubbles [7]. When U-Mo fuel particles containing Si reacted with the Al matrix, the interaction product would improve from the aspect of a free volume reduction. So U-7Mo-0.2 Si alloy was adopted as the fuel material in the dispersion and multi-core fuel. As an addition of an alloying element into U-Mo, Zr was proposed from the aspect of retarding the interaction because Zr has a wide range of solid-solubility with U-Mo but almost insoluble with the Al matrix [10]. Accordingly U-7wt%Mo-1wt%Zr was taken as one material of the fuel particles of the dispersion fuel.

As a reference U3Si2 dispersion fuel with a uranium density of 4.0 g-U/cc was selected for KOMO-3 test. The volume fraction of the dispersed U_3Si_2 particles is estimated to be 35.4 %, which is available for a fuel meat extrusion process as well as for upgrading a reactors performance.

3. Reactor physics calculation for the irradiation test in HANARO

The maximum linear heat generation rate (LHGR) is limited to 120 kW/m, which is the same as the LHGR for KOMO-2. For the KOMO-3 test, the reactor power of HANARO will be increased by 25% when compared to the power for the KOMO-2 test. As the reactor power is too high, an irradiation test for a full length of a fuel is dangerous. As the control absorber rods (CARs) are inserted from the upper position, the upper position is the lower power region. In order to mitigate the risk of a failure, all the fuels are situated at the upper positions as shown in Fig. 3.

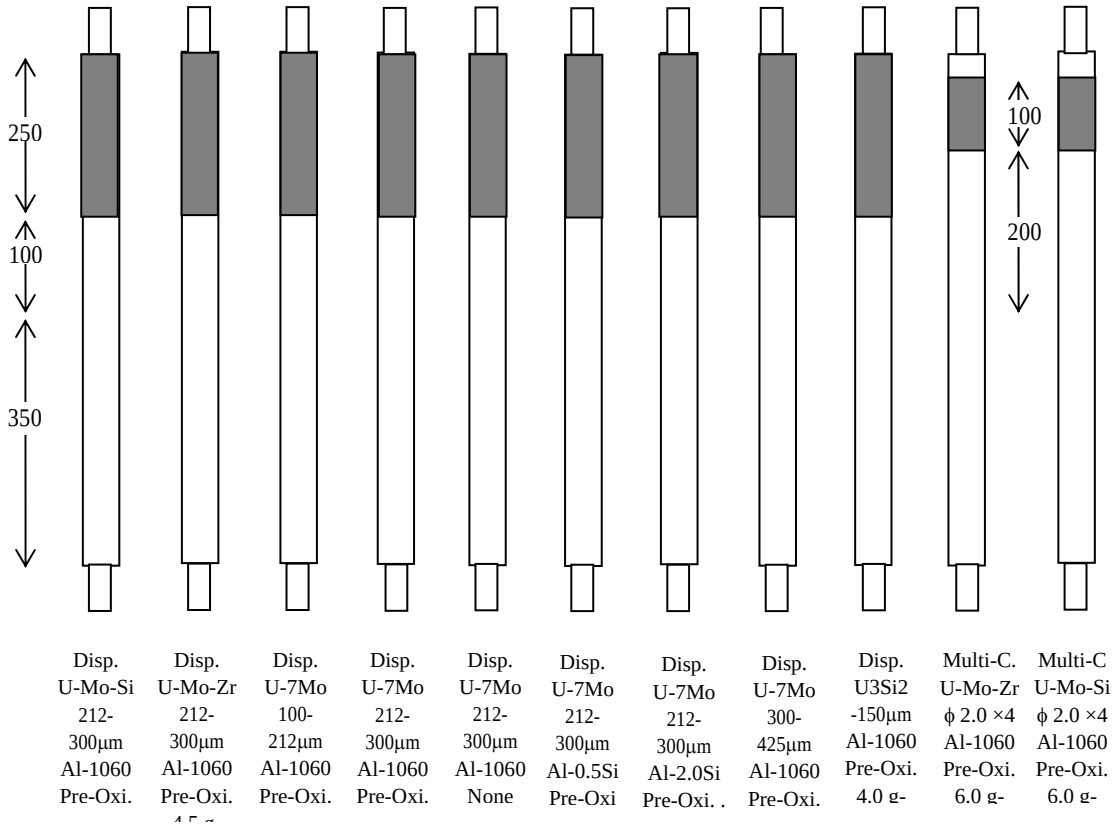


Fig. 3. Fuel meat positions for the irradiation fuels

The 11 irradiation fuels will be assembled as a cylindrical bundle consisting of 18 rods, which is scheduled to be loaded in to the OR-5 hole of HANARO. All the dispersion fuels are located from +100 mm to +350 from the centerline. The multi-core fuel is located from +200 mm to 300 mm. To obtain a more accurate calculation, the end plug of a fuel in the dispersion fuel is modeled in detail. In order to calculate the linear power under an irradiation test the related conditions are assumed as follows; 1) control rod is positioned at 650 mm from the top, 2) the average burnup of the fuels is 29.4 % of U-235, and 3) the total power of the reactor is 30 MW.

4. Progress in Preparing the Irradiation Fuels

1) Multi-core Fuel Meat

U-Mo rods for a multi-core fuel meat were successfully produced by a vacuum injection casting method. The mold used for the vacuum injection casting was a quartz tube. The preliminarily experiments using depleted uranium appeared to cause a little contamination of Si into the U-Mo rods as shown in Table 2. In order to prevent the contamination of Si, a ceramic coating on the inner surface of quartz tube was implemented so that the Si content of the U-Mo rods could be reduced remarkably. Actual irradiation U-Mo rods were produced by coating a

ceramic on the inner surface of the tubes. A heat treatment will be applied for homogenizing the Mo as well as the contaminated Si in the U-Mo.

U-Mo rods are inserted in to the Al matrix rod, which is fabricated by extruding an Al ingot and making grooves on the rod. Then the assembled rod of the Al matrix rod with U-Mo rods is formed into a multi-core fuel meat by swaging method. It was established that the contact between U-Mo rods and Al matrix was good without any void as shown in Fig. 4.

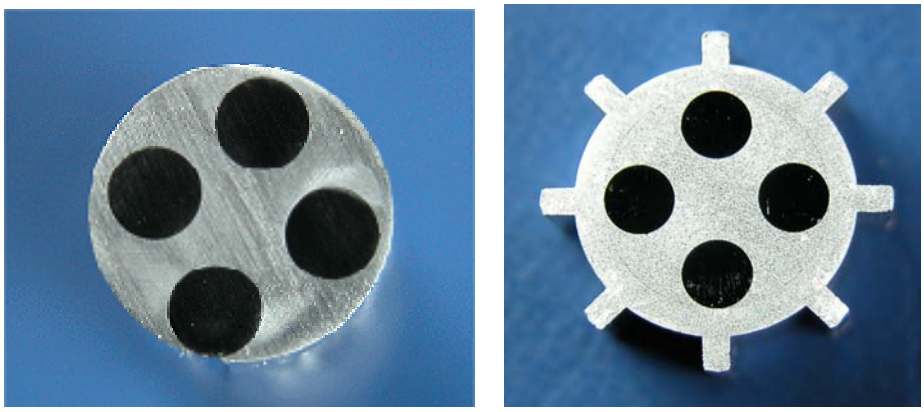
2) Larger U-Mo Particle

A larger U-Mo particle powder could be produced by a centrifugal atomization. In order to obtain a larger particle atomizing parameters were adjusted, by adopting a smaller diameter and lower revolution speed of the rotating disk. Additionally, the cooling gas was changed from argon to helium. U-Mo powders with various larger sized distributions could be obtained as shown in Fig. 5. The morphologies of the atomized large U-Mo particles are shown in Fig. 6.

Standard size of a large U-Mo particle powder was chosen as 212-300 μm. In order to investigate a particle size effect on the irradiation behavior, a smaller particle powder with 100-212 μm and a larger particle powder with 300-425 μm were taken for fabricating the irradiation test fuels. U-Mo-X powders containing Si and Zr were produced and the powder having standard particle size distribution was taken for fabricating the fuel meat.

Table 2. Chemical analysis results for three parts of the U-Mo rod produced by a vacuum injection

Position	Bottom		Middle		Top	
Element	Mo(wt%)	Si(wt%)	Mo(wt%)	Si(wt%)	Mo(wt%)	Si(wt%)
Non-coating	7.2	0.92	7.2	1.23	7.0	0.72
Coating	7.1	0.21	7.0	0.34	7.0	0.11



(a) fuel meat (b) fuel rod with Cladding

Fig. 4. Multi-core fuel meat and the multi-core fuel rod with the cladding

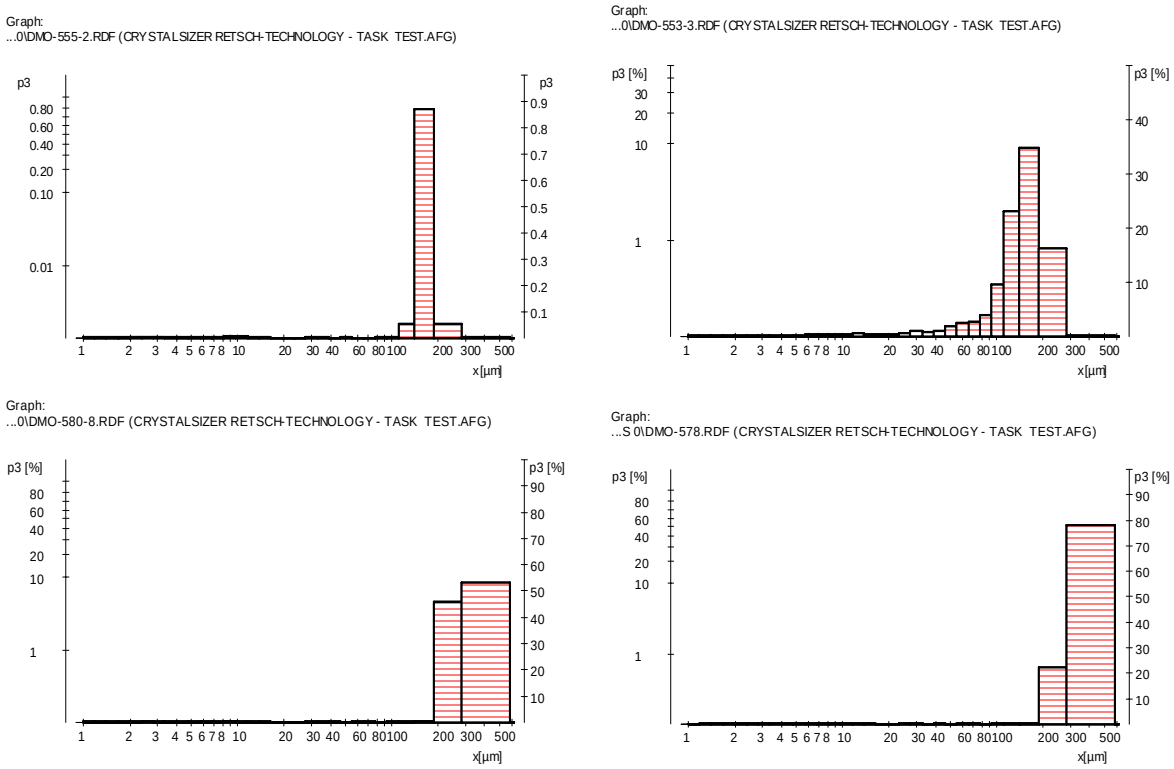
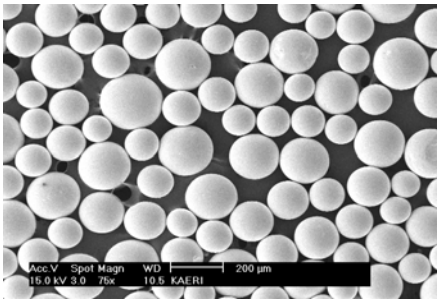
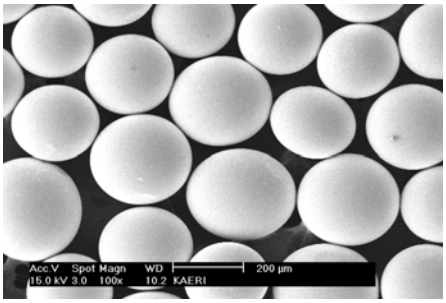


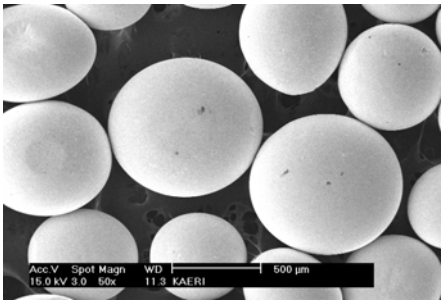
Fig. 5 Particle size distributions of various U-Mo powders produced by adjusting the operating parameters



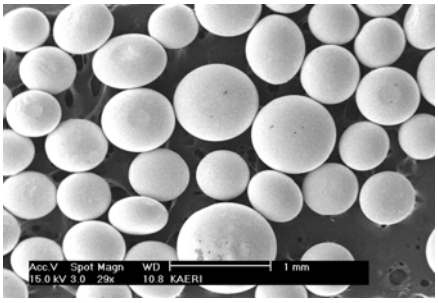
(a) small



(b) medium

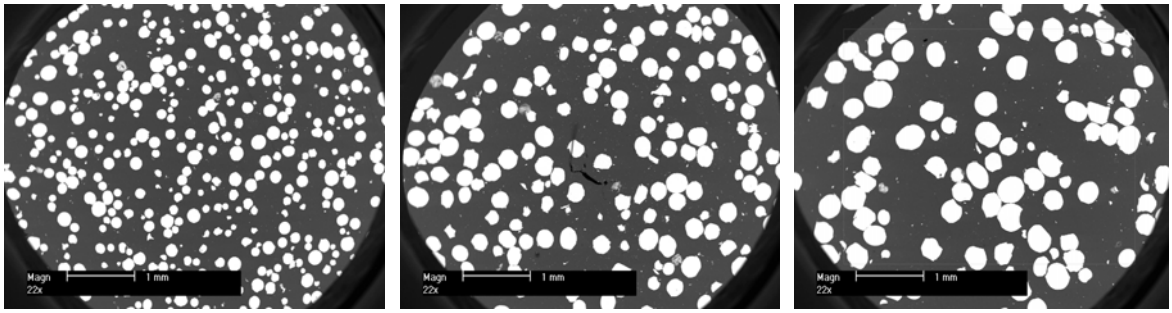


(c) large



(d) super large

Fig. 6 Morphologies of various large U-Mo particles



a) small particle dispersion b) medium particle dispersion c) large particle dispersion

Fig. 7. Particle dispersion homogeneities of three different particle size powders in extruded fuel meats

4. Irradiation and PIE

The fabrication for the irradiation fuels is still underway. It is expected to be finished by the end of this year. The fuels will be loaded into HANAR at around the end of January, 2006 and irradiated until the end of 2006. The post-irradiation examination will be done from around the spring time of 2007 presumably.

5. Summary

In the KOMO-3 test efforts have been made for overcoming the severe interaction problem shown in the latest irradiation tests. Considerations taken into account when selecting irradiation fuels could be summarized as follows.

1) Instead of the tube fuel in the KOMO-2, a multi-core fuel with 4 U-Mo rods of about 2 mm in diameter and 6.0 g-U/cc was chosen, when considering the fabrication process, interface temperature, and center temperature of the U-Mo rod.
2) In order to improve the irradiation behavior of the fuel material two kinds of third elements such as Si and Zr were added into the U-Mo alloy.
3) Larger U-Mo particle dispersion fuels were involved in the KOMO-3.test The larger particle U-Mo powders could be successfully prepared by atomization process.
4) Al alloys containing 0.5wt% and 2.0wt% of Si were used as a matrix of the dispersion fuel meat for stabilizing the interaction product.
5) Uranium densities of the irradiation fuels were selected as 4.5 g-U/cc and 6.0 g-U/cc for the dispersion fuels and the multi-core fuels, respectively, in connection with an upgrading of a reactors performance.

In order to mitigate the risk of a failure, all the fuels are situated at the upper positions. The 11 irradiation fuels will be assembled as a cylindrical bundle consisting of 18 rods, which is scheduled to be loaded in to the OR-5 hole of HANARO at around the beginning of next year.

Acknowledgement

This study was supported as a National Nuclear Research Program by the Ministry of Science and Technology of Korea.

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