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KOMO-4 TEST PIE RESULTS

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ABSTRACT

The KOMO-4 test was designed at KAERI and irradiated in the HANARO to burnup of ~50% LEU equiv. at ~200 ^{o}C. The objectives of the test were mainly to examine the effect of the Si content in the matrix, the effect of pre-irradiation heating to form Si-containing ILs, and demonstration of the effect of large particle size (~250 μm). U-Mo/Al-Si dispersion samples with 2 – 8%Si additions in the matrix were tested. A sample with pre-irradiation Si-containing interaction layers (ILs) was also included. In general, the test showed consistent results regarding the Si effect in reducing IL growth observed in US RERTR tests. As the Si content in the matrix increases, the IL growth was progressively reduced. The Al/U ratio is ~3 for all Si-content cases. Contrary to the thermodynamics prediction and out-of-pile data, however, Si enrichment in the ILs occurred at near the IL-matrix interface with only a slight increase in concentration. The pre-formed ILs were not more effective in reducing IL growth. The use of large particles again showed better performance than typical sized particles. By reflecting the KOMO-4 irradiation results, the KOMO-5, a full-sized fuel, test, is planned for irradiation next year.

1. Introduction

U-Mo fuel with high U density has been developed to be used for high performance reactor through the RERTR program.[1] However, severe pore formation due to an extensive interaction between U-Mo and Al matrix, although an irradiation performance of U-Mo itself showed most promising, tackled a use of U-Mo fuel for high performance research reactor. Because reaction product, i.e. U(Mo)Alx, is less dense than the combined reactants, the volume of the fuel meat increases after formation of IL. In addition to the effect on the swelling performance, the reaction

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layers between the U-Mo and Al matrix induces a degradation of the thermal properties of the U-Mo/Al dispersion fuels [2].

Since the year 2000, KAERI has focused on qualifying rod type U-Mo fuel with U-densities of 5-6 gU/cc by applying atomized U-Mo powders. The campaign has been performed by the KOMO test series at HANARO. The specific objectives of the tests have been: 1) upgrading HANARO research reactor to achieve a more compact core, 2) solving the back-end option of spent fuel, and 3) scientific contribution to understand U-Mo fuel performance.[3-4]

From the previous KOMO-1, -2, and -3 tests, it was found that the formation of IL in rod type U-Mo/Al dispersion fuel with U-loadings up to 5~6 gU/cc is very severe and inevitable due to high temperature irradiation condition. Although the use of large-sized(~250μm) U-Mo particles somewhat reduced the formation of IL by the reducing interfacial area between U-Mo and Al, this method was considered a partial remedy to solve interaction problem. The main obstacle for using the large particle powders is fabrication difficulty in plate type geometry. Instead, small addition of Si(up to 2wt%) into Al matrix and the use of ternary alloy fuel such as U-7Mo-1Zr, from the KOMO-3 test, gave us a positive sign to solve intrinsic nature of U-Mo fuel.[4]

KOMO-4 irradiation test of rod type U-Mo-X(X=Zr,Ti)/Al-xSi(x=2,5,8wt%) dispersion fuel with 5.0 g-U/cc U loadings was designed, by reflecting the previous KOMO-1,2,3 irradiation results, with the main objectives of evaluating the power level that can be allowed, finding the optimum Si content in matrix and examining the effect of third element addition(Ti or Zr) to U-Mo with a combination of Al-Si matrix at high temperatures of ~200^{o}C. Several U-7Mo/Al dispersion fuels with different fuel particle size (105~210μm, 210~300μm, and 300~425μm) were also included as a reference fuel to quantify intrinsic IL growth behavior.

Post-irradiation examinations of the KOMO-4 test samples have been on-going focused on optical observation, SEM characterization of microstructures and EPMA analysis with different local burn-ups. In this paper, the first batch of results is presented.

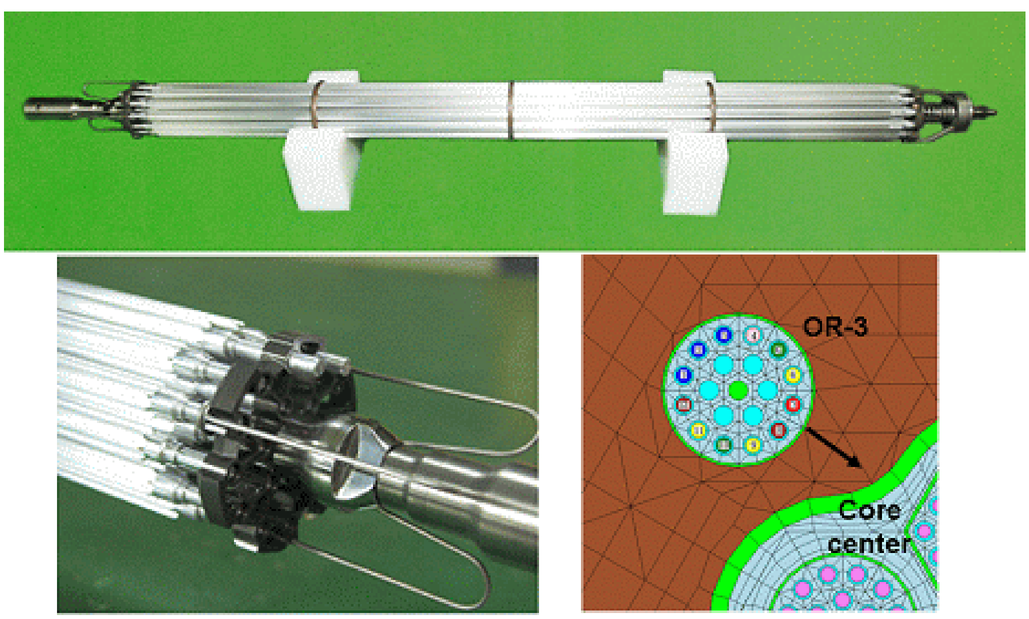


Fig. 1. The KOMO-4 test assembly.

2. KOMO-4 irradiation test

Details of the KOMO-4 test fuels are listed in Table 1. The irradiation test bundle was loaded in the OR-3 hole of the HANARO on Dec. 22, 2008 and was discharged on Jan. 03, 2010 after 132.1 EFPD(Effective Full Power Day) of irradiation. The KOMO-4 test assembly, shown in Fig. 1, precisely kept its directionality over its irradiation life, in order to obtain power histories of the sample rods. Fig. 2 shows the variation of the linear power histories of the sample rods during irradiation.

Table 1. Details of the KOMO-4 test fuels

No	Fuel ID	U-Mo Composition	U-Mo Particle Size (μm)	Matrix	Fuel Length (mm)	U-Density (gU/cc)	Objective
1	557-LD3	U-7Mo	300-425	Al	50	4.5	Reference Fuel
2	557-MD3	U-7Mo	210-300	Al	50	4.5	
3	557-SD3	U-7Mo	105-210	Al	50	4.5	
4	557-2S1	U-7Mo	210-300	Al-2Si	200	5.0	Si Effect (2wt%)
5	676-5S1	U-7Mo	210-300	Al-5Si	200	5.0	Si Effect (5wt%)
6	676-ND1	U-7Mo	<150	Al-5Si	200	5.0	Si Effect (5wt%) under Normal U-Mo Particle Size Distribution
10	676-CB1	U-7Mo	210-300	Al-5Si + Poison	200	5.0	Si Effect(5wt%) with Poison CdO 0.2 wt% + B4C 0.1 wt%
9	676-8S2	U-7Mo	150-210	Al-8Si	200	5.0	Si Effect (8wt%)
7	558-5S1	U-7Mo-1Zr	210-300	Al-5Si	200	5.0	Si Effect (5wt%) + Ternary Alloy(Zr, Ti)
8	677-5S1	U-7Mo-1Ti	210-300	Al-5Si	200	5.0	
11	676-IL1	U-7Mo	210-300	Al-5Si	50	5.0	Pre-Interaction layer(~10μm) at Fuel Surface by HT(580°C-1h)
12	677-IL1	U-7Mo-1Ti	210-300	Al-5Si	50	5.0	

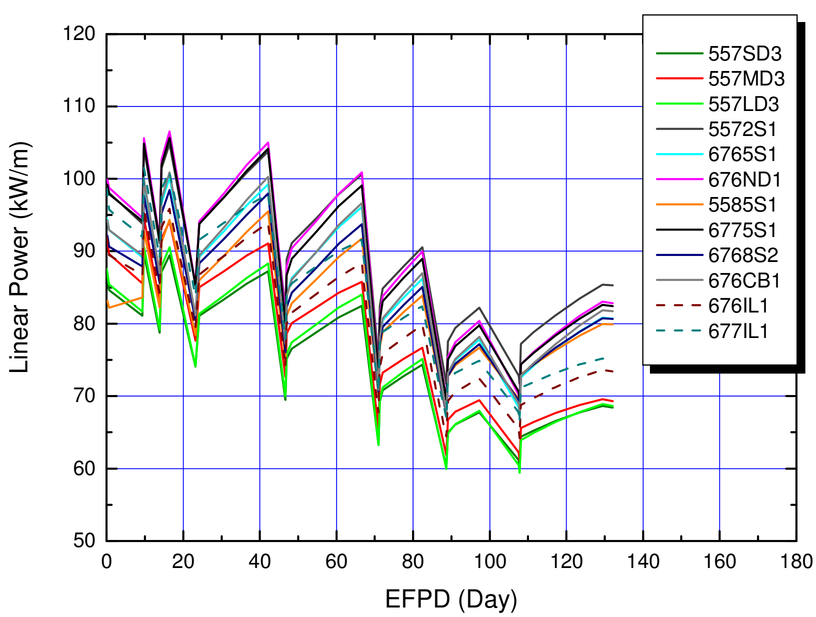


Fig.2. Linear power history of the KOMO-4 test fuels.

3. Results and discussion

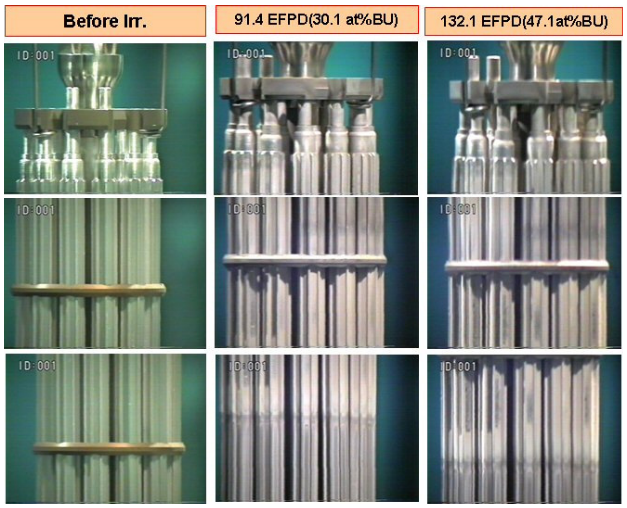


Fig.3. Visual inspection of KOMO-4 test assembly during irradiation.

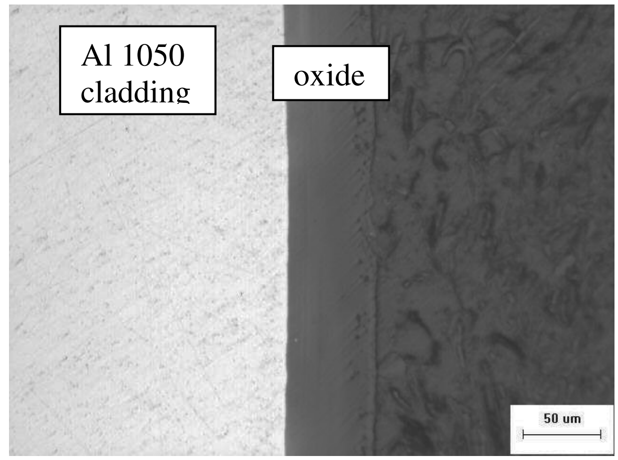


Fig. 4. Oxide layer at cladding surface. U-7Mo/Al-8Si (48% BU)

Table 2. Irradiation history of the KOMO-4 test fuels.

No	Fuel ID	Fuel Composition	Max. BU (at%U-235)	Fuel Meat Swelling (ΔV/V %)	Max. Linear Power (kW/m)	BOL T (^{o}C)
1	557-LD3	U-7Mo/Al (300-425 μm)	53.3	3.9	89.7	167.8
2	557-MD3	U-7Mo/Al (210-300 μm)	55.3	8.8	94.6	173.6
3	557-SD3	U-7Mo/Al (105-210 μm)	53.7	6.8	90.6	169.4
4	557-2S1	U-7Mo/Al-2Si	50.9	7.0	104.8	193.9
5	676-5S1	U-7Mo/Al-5Si	49.0	6.4	100.2	189.2
6	676-ND1	U-7Mo/Al-5Si (<150μm)	51.2	6.5	106.6	198.5
7	676-CB1	U-7Mo/Al-5Si (CdO+B4C)	47.5	4.7	95.5	183.9
8	676-8S2	U-7Mo/Al-8Si	48.0	7.2	98.5	188.4
9	558-5S1	U-7Mo-1Zr/Al-5Si	48.7	5.2	100.9	189.9
10	677-5S1	U-7Mo-1Ti/Al-5Si	51.1	5.4	105.7	199.5
11	676-IL1	U-7Mo/Al-5Si (pre-IL)	51.2	-	95.9	194.7
12	677-IL1	U-7Mo-1Ti/Al-5Si (pre-IL)	47.5	-	101.5	200.8

Visual inspection on the KOMO-4 irradiated fuels, prior to the destructive examination, revealed a sound fuel surface without any break-away swelling, as shown in Fig. 3. Average BU was calculated to be 47.1 at.% U-235(of initial enrichment of 19.75% U-235) and the maximum local BU was 55 at.% U-235. Table 2 shows the local BU(max.), swelling, maximum linear power, and BOL temperature at meat center for twelve irradiated fuel rods. The maximum linear power of dispersion fuels with mostly 5.0 U-density was slightly higher than that of the KOMO-3 fuels(4.5gU/cc).[4] The BOL temperatures are calculated by using the maximum linear powers and initial meat conductivities. Metallographic samples were prepared from the fuel meats with maximum and 40% local BUs. Swelling was measured from the diameter change measurement before and after irradiation, in which 3.9~8.8% (ΔV/V) were evaluated for all test samples. Thicknesses of oxide layer at cladding surface were measured to be in the range of 40~50 μm after ~50% BU.(see Fig. 4)

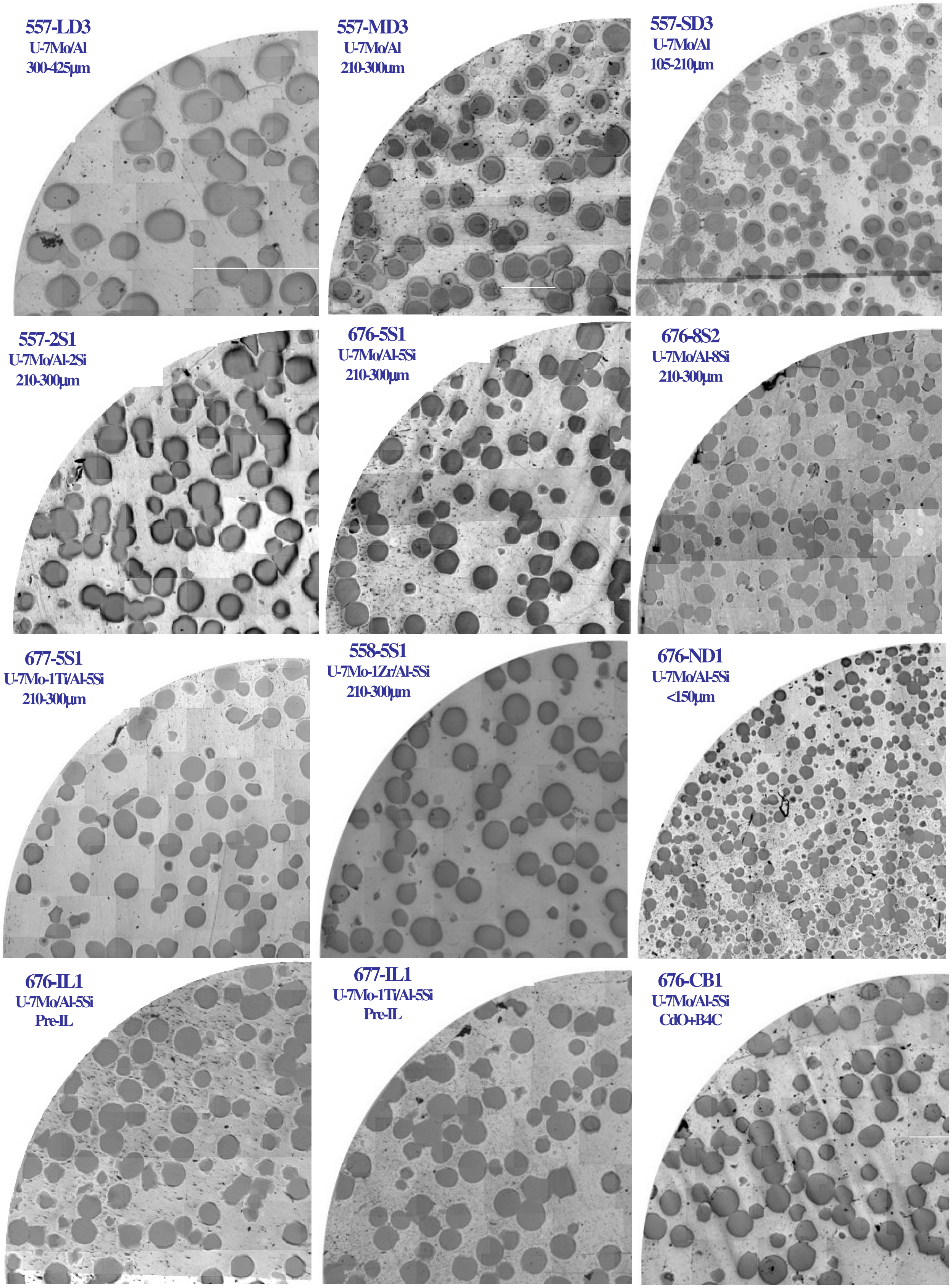
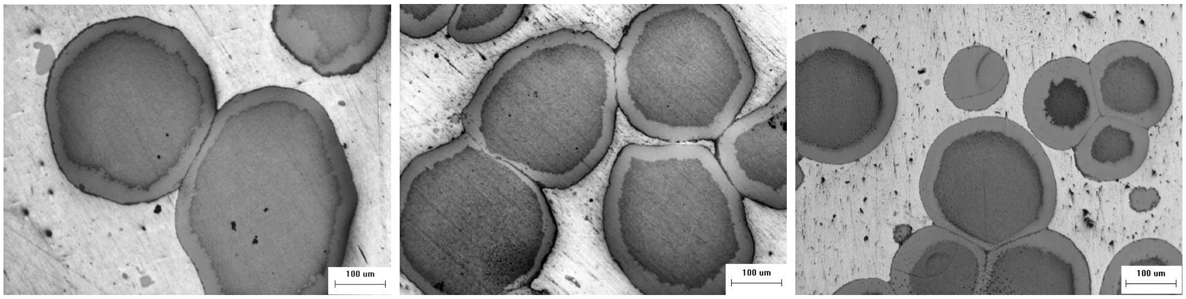


Fig. 5. Metallographic cross sections of the KOMO-4 irradiated fuels. (~50at%U-235 BU)



(a) 300-425μm (53%BU) (b) 210-300μm (55%BU) (c) 105-210μm(54%BU)

Fig. 6. Microstructures of irradiated U-7Mo/Al.

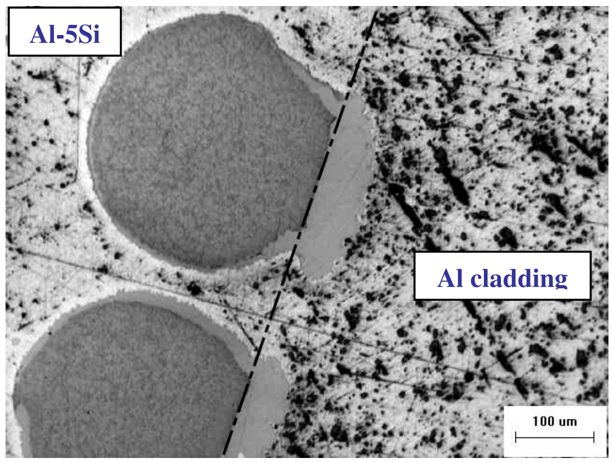
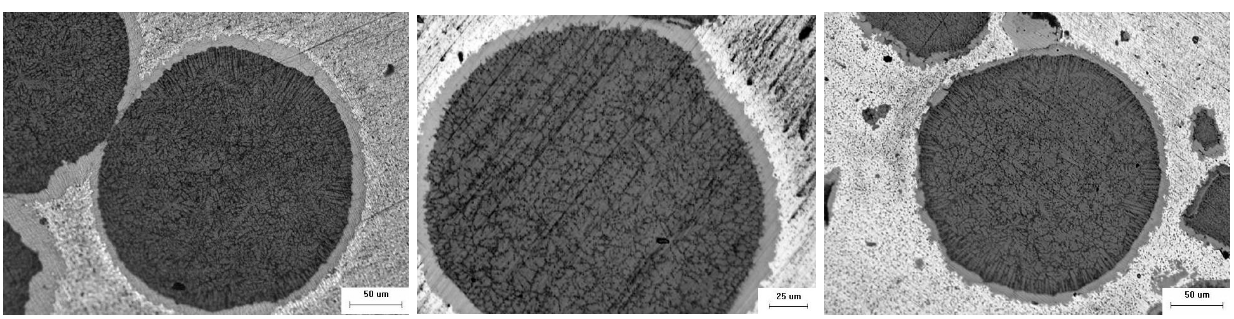
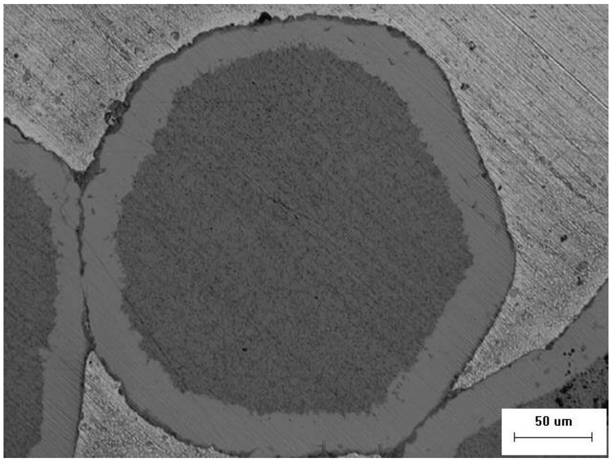


Fig. 7. Irradiated U-7Mo/Al-5Si (49% BU) at fuel meat periphery showing different IL thickness.

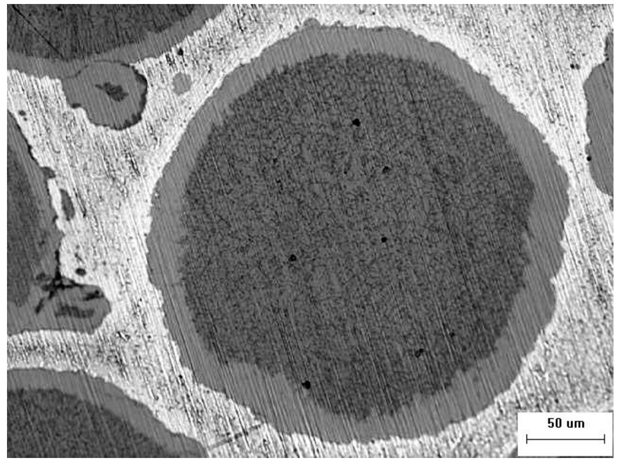


(a) 557-2S1 (b) U-7Mo/Al-5Si (c) U-7Mo/Al-8Si

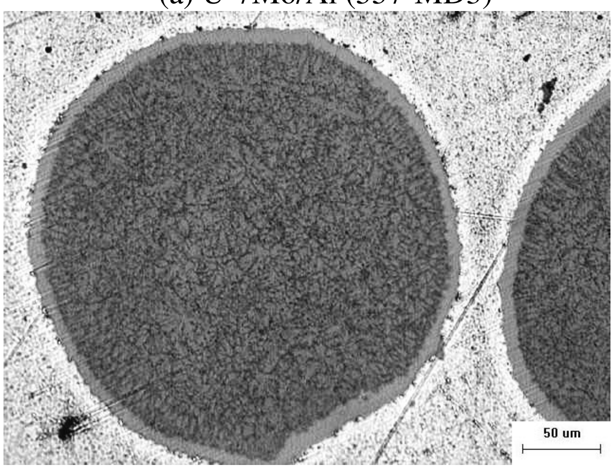
Fig. 8. Microstructures of irradiated U-Mo/Al-Si fuel. (40% BU)



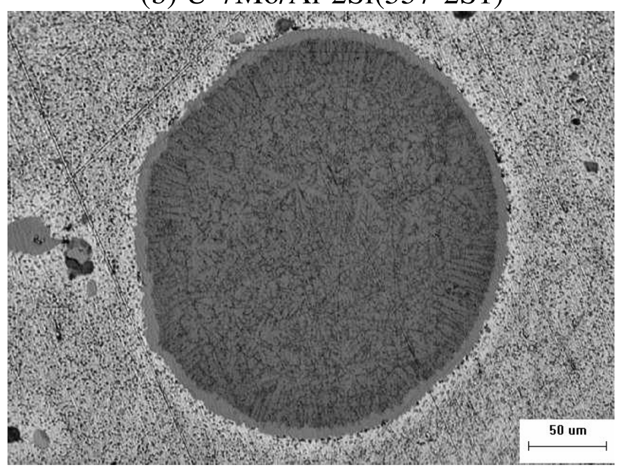
(a) U-7Mo/Al (557-MD3)



(b) U-7Mo/Al-2Si(557-2S1)



(c) U-7Mo/Al-5Si (676-5S1)



(d) U-7Mo/Al-8Si(676-8S2)

Fig. 9. Microstructures of irradiated U-Mo/Al-Si fuel. (~50% BU)

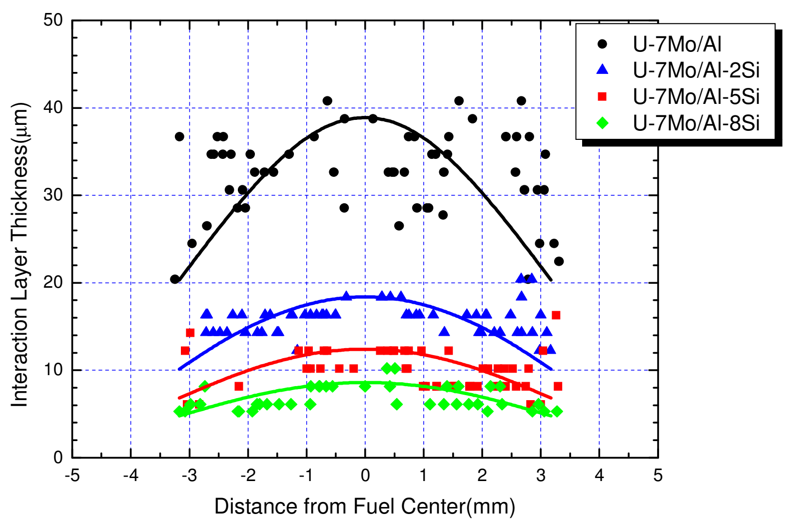


Fig. 10. IL thickness distribution of irradiated U-Mo/Al-Si samples.(~50% BU)

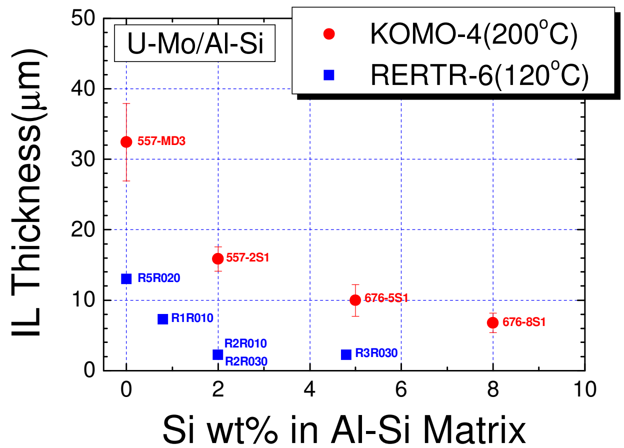


Fig. 11. Comparison of IL thickness between the KOMO-4 and RERTR-6 tests.

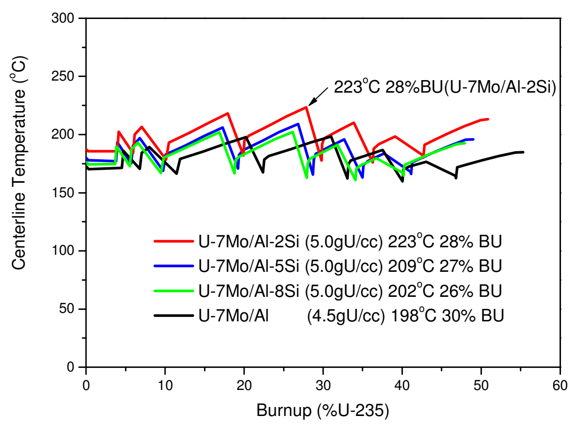
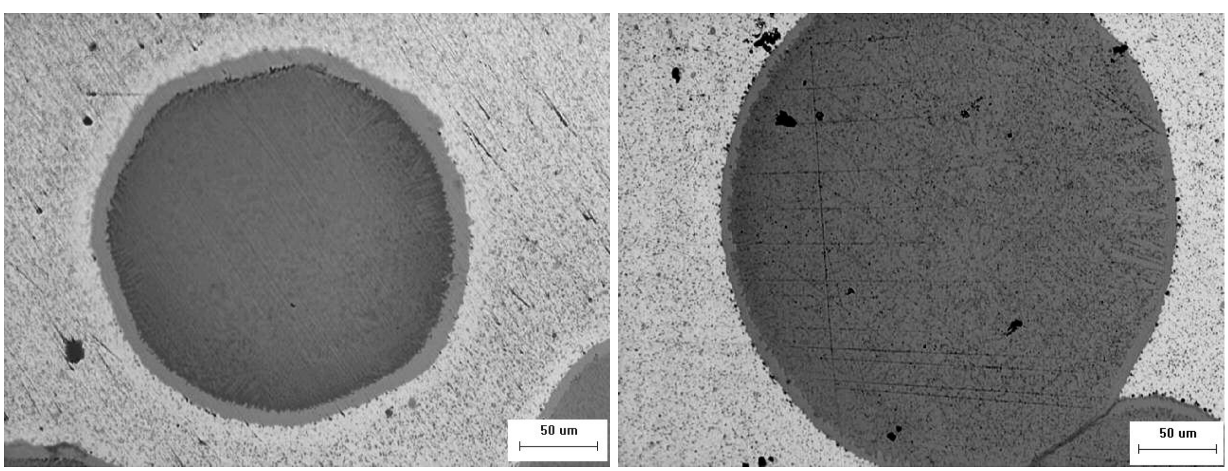
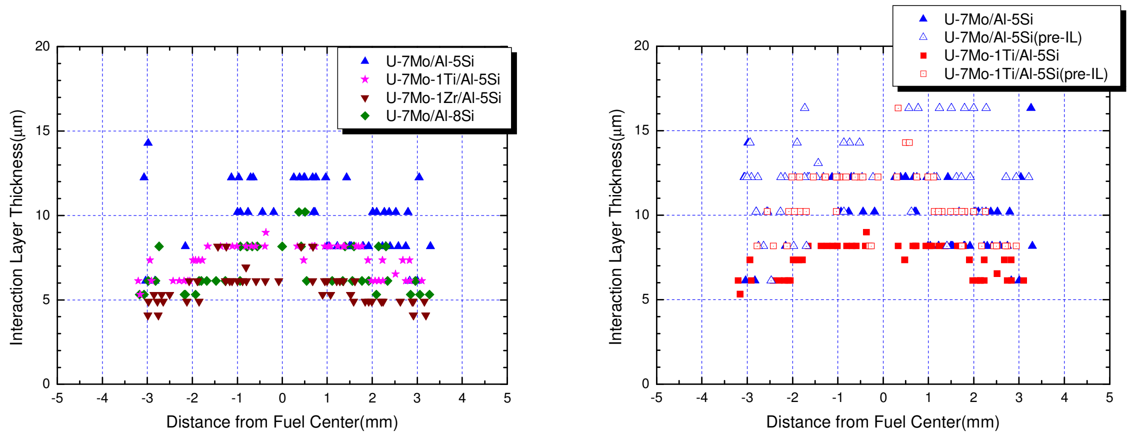


Fig. 12. Calculated temperature history of U-Mo/Al-Si fuels vs. BU.



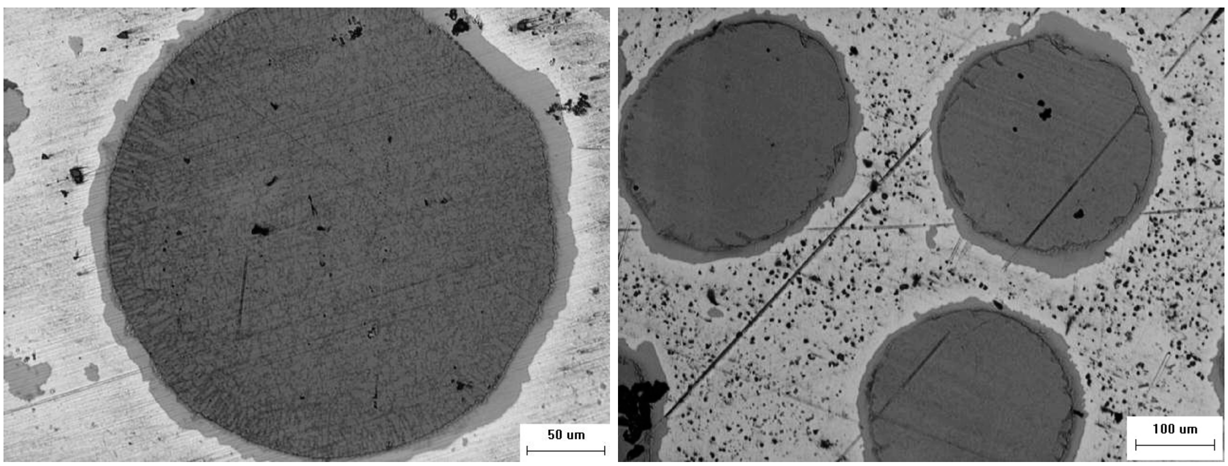
(a) U-7Mo-1Ti/Al-5Si (677-5S1) (b) U-7Mo-1Zr/Al-5Si(558-5S1)

Fig. 13. Microstructures of irradiated U-Mo-X/Al-Si fuel. (~50%)



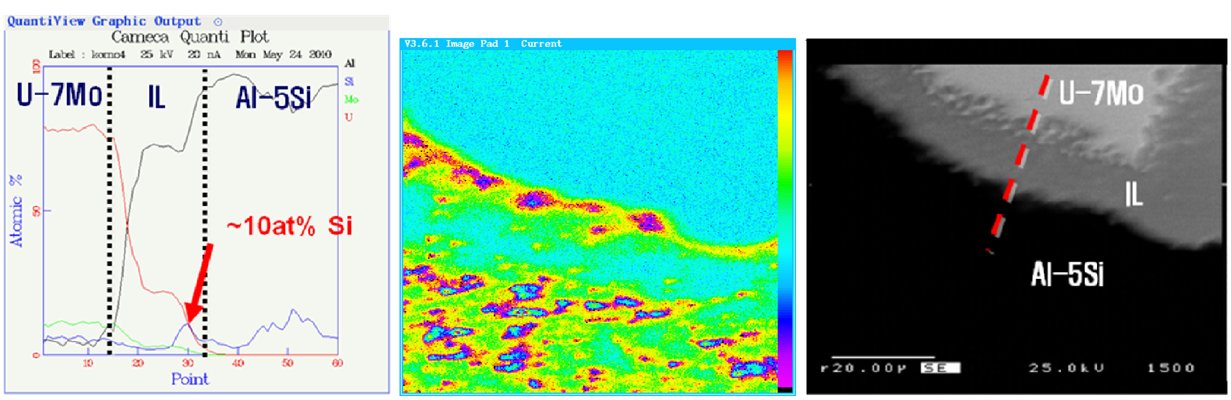
(a) Comparison with U-Mo-X/Al-Si (b) Comparison with pre-IL samples

Fig. 14. IL thickness distribution of irradiated KOMO-4 fuels.



(a) U-7Mo/Al-5Si (676-IL1) (b) U-7Mo-1Ti/Al-5Si(677-IL1)

Fig. 15. Microstructures of irradiated fuel with pre-IL. (~50%)



(a) (b) (c)

Fig. 16. EPMA scanning (a) and Si X-ray mapping(b) on IL of irradiated U-7Mo/Al-5Si fuel. (49%BU)

Fig. 5 shows quadrants of the KOMO-4 irradiated fuel meats at local BUs of ~50 at%U-235, in which the overall image was synthesized by tiling optical microstructures at different locations. These cross sections, in general, indicate that neither extensive IL phases between U-Mo and matrix nor pore-like defects have formed, although irradiation temperature(190~200^{o}C) of the KOMO-4 was higher than that of the KOMO-3 test(~180^{o}C).[4]

Fig. 6 represents microstructures of irradiated U-7Mo/Al dispersion fuels with different U-Mo particle sizes at ~50% BU. Similar to the previous KOMO-3 result, thicker ILs form as the U-Mo particle size decreases, which implies that use of large-sized U-Mo powder is beneficial in overall fuel performance by retarding IL growth.

Microstructures of irradiated U-Mo/Al-Si dispersion fuels as Si addition increases up to 8wt% are illustrated from Figs. 7~9. Reduction of the population of Si precipitates near U-Mo surface (approximately matching the recoil zone) is also observed. The Si effect on IL growth in U-Mo/Al-Si dispersion fuel is clearly visible at meat/cladding interface, as shown in Fig. 7., in which ILs formed on the Al-5Si matrix side were very thin(~10μm), whereas thicker ILs(50~60μm) were found on Al 1050 cladding (Si content is less than 0.15wt%) side.

From Figs. 8-10, IL thickness in U-7Mo/Al-xSi(x=0, 2, 5, 8 wt%) decreases progressively with increasing Si content in the Al matrix. This result is consistent with previous in-pile and out-of-pile test data.[5-8] It is noticeable that the higher Si content in the matrix reduces IL growth further up to 8 wt%Si at irradiation temperature of ~200^{o}C.

U-7Mo/Al-5Si with normal-sized fuel particles(676-ND1) (<150μm) showed also sound irradiation performance, which is attributable to the presence of Si in the matrix. Swelling as well as IL growth were measured to be similar to the test fuel with large-sized particles(676-5S1) (210-300μm), which implies that 5wt% Si is enough to suppress IL growth under high temperature irradiation condition.

Averaged IL thickness vs. Si content in U-Mo/Al-Si dispersion fuel was compared with the RERTR-6 results-(see Fig. 11) [8]. The RERTR-6 test plates were irradiated up to fission density(BU) similar to the KOMO-4 test. However, irradiation temperature in the RERTR-6 was much lower due to its plate-type geometry.-Hence, much thinner IL thickness for the RERTR-6. The effect of Si on IL growth in the RERTR-6 appeared to be saturated at 2wt% Si, whereas, in the KOMO-4, the IL growth was progressively reduced as the Si contents increased up to 8wt%. It is noticeable that the more Si in matrix is required to stabilize the IL growth in high temperature irradiation conditions.

Fuel temperature history of rod-type U-Mo/Al dispersion fuel was calculated as BU increases by using a modified correlation of interaction layer growth.[9] Fuel temperatures were calculated by solving the cylindrical heat transfer equation with the estimated thermal conductivities of the dispersion fuel meat, Al clad, and oxide film. Among the KOMO-4 test samples, U-7Mo/Al-2Si fuel appeared to reach highest temperature of 223^{o}C at 28% BU during irradiation. (Fig. 12)

Figs. 13-14 show the effect of ternary alloy addition to U-7Mo on IL growth. Ti and Zr additions to U-Mo both reduce IL growth additionally to the Si addition in the matrix. IL thicknesses of U-7Mo-1Ti/Al-5Si and U-7Mo-1Zr/Al-5Si fuels were measured to be ~8 μm and ~6 μm, respectively, which is similar to or slightly lower than IL thickness of U-7Mo/Al-8Si. This observation is consistent with the lower temperature RERTR-8 result as well as out-of-pile results and implies that addition of Ti or Zr to U-Mo with a combination of Al-Si matrix is more effective in reducing IL growth from a practical point of view of minimizing Si addition to U-Mo dispersion fuel.[10-13] Details of fuel performance in U-Mo-X/Al-Si dispersion fuel based on EPMA analysis is presented elsewhere in this meeting.[14]

Pre-heated U-7Mo/Al-Si and U-7Mo-1Ti/Al-5Si samples having Si rich IL with thickness of 8~10 μm were irradiated and their PIE results are presented in Figs. 14-15. Somewhat irregular ILs were observed although no porosity could be seen. However, it is of importance to note that IL grew a little more during irradiation, by about ~5 μm, but pre-heating itself seems to be useless because addition of 5wt% Si is already sufficient to suppress IL growth under irradiation condition. The irregular ILs formed during pre-heating are due to phase transformation of the meta-stable γ to the $\alpha+\gamma'$, for which IL growth is faster [13]. The EPMA analysis also revealed that initial 40 at% of Si in the pre-formed layer in the pre-annealed U-7Mo/Al-5Si sample was attenuated uniformly to less than 20 at% Si as IL grew additionally during irradiation, probably because Si was depleted during pre-heating from the fission fragment recoil zone. A detailed analysis is presented elsewhere in this meeting [15, 16].

EPMA analysis on ILs of irradiated U-Mo/Al-Si samples was carried out. Fig. 16 shows typical EPMA result for U-7Mo/Al-5Si, in which compositional measurement in the IL as well as Si X-ray mapping are included. Si does not continue to diffuse up to the unreacted U-Mo surface. It only makes a mount near the matrix. Nevertheless, it is evidently effective in reducing IL growth. The EPMA analysis also revealed that Al/U ratio in IL is less than 3, implying that stable ILs were formed [17]. The 5% minimum Si content obtained theoretically and applicable for out-of-pile tests appears to be inapplicable for in-pile tests. A detailed analysis is available elsewhere in this meeting [16].

4. Plan for KOMO-5 test

By reflecting PIE results of the KOMO-4 irradiation test and previous out-of-pile results, the KOMO-5 irradiation test has been planned to be designed. The KOMO-5 irradiation test is to start by the first half of 2011 after fabricating test fuels. Because it appeared that Al-5Si is sufficient to suppress IL growth during irradiation even at high temperature and U-Mo alloy modification by adding small amount of Zr or Ti is effective, only 5wt% Si addition is focused. Main considerations of the KOMO-5 fuel design are as follows :

1) U-Mo/Al-Si and U-Mo-X/Al-Si(X=Ti or Zr) dispersion fuels
   - 5 gU/cc with full length fuel (700 mm in length)
   - 5 wt%Si content in matrix
   - Burnable absorber material effect will be included
   - U-Mo particle size less than 150 μm
   - Higher Irradiation temperatures will be tested (>200^{o}C)
2) Si coated U-Mo/Al and U-Mo-X/Al-Si(X=Ti or Zr) dispersion fuels
   - 5 gU/cc with reduced length fuel (50-200 mm in length)
   - Less than 5 wt%Si content in matrix
   - Use of large-sized U-Mo particle to quantify irradiation performance
   - Variable irradiation power condition
3) Higher target BU-(higher than 60% average BU)

5. Conclusions

PIE of the KOMO-4 irradiation test exhibited a sound fuel performance at high temperature irradiation condition. It confirmed again that Si addition in U-Mo/Al dispersion fuel is effective to suppress IL growth. The maximum Si content for reducing IL growth was found at 8wt% Si from the tests at irradiation temperatures of ~200^{o}C, which is higher than the ~2wt% Si observed from the low temperature tests in US RERTR tests. Addition of Ti or Zr to U-Mo with a combination of Al-Si matrix is more effective in reducing IL growth than the Si addition alone to the matrix. From a practical point of view, it is also beneficial because it reduces the amount of Si addition to achieve the same result. Pre-heating appears to be useless because addition of 5wt% Si in U-Mo/Al dispersion fuel is already sufficient to suppress IL growth under irradiation condition. EPMA analysis show that Si does not continue to diffuse up to the unreacted fuel surface. It only accumulates near the matrix. However, this is still effective in reducing IL growth. Therefore, the threshold of 5% minimum Si content generally in the IL obtained theoretically and applicable for out-of-pile tests appears to be inapplicable for in-pile tests.

6. Acknowledgement

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7. References

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