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ABSTRACT

Two irradiation test vehicles, designated RERTR-1 and RERTR-2, were inserted into the Advanced Test Reactor in Idaho in August 1997. These tests were designed to obtain irradiation performance information on a variety of potential new, high-density uranium alloy dispersion fuels, including U-10Mo, U-8Mo, U-6Mo, U-4Mo, U-9Nb-3Zr, U-6Nb-4Zr, U-5Nb-3Zr, U-6Mo-1Pt, U-6Mo-0.6Ru and U-10Mo-0.05Sn; the intermetallic compounds U_2Mo and U_3Si_2 were also included in the fuel test matrix. These fuels are included in the experiments as "microplates" (76 mm x 22 mm x 1.3 mm outer dimensions) with a nominal fuel volume loading of 25% and irradiated at relatively low temperature (~100°C). RERTR-1 and RERTR-2 were discharged from the reactor in November 1997 and July 1998, respectively, at calculated peak fuel burnups of 45 and 71 at.%-U^{235}. Both experiments are currently under examination at the Alpha Gamma Hot Cell Facility at Argonne National Laboratory in Chicago. This paper presents the postirradiation examination results available to date from these experiments.

INTRODUCTION

Work is underway to develop a very high-density (8 to 9 g-U/cm^3 in fuel meat), low-enriched uranium (LEU) dispersion fuel for use in high power research and test reactors [1]. The current research focus within the U.S. Reduced Enrichment for Research and Test Reactors (RERTR) program centers on aluminum matrix dispersion fuels that employ uranium alloys as the fuel phase. In particular, the U-Mo and U-Nb-Zr alloy systems are being investigated [1-2]. Two irradiation experiments designated RERTR-1 and RERTR-2 made up of a total of 64 dispersion fuel microplates fabricated using 10 different uranium alloys were performed in the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL); the experiment design and irradiation conditions have been described previously [3-4]. The purpose of these irradiation experiments was to obtain initial irradiation performance data on a variety of uranium alloy dispersion fuels, allowing more refined subsequent irradiation tests to be performed on those alloys that show promise. RERTR-1, containing 32 microplates, was discharged from the ATR after 94 effective full-power days (EFPDs) of irradiation at calculated average microplate burnups between 39 and 45 at.%-U^{235}. The remaining 32 microplates contained in RERTR-2 were discharged following 232 EFPDs at calculated burnups between 65 and 71 at.%-U^{235}. Postirradiation examination (PIE) of these microplates is currently underway.

MICROPLATE DESCRIPTION

The dispersion fuel plates fabricated for these experiments are referred to as microplates due to their unusually small size. The external dimensions of the microplates are 76 mm in length, 22 mm in width, and 1.3 mm in thickness. The microplate cladding is Al-6061 of 0.4 mm thickness. The fuel-matrix powder compacts were pressed in a cylindrical die, resulting in an elliptically shaped fuel zone in the finished microplates; these elliptical fuel zones have major and minor axes of approximately 51 mm and 10 mm, respectively, and a thickness of 0.4 mm. Detail regarding the design and fabrication of these microplates has been reported elsewhere [3].

Table 1 shows the fuel type, calculated discharge burnup and fission density for each of the sixty-four microplates. Also shown is the as-fabricated fuel loading for each microplate as determined by x-ray density measurements. Although the fuel/matrix powder compacts were loaded to a nominal value of 25 vol.-% fuel, measured densities show the loadings of the final microplates to be higher than this value. Measured values for fuel volumetric loading varied between 26 and 41 vol.-%, with an average loading of 30 vol.-%.

POSTIRRADIATION EXAMINATION

All 64 microplates are currently undergoing postirradiation examination at the Alpha-Gamma Hot Cell Facility (AGHCF) at Argonne National Laboratory (ANL) in Chicago. Examinations to be performed include visual inspection, dimensional characterization, gamma-ray spectroscopy, swelling measurements, burnup determination, metallography and scanning electron microscopy. An overview of the PIE results available to date is given in the following sections.

Visual Inspection

Visual inspection of each of the thirty-two microplates from both RERTR-1 and RERTR-2 was performed. Significant corrosion of the microplates was noted, being more prominent in the fuel zone; a greater contrast between fueled and unfueled regions was observed for the higher burnup microplates. Cladding breaches were identified for two microplates from RERTR-1 (I005 and N002) and three microplates from RERTR-2 (M003, M005 and N005). Failure appears to be due to pitting corrosion. Five microplates from RERTR-1 and one from RERTR-2 were selected to proceed directly to metallographic preparation and examination; the remaining microplates underwent further non-destructive examination.

Thickness Measurements

Thickness measurements were made on twenty-seven microplates from RERTR-1. Microplate thicknesses were measured at eight predetermined locations on each microplate, seven locations being within the fuel zone and one being outside it. In general, the averages of the seven thicknesses measured within the fuel zone was smaller than the as-fabricated microplate thicknesses, indicating significant erosion of the cladding occurred during irradiation. Subsequent metallography showed a rough cladding surface, confirming the erosion or spallation of a corrosion product. Thickness measurements on the microplates from RERTR-2 has not been completed.

Table 1. Microplate Description and Burnup Data for RERTR-1 and -2.

Capsule Position	Microplate Serial No.	Fuel Phase Composition†	Alloy U-Density[1] (g/cm^3)	Meat U-Density[2] (g/cm^3)	As-Fabricated Fuel Loading (%)	Calculated Fuel Burnup (at.%-U^{235})	Meat Fission Density ($\bullet 10^{21}$ fiss./cm^3)	Fuel Fission Density ($\bullet 10^{21}$ fiss./cm^3)
A-1	U001	U_3Si_2	11.3	4.6	41	40	0.8	2.0
A-2	T001	U_2Mo	13.8	5.4	39	40	1.0	2.5
A-3	F001	U-6Nb-4Zr	14.8	4.2	28	40	0.8	2.7
A-4	I004	U-5Nb-3Zr	15.5	4.4	28	40	0.8	2.8
B-1	C001	U-6Mo	16.7	5.1	31	41	0.9	3.1
B-2	N002	U-6Mo-1Pt	16.5	4.8	29	40	0.9	3.0
B-3	A001	U-10Mo	15.3	4.5	29	41	0.8	2.8
B-4	M001	U-6Mo-0.6Ru	16.5	4.7	28	42	0.9	3.1
C-1	U003	U_3Si_2	11.3	4.3	38	43	0.8	2.2
C-2	W001	U_3Si_2[a]	11.3	3.1	27	42	0.6	2.1
C-3	D002	U-4Mo	17.4	4.7	27	42	0.9	3.3
C-4	A002	U-10Mo	15.3	4.3	28	43	0.8	3.0
D-1	A006	U-10Mo	15.3	4.8	31	44	1.0	3.0
D-2	P003	U-10Mo-0.05Sn	15.3	4.7	31	43	0.9	3.0
D-3	J001	U-9Nb-3Zr	14.2	4.4	31	45	0.9	2.9
D-4	B001	U-8Mo	16.0	4.7	29	43	0.9	3.1
E-1	C004	U-6Mo	16.7	5.3	32	43	1.0	3.2
E-2	N003	U-6Mo-1Pt	16.5	4.9	30	43	0.9	3.2
E-3	J002	U-9Nb-3Zr	14.2	4.3	30	44	0.9	2.8
E-4	B002	U-8Mo	16.0	4.6	29	43	0.9	3.1
F-1	A007	U-10Mo	15.3	4.8	31	40	0.9	2.7
F-2	P002	U-10Mo-0.05Sn	15.3	4.7	31	41	0.9	2.8
F-3	V001	U-10Mo[a]	15.3	4.4	29	42	0.8	2.9
F-4	M002	U-6Mo-0.6Ru	16.5	5.1	31	43	1.0	3.2
G-1	F002	U-6Nb-4Zr	14.8	4.5	30	42	0.9	2.8
G-2	I005	U-5Nb-3Zr	15.5	4.3	28	41	0.8	2.9
G-3	T002	U_2Mo	13.8	5.0	36	41	0.9	2.5
G-4	A008	U-10Mo	15.3	4.7	31	42	0.9	2.9
H-1	D004	U-4Mo	17.4	4.7	27	39	0.8	3.0
H-2	W002	U_3Si_2[a]	11.3	3.1	27	40	0.6	2.0
H-3	V002	U-10Mo[a]	15.3	4.3	28	39	0.8	2.7
H-4	A003	U-10Mo	15.3	4.9	32	40	0.9	2.7
Z-1	U004	U_3Si_2	11.3	4.2	37	66	1.3	3.5
Z-2	T003	U_2Mo	13.8	5.4	39	65	1.6	4.2
Z-3	F003	U-6Nb-4Zr	14.8	4.5	30	66	1.4	4.5
Z-4	N001	U-6Mo-1Pt	16.5	5.1	31	67	1.6	5.1
Y-1	C002	U-6Mo	16.7	5.0	30	68	1.6	5.3
Y-2	N004	U-6Mo-1Pt	16.5	5.0	30	68	1.6	5.2
Y-3	A004	U-10Mo	15.3	4.9	32	68	1.5	4.8
Y-4	M003	U-6Mo-0.6Ru	16.5	4.6	28	68	1.5	5.2
X-1	U005	U_3Si_2	11.3	4.2	37	70	1.4	3.7
X-2	W003	U_3Si_2[a]	11.3	3.1	27	70	1.0	3.7
X-3	P004	U-10Mo-0.05Sn	15.3	4.3	28	68	1.4	4.8
X-4	M004	U-U-6Mo-0.6Ru	16.5	4.6	28	69	1.5	5.3
W-1	A009	U-10Mo	15.3	4.8	31	71	1.6	5.1
W-2	P001	U-10Mo-0.05Sn	15.3	4.6	30	70	1.5	5.0
W-3	J003	U-9Nb-3Zr	14.2	4.2	30	71	1.4	4.7
W-4	B003	U-8Mo	16.0	4.6	29	71	1.5	5.3
V-1	C003	U-6Mo	16.7	4.6	28	67	1.4	5.2
V-2	N005	U-6Mo-1Pt	16.5	4.8	29	68	1.5	5.2
V-3	J004	U-9Nb-3Zr	14.2	4.3	30	68	1.4	4.5
V-4	B004	U-8Mo	16.0	4.4	28	70	1.4	5.2
U-1	A010	U-10Mo	15.3	4.4	29	70	1.4	5.0
U-2	P005	U-10Mo-0.05Sn	15.3	4.5	29	70	1.5	5.0
U-3	V003	U-10Mo[a]	15.3	4.2	27	70	1.4	5.0
U-4	M005	U-6Mo-0.6Ru	16.5	4.7	28	71	1.6	5.5
T-1	F005	U-6Nb-4Zr	14.8	4.1	28	70	1.3	4.8
T-2	C005	U-6Mo	16.7	4.7	28	69	1.5	5.4
T-3	T004	U_2Mo	13.8	5.7	41	68	1.8	4.4
T-4	B005	U-8Mo	16.0	4.7	29	69	1.5	5.1
S-1	D005	U-4Mo	17.4	4.6	26	69	1.5	5.6
S-2	W004	U_3Si_2[a]	11.3	3.1	27	68	1.0	3.6
S-3	V004	U-10Mo[a]	15.3	4.2	27	67	1.3	4.8
S-4	A005	U-10Mo	15.3	4.5	29	69	1.4	4.9

†Nominal alloy compositions given in wt.% ,
[a]Atomized alloy powder provided by KAERI,

[1]Theoretical Density
[2]Measured X-ray Density

Gamma-Scanning

Axial gross and isotopic gamma ray spectroscopy was performed on twenty-seven microplates from RERTR-1. The Nb-95 axial traces through the microplate fuel zones, when normalized with respect to the axial uranium density (which varies due to the elliptical shape of the fuel zone), are essentially flat. This indicates that the burnup is uniform within each microplate, which is to be expected due to their small size. Gamma-scanning of the microplates from RERTR-2 has not been completed.

Metallography

Metallography and/or scanning electron microscopy (SEM) has been performed on six microplates from RERTR-1 (U-10Mo, U-10Mo[a], U-8Mo, U-6Mo-0.6Ru, U-6Mo-1Pt, and U-5Nb-3Zr fuel types) and one microplate from RERTR-2 (U-10Mo fuel type). The results of these examinations are shown in Figs. 1 through 6.

Metallographic cross sections of four microplates at ~40% burnup are shown in Fig. 1; no unusual features are noted for the U-10Mo, U-10Mo[a], U-6Mo-0.6Ru or U-6Mo-1Pt fuel types. The dark particles, particularly evident in Fig. 1 (c) and (d), are contaminant tungsten carbide particles introduced during the fuel powder grinding process; though undesirable, they do not appear to have any adverse effect on fuel behavior. Figure 2 is a higher magnification metallographic cross section of the U-5Nb-3Zr fuel type; this alloy is already beginning to show evidence of breakaway fission gas bubble growth at 41% burnup. Extensive fuel particle-matrix interaction and the formation of large gas bubbles indicate that this fuel alloy is performing poorly. In contrast, the U-10Mo, U-10Mo[a], U-6Mo-0.6Ru and U-6Mo-1Pt alloys shown in Fig. 1 appear much more stable at this burnup level.

Figure 3 shows SEM micrographs for two U-10Mo microplates also at ~40% burnup. Figure 3 (a) and (b) are from a U-10Mo microplate fabricated using mechanically ground fuel powder, whereas Fig. 3 (c) and (d) are for a microplate fabricated using atomized fuel powder provided by the Korea Atomic Energy Research Institute (KAERI). The fuel-matrix interaction layer is very uniform for the atomized, spherical fuel particles and in the range of a few microns at ~40% burnup; the interaction layer on the mechanically ground fuel powder is more irregular and appears to be as much as twice the thickness. Furthermore, the fission gas bubble morphologies appear quite different for these two fuel powder types. The mechanically ground fuel powder has a higher density of gas bubbles, having in general bubbles of larger diameter that are distributed uniformly within fuel particles as well as on grain or subgrain boundaries. In contrast, the atomized fuel powder has fewer bubbles of generally smaller diameter that appear to be concentrated on grain or subgrain boundaries almost exclusively. The high density of dislocations undoubtedly present in the mechanically ground U-10Mo fuel powder may be providing more sites for gas bubble nucleation within fuel grains than the atomized powder produced at high temperature.

Figure 4 shows SEM micrographs for the U-8Mo fuel type at ~40% burnup, with the interaction layer seen in Fig. 4 (a) and the bubble morphology with a fuel particle in Fig. 4 (b). The interaction layer seen in Fig. 4 (a) is a few microns thick and fairly uniform. The bubble morphology seen in the U-8Mo fuel type is similar to that of the mechanically ground U-10Mo, although the density of bubbles is higher for the U-8Mo.

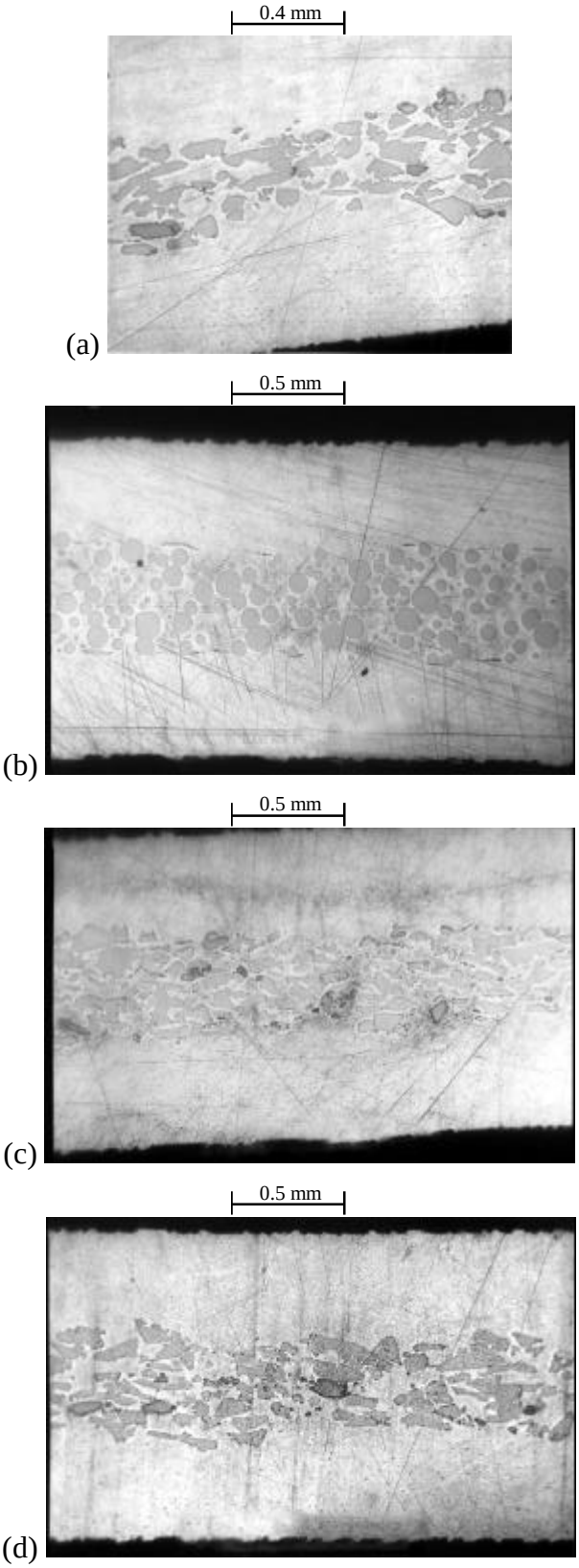

Figure 1. Metallographic cross sections of irradiated RERTR-1 microplates at ~40% burnup; (a) A003, U-10Mo (b) V002, U-10Mo[a] (c) N002, U-6Mo-1Pt and (d) M001, U-6Mo-0.6Ru.

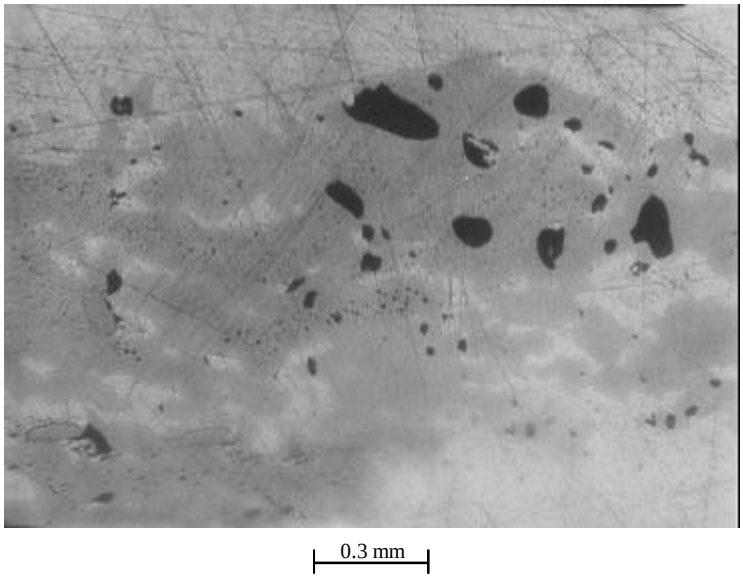

Figure 2. Metallographic cross section of irradiated RERTR-1 microplate I005, U-5Nb-3Zr fuel at 41% burnup.

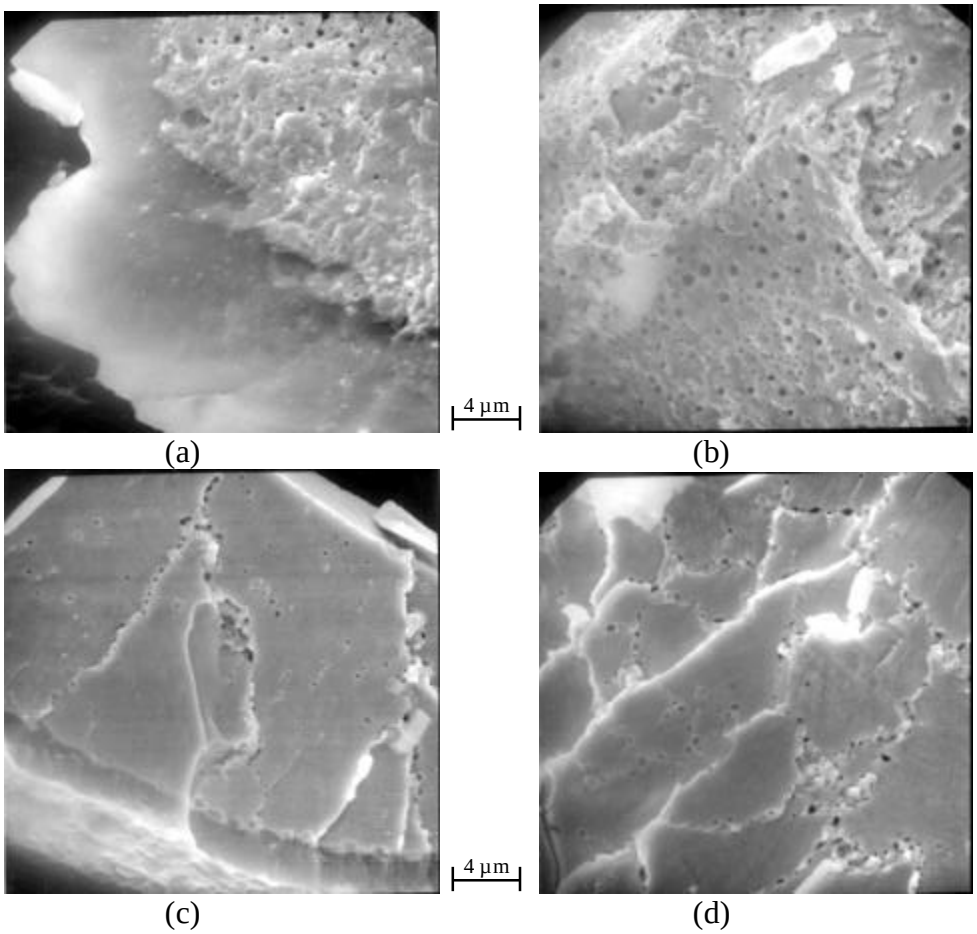

Figure 3. SEM micrographs of U-10Mo microplates from RERTR-1; (a) interaction layer, and (b) fuel particle bubble morphology for A003 (ground powder at 40% burnup), (c) interaction layer, and (d) fuel particle bubble morphology for V002 (atomized powder at 39% burnup).

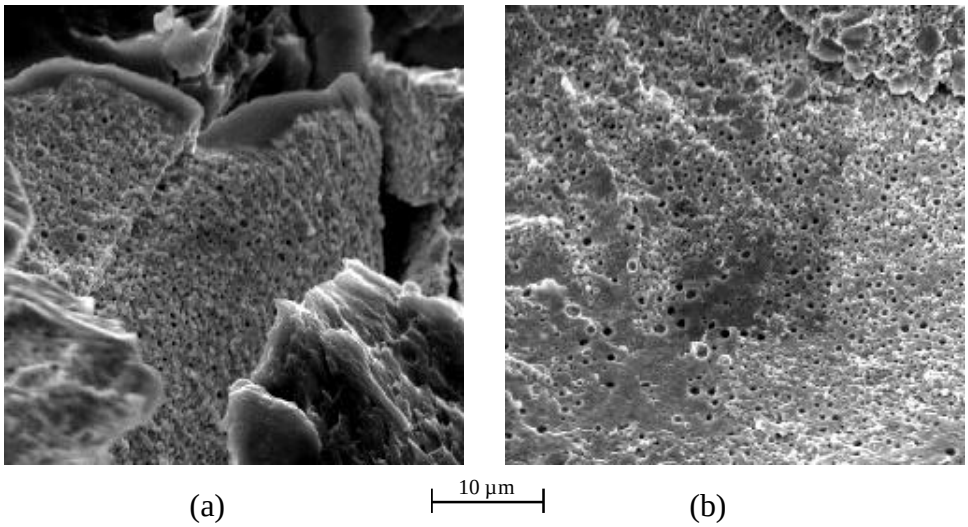

Figure 4. SEM micrographs of irradiated RERTR-1 microplate B002 (U-8Mo) at 43% burnup.

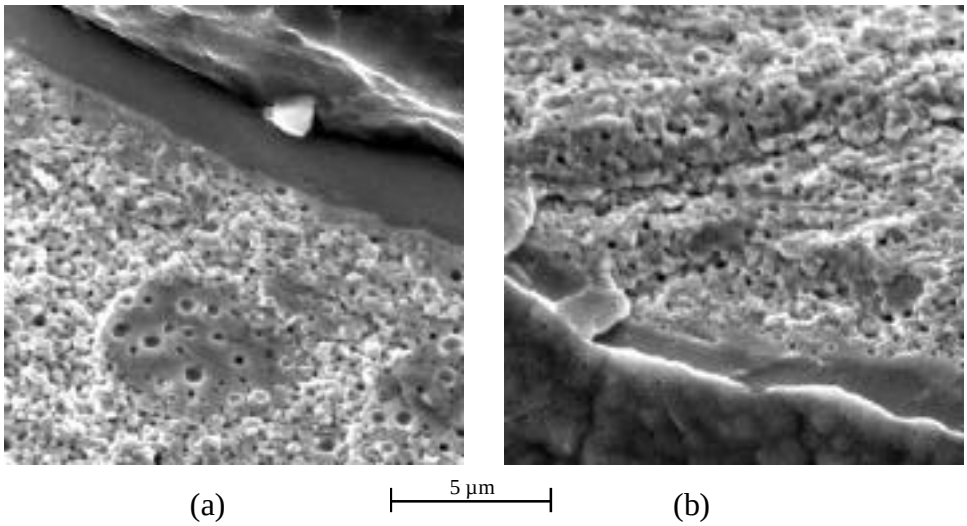

Figure 5. SEM micrographs of irradiated RERTR-1 microplates (a) M001 (U-6Mo-0.6Ru) at 42% burnup and (b) N002 (U-6Mo-1Pt) at 40% burnup.

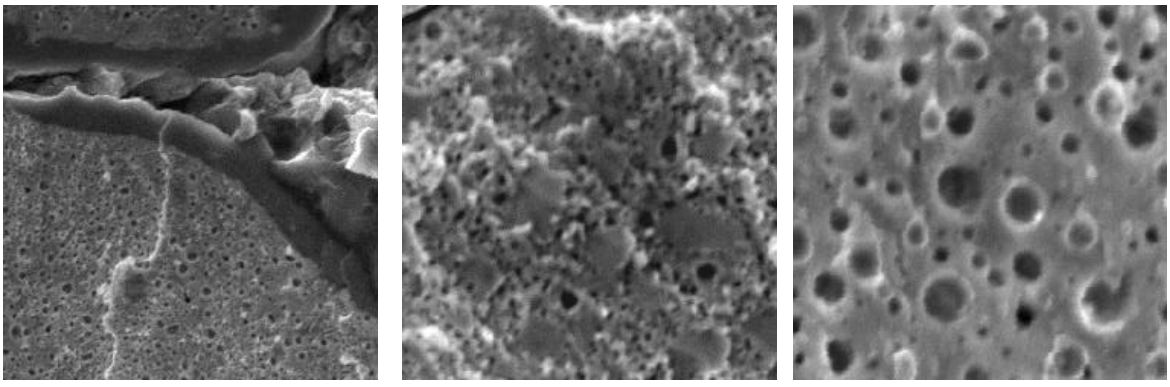

Figure 6. SEM micrographs of irradiated RERTR-2 microplate A005 (U-10Mo) at 69% burnup.

Figure 5 shows SEM micrographs for the ternary alloy U-6Mo-0.6Ru and U-6Mo-1Pt fuel types. These two ternary alloys behaved very similarly, both having a similar density of fission gas bubbles substantially higher than that observed in the mechanically ground U-10Mo and slightly higher than that in the U-8Mo. There seems to be a distinct difference in gas bubble nucleation and growth between the U-10Mo and the U-8Mo alloys, and between the U-8Mo and the U-6Mo-X ternary fuel alloys. The interaction layers for these two ternary alloys are also in the range of a few microns at ~40% burnup.

Finally, Fig. 6 shows SEM micrographs for the mechanically ground U-10Mo fuel type at ~70% burnup. Figure 6 (a) shows a fairly uniform interaction layer of ~5 µm. In Fig. 6 (b), some tendency for preferential bubble growth associated with grain or subgrain boundaries can be observed, as was very pronounced for the atomized U-10Mo in Fig. 3 (d). Figure 6 (c) is a high magnification micrograph showing the maximum bubble diameter is approximately 1 µm at 70% burnup.

CONCLUSIONS

Postirradiation examination is currently underway in the AGHCF on a total of 64 microplates from experiments RERTR-1, discharged at 40-45% U^{235} burnup, and RERTR-2, discharged at 65-70% U^{235} burnup. The design of these irradiation vehicles, which made use of a large number of small microplates, has allowed the irradiation behavior of a significant variety of uranium alloys to be investigated simultaneously. Comparisons of the resulting data has provided the ability to differentiate irradiation performance between fuel types.

Detailed information from the lower burnup experiment is available only for the U-10Mo, U-10Mo[a], U-8Mo, U-6Mo-0.6Ru, U-6Mo-1Pt and U-5Nb-3Zr fuel types, and only for the mechanically ground U-10Mo from the higher burnup experiment. The U-5Nb-3Zr fuel alloy had reacted extensively with the aluminum matrix and showed signs of breakaway fission gas bubble growth at ~40% burnup. The remaining five fuel alloys examined at this burnup appeared to be performing acceptably with relatively small fuel-matrix interaction layers and stable bubble growth.

The atomized U-10Mo[a] alloy showed the smallest-sized and lowest density of fission gas bubbles, with the gas bubbles forming almost exclusively on grain boundaries. The mechanically ground U-10Mo exhibited a generally larger bubble size and higher density of bubbles than the atomized alloy, with bubbles distributed more uniformly throughout fuel particles and grains; however, some indication of preferential bubble growth on grain boundaries was noted, especially at higher burnups. The U-8Mo fuel appears microstructurally similar to the U-10 fuel, but exhibits a higher density of fission gas bubbles. The U-6Mo-0.6Ru and U-6Mo-1Pt fuel alloys behave very similarly to each other, both having a higher density of fission gas bubbles than the mechanically ground U-8Mo and U-10Mo alloys.

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