PROTOTYPIC IRRADIATION TESTING OF HIGH-DENSITY U-Mo ALLOY DISPERSION FUELS

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ABSTRACT

An irradiation test vehicle has been designed, fabricated, and inserted into the Advanced Test Reactor in Idaho. Irradiation of this experiment began in October 1999. This irradiation test is designed to obtain irradiation performance data on a series of high-density U-Mo alloy dispersion fuels at prototypic reactor conditions. The irradiation experiment contains 47 miniature fuel plates. The U-Mo alloy fuel compositions include: U-10Mo, U-8Mo, U-7Mo, U-6Mo, U-6Mo-1.7Os and U-6.1Mo-0.9Ru, all fabricated at densities >8 g-U/cm^3. U_3Si_2 fuel plates have also been included in the test matrix at a density of 6 g-U/cm^3. A variety of fabrication techniques were used to produce the fuel powders, including machining, atomization, arc-sputtering and comminution. Fuel alloys are being tested in both as-fabricated and heat treated conditions. The U-6Mo alloy is being tested in both aluminum and magnesium matrices, while all others are being tested in an aluminum matrix only. The peak fuel temperatures are >200°C. The experiment will be discharged at peak fuel burnups of greater than 30 at.% U^{235}. Of particular interest are the extent of reaction of the fuel and matrix phases and the fission gas retention/swelling characteristics under conditions of fissile uranium densities and fuel temperatures prototypic of today's highest enrichment, highest power research reactors. This paper presents the design of the irradiation test and the irradiation conditions.

INTRODUCTION

Two prior irradiation experiments for the U. S. Reduced Enrichment for Research and Test Reactors (RERTR) Program, designated RERTR-1 and RERTR-2 [1], have been conducted to investigate the potential of metallic uranium alloy dispersion fuels to meet the high density requirements for the conversion of research reactors that employ the highest enrichments and operate at the highest powers. The results of these irradiation experiments have been reported previously [2, 3]. In general, U-Nb-Zr alloys exhibited unacceptable irradiation performance in the prior tests, while a series of U-Mo alloys appeared quite promising. While the RERTR-1 and -2 tests took these alloy fuels to high exposures (70 at.% U^{235} burnup, $5 \cdot 10^{21}$ fiss./cm^3 fuel fission density), the peak fuel temperatures of <100°C and fuel loadings of ~4 g-U/cm^3 were below the values needed for use in high power research reactors.

A third irradiation test, designated RERTR-3, has been designed, fabricated and inserted into the Advanced Test Reactor (ATR) in Idaho. This experiment has been designed to subject a variety of U-Mo alloy dispersion fuels, fabricated with uranium loadings above 8 g-U/cm^3, to irradiation temperatures in excess of 200°C. It is anticipated that this experiment will be discharged after either one or two irradiation cycles in the ATR with peak fuel burnups of >30 at.% U^{235}. Thus, this experiment will achieve conditions of U^{235} density and fuel temperature using low-enriched uranium that are prototypic of high-power research reactors that currently use high-enrichment fuels.

IRRADIATION TEST VEHICLE

The RERTR-3 irradiation vehicle is currently undergoing irradiation in a small "B" position (B-7) of the ATR. This position is a vertical, 0.875-in. (2.2 cm) diameter hole located just outboard of ATR Driver Element No. 33 in the northwest lobe.

The irradiation vehicle is comprised of a standard ATR Y-basket that holds 6 flow-through capsules designated "A" through "F". These capsules are stacked vertically within the basket, and each contains 8 miniature fuel plates, designated "nanoplates" due to their small size. The 8 nanoplates in each capsule are held in a 2x4 array; two rows of four nanoplates are arranged end-to-end in each capsule. A horizontal cross-section of this configuration is shown in Fig. 1.

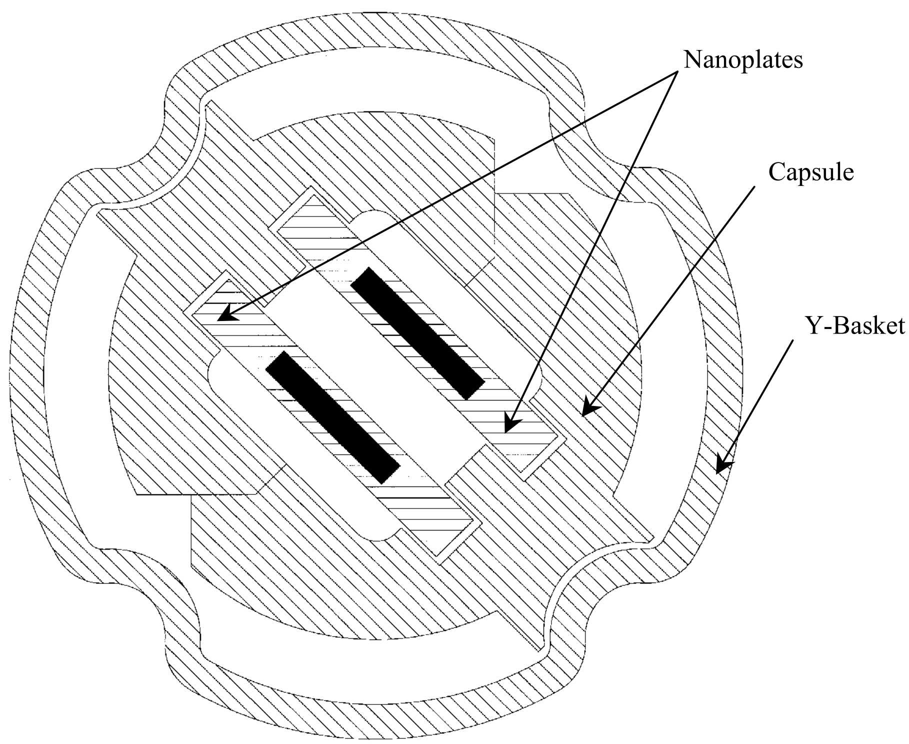


Figure 1. Horizontal cross-section of Y-basket, flow-through capsule, and two nanoplates.

Flow-through spacers are employed to center the six capsules vertically about the core midplane. The B-7 position receives primary reactor coolant, which flows from top to bottom. Thus, coolant flow enters the experiment at capsule "A" and exits at capsule "F". Table 1 shows the configuration of the nanoplates by fuel type within each capsule.

Table 1. Nanoplate Configuration in RERTR-3

Capsule	Capsule Position	Fuel Type†	Heat Treatment	Capsule Position	Fuel Type†	Heat Treatment
A	A-1	U-6Mo[a]	---	A-5	U-6Mo	---
	A-2	BLANK*	---	A-6	U-6Mo[arc] (Mg)	---
	A-3	U-10Mo	B	A-7	U-10Mo[a]	---
	A-4	U-10Mo[a]	A	A-8	U-10Mo[a]	B
B	B-1	U-10Mo[a]	A	B-5	U_3Si_2	---
	B-2	U-10Mo	---	B-6	U-7Mo[a]	---
	B-3	U-6.1Mo-0.9Ru[a]	---	B-7	U-6Mo[a]	---
	B-4	U-6Mo-1.7Os[a]	---	B-8	U-6Mo	---
C	C-1	U-8Mo	---	C-5	U-10Mo[a]	---
	C-2	U-7Mo[a]	---	C-6	U-10Mo	---
	C-3	U-10Mo[a]	---	C-7	U-6Mo-1.7Os[a]	---
	C-4	U-6.1Mo-0.9Ru[a]	---	C-8	U-6Mo[a]	---
D	D-1	U-6Mo[a]	---	D-5	U-6.1Mo-0.9Ru[a]	---
	D-2	U-6Mo	---	D-6	U-7Mo[a]	---
	D-3	U-10Mo[a]	B	D-7	U_3Si_2	---
	D-4	U-8Mo	---	D-8	U-6Mo-1.7Os[a]	---
E	E-1	U-10Mo	A	E-5	U_3Si_2	---
	E-2	U-10Mo[a]	---	E-6	U-6.1Mo-0.9Ru[a]	---
	E-3	U-10Mo[a]	B	E-7	U-7Mo[a]	---
	E-4	U-8Mo	---	E-8	U-10Mo[a]	A
F	F-1	U-6Mo	---	F-5	U-10Mo	A
	F-2	U-8Mo	---	F-6	U-6Mo-1.7Os[a]	---
	F-3	U_3Si_2	---	F-7	U-7Mo[a]	---
	F-4	U-10Mo	B	F-8	U-6.1Mo-0.9Ru[a]	---

†Nominal alloy compositions given in wt.%.
[a]Atomized alloy powder supplied by KAERI.
[arc]Arc-sputtered alloy powder.
*Al-6061 nanoplate containing no fuel.
(Mg) denotes magnesium matrix.

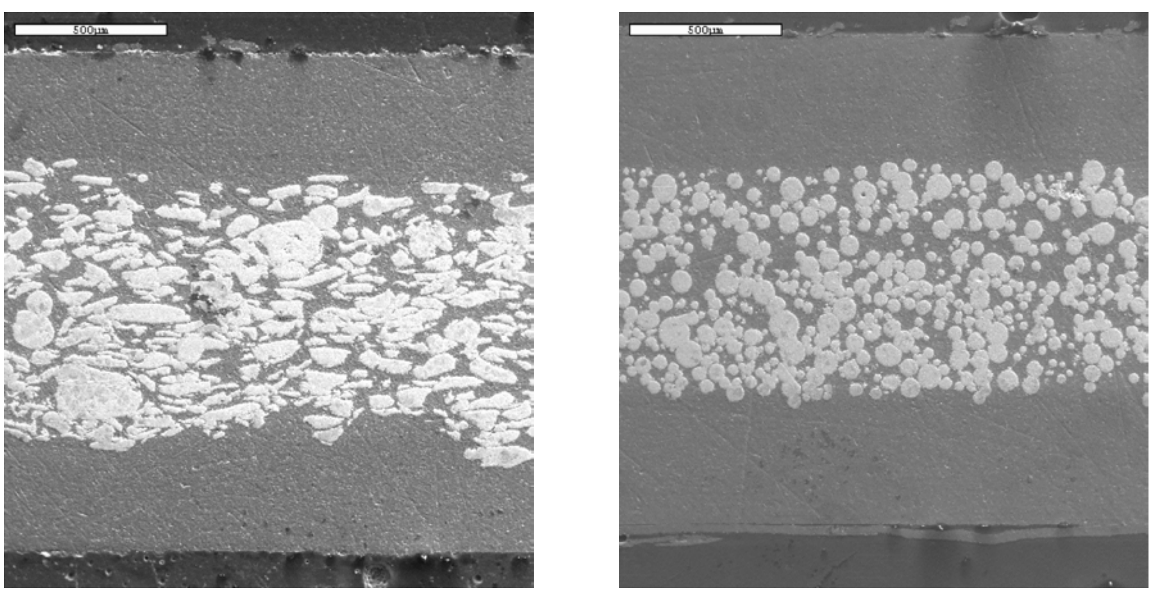
NANOPLATE DESCRIPTION

The miniature fuel plates fabricated for use in this test are referred to as "nanoplates". The external dimensions of each nanoplate are 1.62-in. (41 mm) in length, 0.394-in. (10 mm) in width, and 0.060-in. (1.5 mm) in thickness. The fuel meat thickness is nominally 0.030-in. (0.75 mm) with 0.015-in. (0.38 mm) thick cladding. All nanoplates are clad in Al-6061.

Fuel powder for use in nanoplate fabrication was produced using four techniques. U-10Mo, U-8Mo and U-6Mo metallic powders were produced by machining; U-10Mo, U-7Mo, U-6Mo, U-6.1Mo-0.9Ru and U-6Mo-1.7Os metallic powders supplied by KAERI [4] were produced by atomization (atomized fuel alloys denoted by superscript "a" in Table 1); U-6Mo metallic powder was produced by arc-sputtering (denoted by superscript "arc" in Table 1); and U_3Si_2 powder was produced by communition. The four uranium silicide nanoplates have been included in the test matrix as control nanoplates having well-known irradiation performance characteristics.

The as-cast U-Mo alloys to be used for powder production by machining were first homogenized by heat treatment as described elsewhere [5]. Microscopic examination of the irradiated U-Mo fuels from RERTR-1 and -2 revealed significant differences in fission gas bubble morphology between fuel powders produced by machining verses atomization, speculated to be caused by differences in fuel phase dislocation structure. To allow for these differences to be studied more systematically, some of the U-10Mo alloy powders prepared for use in this experiment, both machined and atomized, were subjected to additional heat treatments as indicated in Table 1. Heat treatment "A" was performed at 500°C, yielding an $\alpha + \gamma + \gamma'$ decomposition microstructure. Heat treatment "B" was performed at 800°C, yielding a stress-relieved γ microstructure. Fuel powder was mixed with aluminum or magnesium (one nanoplate, located in capsule position A-6) powder and pressed into compacts. Compacts were placed in Al-6061 picture frames, rolled between Al-6061 coverplates to final thickness, and sheared to final nanoplate length and width. Finished nanoplates were cleaned and autoclaved in saturated water at 180°C for 16 hours to pre-film the cladding surface with a 0.1 to 0.2 mil (3 to 5 μm) thick corrosion-resistant boehmite layer.

All nanoplates make use of low-enriched uranium (~19.5% U^{235}). X-ray density measurements indicate that metallic alloy nanoplates were fabricated having fuel meat densities between 8.4 and 8.9 g-U/cm^3; uranium silicide nanoplates were fabricated at 6.3 g-U/cm^3. Metallographic cross-sections of typical nanoplates fabricated to these densities are shown in Fig. 2.



(a) (b)

Figure 2. U-10Mo nanoplates fabricated at >8 g-U/cm^3; (a) machined, and (b) atomized powders.

IRRADIATION TEST CONDITIONS

Irradiation of RERTR-3 in the ATR's B-7 position provides a high thermal flux and thus high nanoplate powers and temperatures. The 47 fueled nanoplates generate a total of 29 kW at beginning-of-life. The flow-through capsules allow cooling of the experiment by the primary reactor coolant which enters capsule A at 52°C and exits capsule F at 92°C. Thermal calculations indicate that a peak cladding temperature of 176°C and a fuel temperature of 222°C at beginning-of-life are expected in the nanoplate located in capsule position D-2; the minimum peak fuel temperature of 142°C occurs in the nanoplate located in capsule position A-1. Essentially all of the nanoplates in capsules C, D and E will have beginning-of-life peak fuel temperatures ≥200°C. For this reason the nanoplate configuration was designed so as to approximately reproduce the same distribution of nanoplate fuel types in capsules A, B and F as in capsules C, D and E, thus generating irradiation performance data in two somewhat different temperature and burnup regimes.

Extrapolation of the U-Mo alloy and aluminum matrix interaction rates observed in postirradiation examination of fuels from RERTR-1 and -2 [2, 3] to the higher temperatures to be experienced by the nanoplates of RERTR-3 suggest that the aluminum matrix material of some nanoplates may be entirely consumed during irradiation. Should this occur a significant reduction in the fuel meat thermal conductivity would be expected, resulting in fuel temperatures even higher than the values predicted at beginning-of-life. If aluminum depletion occurred at 15 at.% U^{235} burnup and the thermal conductivity of the fuel meat were reduced by two-thirds, estimates of peak fuel temperatures would be 161°C and 254°C for the nanoplates located in capsule positions A-1 and D-2, respectively. To evaluate this potential phenomenon, the RERTR-3 irradiation experiment will be discharged at an intermediate burnup level.

CONCLUSION

Irradiation of RERTR-3 began in October 1999. The experiment will be discharged from the ATR following either one or two irradiation cycles (38 or 52 effective full power days) having peak fuel burnups of greater than 30 at.% U^{235} ($2.3 \bullet 10^{21}$ fiss./cm^3). Postirradiation examination of the discharged experiment, to begin in the spring of 2000, will provide irradiation performance data on these U-Mo alloy dispersion fuels tested under conditions of U^{235} density and fuel temperature that are prototypic of high power research reactors that currently make use of high-enrichment uranium.

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