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POSTIRRADIATION EXAMINATION OF EBR-I CORE-IV PROTOTYPE FUEL RODS

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ABSTRACT

Four EBR-I Mark-IV prototype fuel rods containing slugs of plutonium-1 w/o aluminum alloy were irradiated in the EBR-I reactor at central fuel temperatures from 342 to 386°C and at burnups up to 0.1 a/o. No appreciable slumping of the fuel occurred during irradiation, and no significant density nor dimensional changes were observed. Variation of the initial fuel-cladding annulus from 0.004 to 0.019 in. had no significant effect on the slumping behavior, but the larger clearance did allow the fuel pin to bow to a greater extent than that observed in fuel rods with smaller annuli. A niobium restrainer effectively decreased the amount of bowing from that found in a rod with a similar annulus, but did not appear to offer any greater restriction than that provided by a small 0.004-in. annulus.

INTRODUCTION

Although the use of plutonium in fast power reactors is usually in the form of moderate concentrations of the metal in a suitable diluent, it appears that information from measurements of power distribution, spectral indices, ratio of parasitic capture to fission, and the overall breeding ratio can be gained through the operation of a core with a high plutonium alloy loading.(1) Accordingly, a plutonium-rich fuel loading (Mark IV) has been placed in the Experimental Breeder Reactor No. 1 (EBR-I).

Since there are five solid-state transformations occurring in the pure metal, it was not feasible to use plutonium in the unalloyed form. Previous work with the plutonium-aluminum system had indicated that aluminum additions of up to 1.75 w/o (13.6 a/o) could stabilize the body-centered cubic delta phase at room temperature (see Figure 1.)(2) Alloys within this range should not experience the severe dimensional instability of plutonium that occurs on heating or during thermal cycling. In addition, it appeared that not more than 1.59 w/o (12.5 a/o) aluminum nor less than 0.47 w/o (4.01 a/o) aluminum could be used since above this range retained delta will decompose upon subsequent heating to 175°C. Below this

range, the metastable delta phase will transform irreversibly under compression at room temperature.(3) The amount of compression has been found to be important since it has been demonstrated that alloys within this range of interest will creep at loads as low as 7.2 psi.(4) Fuel slumping in a fast reactor would be especially undesirable because of associated reactivity effects.

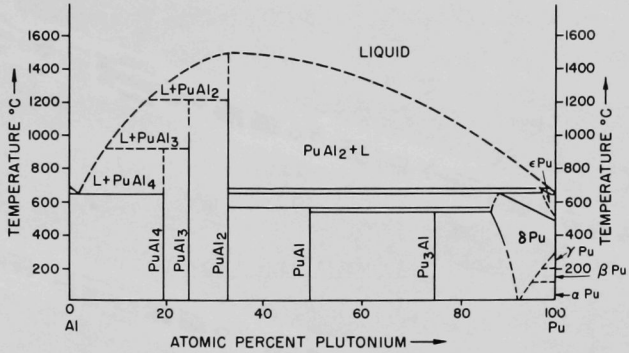

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Figure 1. Aluminum-Plutonium Phase Diagram(2)

In spite of the disadvantages of the plutonium-rich plutonium-aluminum alloy as a reactor fuel, it appeared to be the best choice available for the Core-IV loading of EBR-I. The composition that was selected was plutonium-1.25 w/o (10.1 a/o) aluminum alloy. Before this alloy could be used in EBR-I, however, it was desirable to test prototype fuel rods under conditions expected to be encountered in the reactor. The following report summarizes the results gained from the irradiation of four prototype fuel rods.

PROCEDURE

Fuel Rods

The prototype fuel rods used in this experiment were constructed from 0.020-in.-wall Zircaloy-2 tubing to which three Zircaloy-2 ribs were spot-welded to impart radial restraint and to facilitate uniform spacing of the rods in the reactor. Niobium spacers were clipped on both ends of the fuel and the upper and lower blanket sections to locate and secure them within the jacket, and an Inconel compression spring was placed above the upper blanket to prevent movement of the fuel. The rods were divided into two classes, thermocoupled and nonthermocoupled. Assembled fuel rods of each type are shown in Figure 2. Within each class, one rod was 0.250 in.

in outside diameter and the other rod was 0.280 in. in outside diameter. The variation in cladding diameter resulted in varying the fuel-jacket annulus from 0.004 to 0.019 in., thereby providing for an ascertainment of the effect of this clearance on fuel slumping.

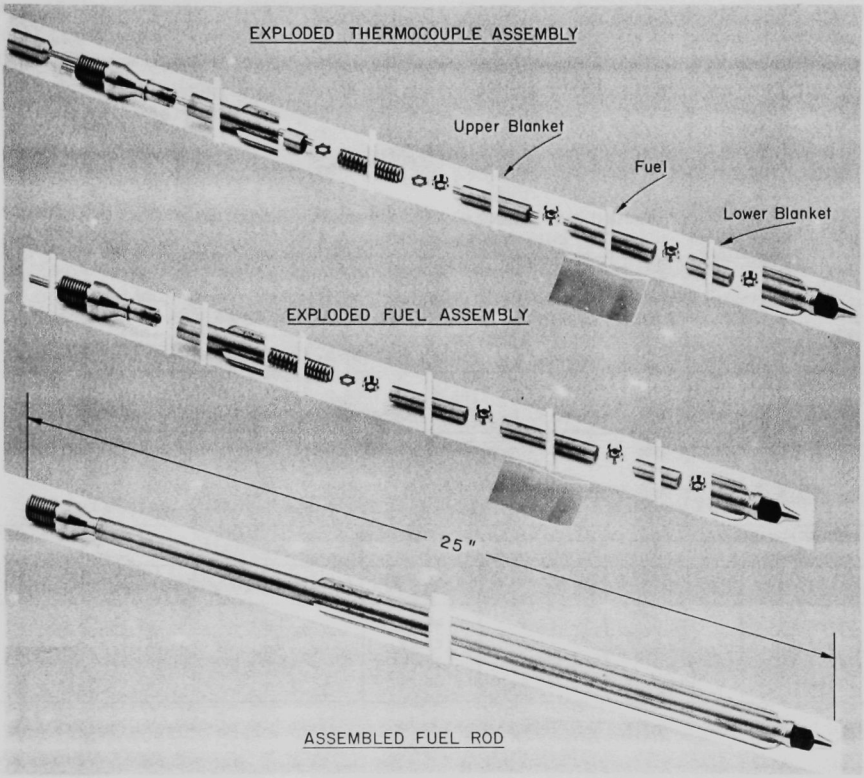

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Figure 2. Appearance of EBR-I Mark-IV Prototype Fuel Rods Prior to Irradiation

Four plutonium-1 w/o (8.2 a/o) aluminum alloy* slugs were made by injection casting into Vycor molds. The resultant castings, originally 0.220 in. in diameter and 9 in. long, were machined to their final dimensions of 0.200-in. diameter and $8\frac{1}{2}$ in. long. Thermocouple holes, 0.086 in.

*This alloy was the original reference fuel composition. The final composition of 1.25 w/o aluminum was chosen when the fissionable requirements were lowered and it was considered more feasible to dilute the fuel rather than to alter the dimensions.

in diameter and 3 in. deep, were drilled into two of the slugs for accurate temperature measurement during irradiation. Preirradiation length and diameter values were taken with calibrated micrometers, and the weight of each fuel sample was measured with a Mettler balance. The density of each rod was calculated from the weight, the length, and the weighted average of the diameter measurements (see Table I). Samples of each rod were sent for chemical analysis and the results were compared with that calculated from a density-composition curve (see Table II). The agreement between the analytical and calculated data was good except for one rod, the difference apparently being due to sample selection.

Table I

PREIRRADIATION DIMENSIONS, WEIGHT, AND DENSITIES OF EBR-I MARK-IV FUEL PINS

Rod No.	Diameter (in.)		Length (in.)	Weight (g)	Density (g/cc)
	Range	Average			
1	0.2005-0.2010	0.2007	8.514	66.3339	15.02
2	0.1993-0.2010	0.2000	8.504	65.8643	15.04
3	0.2005-0.2010	0.2007	8.504	62.0435	15.06
4	0.2000-0.2010	0.2005	8.508	61.9356	15.06

Table II

ALUMINUM CONTENT AND ISOTOPE ANALYSIS OF EBR-I MARK-IV FUEL PINS

Rod No.	w/o Aluminum		Isotope Analysis (m/o)			
	Calculated	Analyzed (±0.03)	Pu^{239} (±0.04)	Pu^{240} (±0.04)	Pu^{241} (±0.002)	Pu^{242} (±0.0001)
1	1.14	1.11	95.74	4.05	0.201	0.0076
2	1.12	1.07	95.43	4.33	0.229	0.0086
3	1.10	0.90	95.55	4.22	0.220	0.0081
4	1.10	1.04	95.00	4.71	0.281	0.0107

Assembly

The fuel specimens and the upper and lower blanket sections of depleted uranium were fitted with niobium spacers, as mentioned previously, and inserted into their respective Zircaloy-2 jackets. A 0.003-in.-wall, snug-fitting niobium cylinder tube made by spot-welding a slightly overlapped piece of foil formed into a tube was placed around the fuel alloy in the 0.280-in.-diameter nonthermocoupled rod in an effort to determine whether or not this was an effective method for restricting slumping of the fuel material. The Inconel spring, spring washer, and collar were then loaded into the fuel tube. A 0.055-in. clearance was provided between the spring and the top of the upper blanket section to decrease the amount of compressive load upon the fuel alloy.

The assembly of the fuel rods was completed by welding on the top connector, filling the tubes with NaK, back-pressurizing with argon, and welding shut the NaK fill lines (see Figure 2). The assembled fuel elements were examined for NaK level and bond integrity by Cyclograph testing with 17-kc and 160-kc coils. Upon completion of the bond tests, the elements were placed inside a vacuum furnace, heat treated at 325°C for 2 hr, and furnace cooled.

The four prototype rods were inserted in the Mark-III core of EBR-I in such a manner that all four would be in approximately the same flux. The nonthermocoupled fuel rods were operated for 802 Mwh at a calculated central fuel temperature of 386°C, and the thermocoupled rods ran at a measured central fuel temperature of 348°C for 966 Mwh.

RESULTS AND DISCUSSION

As previously mentioned, clearances of from 0.004 to 0.019 in. were provided between the fuel surface and the inner jacket wall in an effort to determine whether or not small fuel-cladding separations had a beneficial effect on fuel slumping. If any slumping occurred, it would be expected that the larger amounts would be found in the rods with the 0.019-in. annulus. In addition, it was anticipated that the niobium foil around one fuel slug with a 0.019-in. annulus would tend to reduce slumping from that which would be observed in an unrestrained fuel slug. The results, however, exhibited random behavior, tending to be opposite to that which was expected (see Table III). The largest amount of slumping (0.010 in.) was found in a 0.004-in.-annulus fuel rod. Moreover, the rod with the niobium restrainer (with 0.019-in. annulus) shortened 0.004 in., whereas the equivalent rod without restriction elongated 0.004 in.

Table III

SLUMPING BEHAVIOR OF IRRADIATED PLUTONIUM-1 w/o ALUMINUM ALLOY

Rod Description	Fuel Temp, °C	Estimated Burnup, a/o	Length (in.)		
			Initial	Final	Change
0.004-in. annulus	386	0.09	8.514	8.513	-0.001
0.019-in. annulus with niobium restrainer	386	0.09	8.504	8.500	-0.004
0.004-in. annulus	348	0.11	8.504	8.494	-0.010
0.019-in. annulus	342	0.11	8.508	8.512	+0.004

The bow in the fuel slugs with a 0.004-in. annulus was 0.008 and 0.009 in., whereas the bow in the slugs with a 0.019-in. annulus amounted to 0.028 and 0.019 in. for the fuel without restraint and with a niobium restrainer, respectively (see Table IV). These results indicate that a reduction in the gap between the fuel and the cladding is more effective in restraining bowing than a niobium restrainer of the type used in the experiment. Since the fuel with the 0.003-in. niobium restrainer bowed 0.019 in., it is not likely that a combination of the restrainer and small annulus would have any beneficial effect.

Table IV

BOWING OF PLUTONIUM-1 w/o ALUMINUM ALLOY

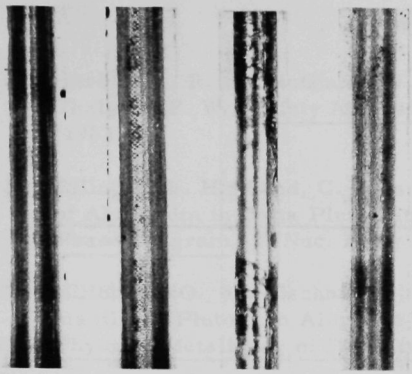
	0.004-in. Gap	0.019-in. Gap, Niobium Restrainer	0.004-in. Gap	0.019-in. gap
Maximum Bow (in.)	0.009	0.019	0.008	0.028

The changes in density of the fuel slugs were random. Two of the fuel samples increased in density and two experienced density decreases. This variation was apparently related to the differences in weight gains and dimensional changes in each of the fuel specimens (see Table V). In general, the fuel pins increased in weight and diameter, and decreased in length. The increases in weight could be due to a number of factors: penetration by NaK into possible defects, oxidation, and zirconium or niobium interaction. The relatively bright appearance of the samples (see Figure 3) and the absence of open surface porosity indicated that the weight increases were not due to these factors. Interaction of the niobium with the plutonium in the restrained sample is unlikely since there appears to be little intersolubility between niobium and plutonium.(5) Diffusion of the zirconium from the cladding to the fuel pin is also unlikely because of the relatively low irradiation temperature, although studies of the plutonium-zirconium binary system indicate that the delta plutonium phase is capable of dissolving and retaining large amounts of zirconium.(6)

Table V

POSTIRRADIATION PHYSICAL MEASUREMENTS OF EBR-I MARK-IV PROTOTYPE FUEL RODS

Rod Description	Annulus (in.)	Fuel Temp, °C	Weight (g)		Avg Diameter (in.)		Density (g/cc)	
			Final	Change	Final	Change	Final	% Change
Nonthermocoupled	0.004	386	65.83	-0.51	0.2007	None	14.91	-0.73
Nonthermocoupled, Niobium Restrainer	0.019	386	67.06	+1.19	0.2000	None	15.32	+1.86
Thermocoupled	0.004	348	62.88	+0.84	0.2024	+0.0017	15.07	+0.07
Thermocoupled	0.019	342	61.96	+0.03	0.2013	+0.0008	14.93	-0.86



31355 (a) 31357 (b) EI-578 (c) EI-581 (d)

Figure 3

Appearance of Plutonium-1 w/o Aluminum Alloy Fuel Samples from EBR-I Mark-IV Prototype Fuel Rods. (a) 386°C, 0.004-in. gap, (b) niobium restrainer, 386°C, 0.019-in. gap, (c) 348°C, 0.004-in. gap, and (d) 342°C, 0.019-in. gap. Note markings from niobium foil on surface of pin (b).

CONCLUSIONS

The plutonium-1 w/o aluminum EBR-I Mark-IV prototype fuel elements operated with little difficulty at burnups up to approximately 0.1 a/o and at central fuel temperatures as high as 386°C. There was no appreciable slumping of the fuel and density changes were not significant. Bowing of the fuel pin was the only notable observed change, and it appears that minimum radial clearance will be necessary to avoid its occurrence.

ACKNOWLEDGEMENTS

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