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PRELIMINARY IRRADIATIONS OF THE CERAMIC FUELS
 UO_2 , $\text{UO}_2\text{-Zr}$, and $\text{ThO}_2\text{-UO}_2$

by

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PRELIMINARY IRRADIATIONS OF THE CERAMIC FUELS UO_2 , $\text{UO}_2\text{-Zr}$, and $\text{ThO}_2\text{-UO}_2$

ABSTRACT

A series of preliminary irradiations have been made on ceramic fuels of interest for thermal reactors. Most of the studies were devoted to $\text{ThO}_2\text{-UO}_2$ compositions because of certain advantages possessed by this material. $\text{ThO}_2\text{-2.5 w/o UO}_2$ and $\text{ThO}_2\text{-10 w/o}$ pellets were irradiated bare and in stainless steel, Zircaloy, and aluminum alloy claddings, with the annulus between the ceramic pellets and the cladding filled with air, a helium-argon mixture, NaK, or lead. It was found that the $\text{ThO}_2\text{-UO}_2$ specimens were highly stable under irradiation. The UO_2 and $\text{UO}_2\text{-Zr}$ specimens showed a relatively greater tendency to fracture during irradiation. Assemblies of $\text{ThO}_2\text{-10 w/o UO}_2$ pellets lead-bonded to aluminum alloy cladding were found to be able to withstand higher heat fluxes without damage than similar assemblies with helium-argon bonding.

INTRODUCTION

The boiling water reactor is one of the major reactor types under active development at Argonne National Laboratory. Like other types of reactors, it has certain characteristic requirements with regard to the materials from which it is constructed. The most severe demands are made on the fuel material, which must be dimensionally stable to burnups of at least 1% of all the atoms in the fuel and which should be highly resistant throughout its life in the reactor to corrosion by water at temperatures of 300°C or higher.

Two parallel investigations are being made by members of the Metallurgy Division at this Laboratory to develop fuel materials which will satisfy the above requirements. The first of these studies has been concerned with corrosion-resistant uranium-base alloys.⁽¹⁾ The effects of irradiation on these alloys are described elsewhere.⁽²⁻⁵⁾

The second investigation, which was started soon after the alloy work, has been concerned with the development of ceramic oxide-type fuels. Fuels of this type are of considerable interest for application in water-cooled reactors because they are highly corrosion resistant to hot water and because they are highly stable dimensionally under irradiation. Most of the ceramic studies have been concerned with solid solutions of UO_2

in ThO_2 . Although fabrication techniques for both UO_2 and ThO_2 are well known,^(6,7) the fabrication of ThO_2 - UO_2 solid solutions with U_3O_8 as the form of uranium oxide in the mixture before firing was a new and promising development.⁽⁸⁾

The use of ThO_2 - UO_2 solid solutions as fuel material offers the following advantages over pure UO_2 :

1. Thoria-urania bodies can be fired in air, whereas urania bodies must be fired in vacuum or a protective atmosphere.
2. The use of thorium atoms in the fuel presents the possibility of constructing a thermal breeder or at least of prolonging the reactivity of a core loading, based on conversion of Th^{232} to U^{233} .

An important aspect of the study of thoria-urania fuels is determination of the ability of the material to withstand irradiation damage. This report is concerned primarily with preliminary irradiation studies made by the Metallurgy Division on two compositions, ThO_2 -2.5 w/o UO_2 and ThO_2 -10 w/o UO_2 , as well as a limited number of earlier irradiations made on UO_2 and cermet of UO_2 and zirconium. The irradiation experiments were primarily intended to determine the dimensional stabilities of the materials when subjected to burnup of a significant fraction of the fuel atoms. Other studies, now in progress, are also concerned with additional factors, including those which affect fission gas release.

EXPERIMENTAL PROCEDURE AND SPECIMEN MATERIALS

All specimens in the irradiation studies were irradiated in the MTR in NaK capsules, with each capsule containing a thermal flux monitor. Procedures for using the NaK capsules and calculating fuel burnups have been previously described.^(2,9) Temperature drops in the capsule assemblies, where cylindrical geometries were used, were calculated using standard heat conduction equations. In the case of the ThO_2 -10 w/o UO_2 material, two specimens were irradiated side-by-side in a single capsule. Because this arrangement was not amenable to direct calculation, use was made of an electrical analogue.⁽¹⁰⁾ Temperature drops in the specimens themselves were calculated with the aid of a high-speed computer. The calculations were programmed so that proper account was taken of the variation in heat generation along the specimen radius because of self-shielding and, even more importantly, the computations took into account the change in thermal conductivity with temperature. All values of burnup and temperature in this report supersede estimated values which have appeared previously.^(6,11,12)

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Weight, dimensions, and visual appearance of each specimen were compared before and after irradiation. The irradiation histories of the specimens are shown in Table I.

UO₂:

The four UO₂ specimens irradiated were each 3/16 in. in diameter and 1/2 in. long. They were made as part of a general study of the properties of pressed and sintered UO₂.⁽⁶⁾ Their densities before irradiation were estimated to be approximately 84% of theoretical. The two specimens with the highest burnups were packed in steel wool during irradiation to prevent damage from mechanical shock. Irradiation conditions are summarized in Table II.

UO₂-Zirconium:

Two UO₂-zirconium cermetes were irradiated. One contained 10 w/o zirconium the other 20 w/o. These specimens were made as part of an investigation on fabricating UO₂-zirconium cermetes.⁽¹³⁾ They were made by hot-pressing in graphite dies for 30 minutes at 3500 psi and 1450°C. Irradiation conditions are summarized in Table III.

ThO₂-UO₂:

As previously mentioned, two thorium-uranium compositions were irradiated - ThO₂-2.5 w/o UO₂ and ThO₂-10 w/o UO₂. Both compositions (initially ThO₂ and U₃O₈) were pressed at 10,000 psi into pellets approximately 1/4 in. in diameter and 1/2 to 3/4 in. long, and fired in air at 1800°C. Densities of the specimens ranged from 85 to 90% of theoretical. The uranium oxide was enriched to approximately 93%.

Twelve specimens of the ThO₂-2.5 w/o UO₂ composition were irradiated. Two specimens were irradiated bare, i.e., directly in NaK. However, steel wool was packed around them in their capsules to prevent damage from mechanical shock. Eight of the specimens were irradiated in closely fitting Zircaloy-2 jackets. A small hole was drilled through the end of four of the jacketed specimens, as shown in Figure 1, to permit NaK to enter and establish a bond between the ceramic pellet and the Zircaloy jacket. Wall thickness of the Zircaloy cladding was 0.015 in. The remaining two specimens were irradiated in 0.008-in. thick Type 304 stainless steel jackets, one of which was drilled to permit entry of NaK. Thickness of the annulus between the pellets and the Zircaloy and stainless steel jacket was approximately 0.005 in. Table IV summarizes the assembly arrangements and irradiation conditions of the ThO₂-2.5 w/o UO₂ specimens.

Eight assembled specimens of the ThO₂-10 w/o UO₂ compositions were irradiated. Each assembly consisted of an aluminum-1 w/o nickel alloy jacket containing two pellets. Wall thickness of the aluminum was

0.020 in. Four of the assemblies contained lead in the annulus between fuel and cladding, while the remaining four contained a welding gas mixture of 80% helium and 20% argon. The annulus thickness in the lead-bonded type of assembly was approximately 0.005 in. and 0.0015 in. in the gas-bonded assembly. Figure 2 shows drawings of vertical sections of the two assemblies. In order to achieve a sound weld above the lead-bonded specimens, it was necessary to allow an appreciable amount of free space, filled with welding gas, above the top surface of the lead. Thus, as shown in Figure 2, the lead-bonded assemblies contained more total gas when finally sealed than did the gas-bonded specimens. As will be shown later, this circumstance had a marked effect on the behavior of some of the assemblies during irradiation. Four irradiation capsules were used, with each capsule containing one lead-bonded and one gas-bonded assembly. Thus, assemblies of each type could be compared after having been irradiated with essentially identical burnups and heat fluxes.

RESULTS AND DISCUSSION

UO₂:

Table II summarizes the results obtained on the UO₂ specimens. Appearance of the specimens before and after irradiation is shown in Figures 3 through 6. All specimens were found to have fractured when examined after irradiation. When the first two specimens, AB-16-1 and AB-16-2, were found to be fractured after irradiation, the possibility of mechanical shock could not be ruled out because the specimens could rattle freely in their capsules. Accordingly, the remaining two specimens were surrounded with steel wool in addition to NaK, so that they were cushioned against mechanical shocks during irradiation. As can be noted, these two specimens fractured in the same manner as the two earlier specimens. It is considered likely, therefore, that the cracking resulted from excessive thermal stresses during irradiation. Thermal fracture of UO₂ pellets has also been frequently observed by investigators at Westinghouse.⁽¹⁴⁾

UO₂-Zr Cermets:

Table III summarizes the changes resulting from irradiation that were noted in the cermet specimens. Changes in the appearance of the specimens are shown in Figures 7 through 10. It was evident that the specimens had increased in volume as a result of the irradiation they received and that some surface roughening occurred. One of the specimens, AA-223, was found to have fractured when examined after irradiation. Because of the small size of the specimen, it is considered unlikely that the fracture resulted from mechanical shock. Since thermal stresses were also relatively low during irradiation, it was concluded that fracture resulted from stresses associated with the volume increase.

ThO₂-2.5 w/o UO₂:

Changes resulting from irradiation of this group of specimens are shown in Table IV. Figures 11 through 15 show the appearance of the specimens receiving the highest burnups in each of the five types of assembly that were used.

In general, no dimensional changes in the specimens outside of experimental error were found to have resulted from irradiation. This was even true of the bare pellets, specimens BF-1 and BF-2, which could be measured directly to 0.0002 in. In comparison, the most stable uranium alloys known would have shown volume changes amounting to several percent after having been subjected to the degree of burnup which these ceramic specimens received.

The performance of the ThO₂-2.5 w/o UO₂ specimens is quite comparable, however, with results obtained on UO₂. WAPD investigators have made numerous irradiations of Zircaloy-2 tubes containing UO₂ pellets without noting any changes in the exterior dimensions of the tube, even after burnups exceeding 3% of the uranium atoms.⁽¹⁵⁾ Since the present ThO₂-UO₂ irradiations include measurements made directly on the pellets, the remarkable dimensional stability of oxide fuel is even more apparent.

The ability of the UO₂ lattice to contain fission products without strain has been attributed by Westinghouse investigators as being inherently due to its CaF₂ structure.^(14,15) The excellent stability of the ThO₂-UO₂ fuels, also having a CaF₂ structure, tends to confirm this view.

ThO₂-10 w/o UO₂:

The eight specimens in this group were deliberately irradiated under severe conditions of temperature and heat flux, as shown in Table V. Although it was realized that some of the assemblies would be damaged from overheating, it was felt that observations on the manner in which the assemblies failed would be useful information. As mentioned earlier, each irradiation capsule contained one lead-bonded and one gas-bonded assembly, so that comparisons of the two types of specimens could be made after they had been subjected to the same burnups and heat fluxes.

The two specimens shown in Figures 16 and 17, CA-1-1 and CA-1-2, were one of the pairs irradiated in the same capsule and showed no external effects of irradiation. Specimens CA-2-1 and CA-2-2, shown in Figures 18 and 19, were irradiated together at higher power outputs and temperatures. They showed a difference in performance which is evident in the photographs. A fissure, or break, in the jacket of the gas-bonded specimen

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occurred during irradiation, although its companion lead-bonded specimen showed no damage. The aluminum alloy jacket of the gas-bonded assembly was then partially removed by etching, as shown in Figure 20. A fragment of fuel was found to be projecting outward, just below the break in the jacket. It is believed that this movement of fuel caused local failure to occur in the cladding. When the jacket was removed from the lead-bonded specimen, as shown in Figure 21, only the lead bond was visible. No fuel particles had shifted to such an extent that they had penetrated through the lead annulus. The better performance of the lead-bonded assembly compared to that shown by the identically irradiated gas-bonded assembly was in part responsible for the selection of this method of assembly for the fuel in the Borax-IV reactor.(16)

The remaining four specimens were overheated to such an extent that they all failed, as shown in Figures 22 through 25. The jackets on the specimens showed different modes of failure, depending on whether a lead bond or a gas bond was originally present. Thus, it may be noted that the cladding on the lead-bonded specimens appears to have failed from a suddenly applied tensile circumferential stress, whereas the jackets on the gas-bonded specimens have evidently failed by melting. The explanation for this difference in behavior is believed to be due to the fact that, as mentioned earlier, the lead-bonded assemblies actually contained more total gas than did the gas-bonded specimens (see Figure 2). When the specimens were brought up to temperature in the reactor it appears that the aluminum jackets on the lead-bonded specimens were not strong enough to contain the pressure developed by the heated gas in the space over the lead, and the jackets therefore burst. From the torn appearance of the fractures, it appears that failure was sudden. The gas-bonded assemblies, on the other hand, apparently remained intact until the temperature of the jackets exceeded the melting point of the alloy. Most of the fuel in both types of the failed assemblies was found to be dispersed in the NaK in the irradiation capsule.

A view of the failed end of specimen CA-4-2, shown in Figure 26, is of interest in that it displays radial fractures and a central void which formed during irradiation. Similar voids have been observed in UO_2 pellets irradiated at high temperature, and have been attributed to melting.(14,15) In the present case, it is considered more likely that the void resulted from additional sintering of the fuel. This conclusion is reached on the basis that the densities of the specimens were only 85 to 90% of theoretical at the start of irradiation, and that the temperature calculations indicated that the center was about 500°C below the melting point of the oxide mixture.

CONCLUSIONS

1. UO_2 and $\text{UO}_2\text{-Zr}$ specimens appear to be somewhat less resistant to stresses developed during irradiation than are $\text{ThO}_2\text{-UO}_2$ specimens.
2. Ceramic pellets with the composition $\text{ThO}_2\text{-2.5 w/o UO}_2$ are exceptionally resistant to dimensional changes under irradiation to burnups of at least 0.75 metal atom per cent (5600 MWD/T oxide).
3. Assemblies of $\text{ThO}_2\text{-UO}_2$ pellets lead-bonded to aluminum alloy cladding are capable of higher heat fluxes without damage than similar assemblies with helium-argon bonding.

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Table I

IRRADIATION HISTORIES OF SPECIMENS

Spec. No.	Composition	Date Placed in Reactor	Date Removed from Reactor	Location in Reactor
AB-16-1	UO ₂	5-7-54	5-15-54	VH-2
AB-16-2	UO ₂	5-7-54	5-15-54	VH-2
AB-102	UO ₂	4-1-55	5-9-55	L-58
AB-103	UO ₂	4-1-55	5-9-55	L-58
AA-223	UO ₂ -20 w/o Zr	5-19-54	9-6-54	L-57
AA-224	UO ₂ -10 w/o Zr	5-19-54	9-6-54	L-57
BF-1	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-2	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-3	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-4	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-5	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-6	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-7	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-8	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-9	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-10	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-11	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
BF-12	ThO ₂ -2-1/2 w/o UO ₂	2-17-55	8-1-55	A-7-SE, A-7-SW
CA-1-1	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-1-2	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-2-1	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-2-2	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-3-1	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-3-2	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-4-1	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE
CA-4-2	ThO ₂ -10 w/o UO ₂	12-27-55	3-19-56	A-13-NE

Table II

EFFECTS OF IRRADIATION ON UO_2 SPECIMENS

Spec. No.	Burnup		Temp., °C		Power Density, cal/sec-cm ³	Heat Flux		Appearance After Irradiation
	Metal, a/o	Oxide, MWD/T	Surface	Center		cal/sec-cm ²	BTU/hr-ft ²	
AB-16-1	0.048	360	120	310	136	16.0	208,000	Fractured into two pieces
AB-16-2	0.048	360	120	310	136	16.0	208,000	Fractured into four pieces
AB-102	0.16	1200	115	300	129	15.6	198,000	Fractured into three pieces
AB-103	0.38	2900	175	510	238	27.6	330,000	Fractured into three pieces

Table III

EFFECT OF IRRADIATION ON UO_2 -Zr CERMETS

Spec. No.	zirconium, w/o	Burnup		Temp., °C		Power Density, cal/sec-cm ³	Heat Flux		Length Change, %	Width Change, %	Thick-ness Change, %
		uranium, a/o	Oxide, MWD/T	Surface	Center		cal/sec-cm ²	BTU/hr-ft ²			
AA-224	10	0.28	2100	130	180	70	3.1	42,000	1.25	3.3	4.1
AA-223	20	0.76	5800	320	460	230	9.8	130,000	(a)	3.0	4.3

(a) Could not be measured because specimen fractured under irradiation.

Table IV

EFFECTS OF IRRADIATION ON ThO_2 -2½ w/o UO_2 SPECIMENS

Spec. No.	Cladding	Type of Bonding	Burnup(a)		Temp. °C		Power Density, cal/sec-cm ³	Heat Flux		Length Change, %	Diameter Change, %	Weight Change, mg
			Metal a/o	Oxide MWD/T	Surface	Center		cal/sec-cm ²	BTU/hr-ft ²			
BF-1	None	-	0.16	1200	80	110	27	4.4	54,000	0.0	0.0	-0.4
BF-2	None	-	0.75	5700	220	480	143	24.0	286,000	0.0	0.0	7.6
BF-3	Zircaloy 2	NaK	0.38	2900	140	340	71	11.6	142,000	-0.1	-0.1	-
BF-4	Zircaloy 2	NaK	0.64	4900	220	440	128	20.8	256,000	0.0	-0.7	-
BF-5	Zircaloy 2	NaK	0.69	5200	230	480	139	22.4	278,000	0.0	-0.7	-
BF-6	Zircaloy 2	NaK	0.30	2300	120	290	54	8.8	110,000	0.0	0.0	-
BF-7	Zircaloy 2	Air	0.25	1900	380	470	46	7.5	92,000	0.3	-0.1	-
BF-8	Zircaloy 2	Air	0.53	4000	580	900	103	16.7	206,000	0.1	-0.1	-
BF-9	Zircaloy 2	Air	0.74	5600	820	1210	149	24.2	298,000	0.2	0.0	-
BF-10	Zircaloy 2	Air	0.43	3300	470	720	82	13.2	164,000	0.0	-0.1	-
BF-11	304 St. Steel	NaK	0.57	4300	200	380	113	18.4	227,000	-0.1	0.0	-
BF-12	304 St. Steel	Air	0.74	5600	810	1200	149	24.2	298,000	-0.1	-0.2	-

(a) Determined by radiochemical analysis.

Table V

EFFECTS OF IRRADIATION ON ALUMINUM ALLOY-CLAD ThO_2 -10 w/o UO_2 SPECIMENS

Spec. No.	Type of Bonding	Burnup		Temp., °C		Power Density cal/sec-cm ³	Heat Flux		Length Change, %	Diameter Change, %	Weight Change, mg	Remarks
		Metal, a/o	Oxide, MWD/T	Surface	Center		cal/sec-cm ²	BTU/hr-ft ²				
CA-1-1	Lead	0.34	2600	150	310	110	16.5	220,000	-0.31	0.90	16.2	Small crack and bulge in cladding.
CA-1-2	Gas	0.34	2600	260	420	110	16.5	220,000	2.21	.18	9.1	
CA-2-1	Lead	0.64	4900	240	780	210	32.0	425,000	.24	.32	2.6	
CA-2-2	Gas	0.64	4900	460	1040	210	32.0	425,000	.33	.26	144.2	
CA-3-1	Lead	1.10	8400	380	1650	350	53.5	710,000	-	-	-	Jacket burst, fuel disintegrated.
CA-3-2	Gas	1.10	8400	740	2080	350	53.5	710,000	-	-	-	Jacket melted, fuel partially disintegrated.
CA-4-1	Lead	1.25	9500	440	2200	415	63.5	840,000	-	-	-	Jacket burst, fuel disintegrated.
CA-4-2	Gas	1.25	9500	860	2740	415	63.5	840,000	-	-	-	Jacket melted, fuel partially disintegrated, with possible evidence of central melting.

16769

2X

Figure 1. Typical Zircaloy-2-jacketed ThO_2 -2.5 w/o UO_2 specimen before irradiation. Note hole drilled in end of jacket to permit entry of NaK into annulus between the ceramic pellet and jacket.

a. Lead-Bonded Assembly

b. Gas-Bonded Assembly

Figure 2. Vertical sections of jacketed ThO_2 -10 w/o UO_2 assemblies.

16126

2X

Figure 3. Typical UO₂ pellets before irradiation.

15963

2X

Figure 4. Effect of 0.048% uranium atom burnup on UO₂ specimens AB-16-1 and AB-16-2.

18,635

2X

Figure 5. Effect of 0.016% uranium atom burnup on UO_2 specimen AB-102.

18,636

2X

Figure 6. Effect of 0.38% uranium atom burnup on UO_2 specimen AB-103.

15,073

5X

Figure 7. Appearance of UO_2 -10 w/o Zr specimen AA-224 before irradiation.

16,596

5X

Figure 8. Effect of 0.21% metal atom burnup on specimen AA-224.

15,072

5X

Figure 9. Appearance of $\text{UO}_2\text{-20 w/o Zr}$ specimen AA-223 before irradiation.

16,598

5X

Figure 10. Effect of 0.44% metal atom burnup on specimen AA-223.

18095

2X

Figure 11. Specimen BF-2, ThO_2 -10 w/o UO_2 , after 0.75% metal atom burnup at a central temperature of 480°C . The appearance and dimensions of the specimen were unchanged by irradiation.

19,621

2X

Figure 12. Specimen BF-5, ThO_2 -2.5 w/o UO_2 , with a NaK bond and Zircaloy-2 jacket, after 0.69% metal atom burnup at a central temperature of 480°C .

18,108

2X

Figure 13. Specimen BF-9, ThO_2 -2.5 w/o UO_2 , with an air bond and Zircaloy-2 jacket, after 0.74% metal atom burnup at a central temperature of 1210°C .

18,111

2X

Figure 14. Specimen BF-11, ThO_2 -2.5 w/o UO_2 , with a NaK bond and stainless steel jacket, after 0.57% metal atom burnup at a central temperature of 380°C .

18,113

2X

Figure 15. Specimen BF-12, ThO_2 -2.5 w/o UO_2 , with an air bond and stainless steel jacket, after 0.74% metal atom burnup at a central temperature of 1200°C .

19,474

2X

Figure 16. Specimen CA-1-1, ThO_2 -10 w/o UO_2 , with a lead bond and aluminum alloy jacket, after 0.34% metal atom burnup at a central temperature of 310°C .

19,473

2X

Figure 17. Specimen CA-1-2, ThO_2 -10 w/o UO_2 , with a gas bond and aluminum alloy jacket, after 0.34% metal atom burnup at a central temperature of 420°C .

19,476

2X

Figure 18. Specimen CA-2-1, ThO_2 -10 w/o UO_2 , with a lead bond and aluminum alloy jacket, after 0.64% burnup of the metal atoms at a central temperature of 780°C .

19,475

2X

Figure 19. Specimen CA-2-2, ThO_2 -10 w/o UO_2 , with a gas bond and aluminum alloy jacket, after 0.64% burnup of the metal atoms at a central temperature of 1040°C . Note the break in the cladding near the center of the assembly.

19527

2X

Figure 20. Specimen CA-2-2 after partial removal of its aluminum alloy jacket. It appeared that the fragment of fuel shown projecting from the center of the lower edge of the specimen caused the jacket failure shown in Figure 19.

19529

2X

Figure 21. Specimen CA-1-1 after partial removal of its aluminum alloy jacket. The lead bond is shown.

19478

2X

Figure 22. Specimen CA-3-1, ThO_2 -10 w/o UO_2 , with a lead bond and aluminum alloy jacket, after 1.10% burnup of the metal atoms at a central temperature of 1650°C .

19477

2X

Figure 23. Specimen CA-3-2, ThO_2 -10 w/o UO_2 , with a gas bond and aluminum alloy jacket, after 1.10% burnup of the metal atoms at a central temperature of 2080°C .

19481

2X

Figure 24. Specimen CA-4-1, ThO_2 -10 w/o UO_2 , with a lead bond and aluminum jacket, after 1.25% burnup of the metal atoms at a central temperature of 2200°C .

19480

2X

Figure 25. Specimen CA-4-2, ThO_2 -10 w/o UO_2 , with a gas bond and aluminum alloy jacket after a burnup of 1.25% of the metal atoms at a central temperature of 2740°C .

19533

8X

Figure 26. Specimen CA-4-2, showing a central void which formed in the oxide pellet during irradiation either from sintering or melting.