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EXAMINATION OF EBWR CORE-IA FUEL

by

R. Carlander

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EXAMINATION OF EBWR CORE-IA FUEL

by

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ABSTRACT

An EBWR fuel element was examined, after the 100-MW operation and a maximum burnup of 0.61 a/o, as part of a continuing evaluation of the in-reactor performance and irradiation damage to the fuel alloy. Although the maximum rate of volume increase per a/o burnup was 7.6% at the point of maximum burnup, increases as high as 13.3% per a/o burnup were found in regions of lower burnup. These larger rates of volume increase were due to a combination of burnup and high centerline fuel temperature. Large-scale buildups, particularly in regions free of nucleate boiling, contributed to the higher centerline fuel temperatures by acting as a thermal insulation barrier between the cladding and the water coolant. The temperatures, which were calculated to be in excess of 500°C (932°F), resulted in an annealing out of the residual stresses that existed in the fuel elements before the 100-MW operation. The results indicated that for satisfactory performance at high power levels, the centerline fuel temperature of fuel elements of the EBWR type should be maintained below 500°C (932°F) through the adequate control of scale accumulation.

INTRODUCTION

The evaluation of reactor fuel elements during the course of the operation of a nuclear reactor is a satisfactory means for determining the irradiation characteristics of a fuel alloy. Of special interest, in addition to the irradiation stability of the fuel, is the increase in effective fuel-plate thickness due to such factors as scaling, which can only be encountered in a full-scale power plant. Furthermore, a continuous evaluation of fuel-element performance provides a basis for predicting the future life or uses of the core, as well as producing information for future users of the reactor type. Such examinations have been conducted on EBWR fuel elements with 0.11 and 0.39 a/o burnup after 20-MW(t) operation.¹ To continue this performance analyses, a fuel element that received 0.61 a/o burnup was examined after the reactor was operated at 100 MW.

EXPERIMENTAL PROCEDURE

The reactor was fueled with plates of U-5w/oZr-1.5w/oNb alloy to which dimensional stability had been imparted by a treatment consisting of a gamma soak at 825°C (1517°F), an isothermal quench and holding at

640°C (1184°F) for 23 hr, followed by air cooling. The plates were roll-bonded with Zircaloy-2 and were either of natural uranium or enriched with 1.44% U^{235} (Ref. 2). The plates were of two different thicknesses, 0.212 or 0.273 in. (5.38 or 6.94 mm), and were placed in a parallel arrangement in the fuel element, which was in the form of a rectangular box enclosed by perforated Zircaloy-2 side plates (see Fig. 1).

111-7279

Fig. 1. EBWR Fuel Assembly

The fuel element chosen for examination was of the "thin" type, 0.212 in. (5.38 mm) thick, 1.44% enriched in U^{235} , and was irradiated to a maximum burnup of 0.61 a/o of the uranium atoms. The procedures for handling and disassembly of the element have been described previously.³ The details and results of the inspection, which included visual examination, dimensional measurements, gamma-activity scans, and metallographic examination, are discussed in this report.

RESULTS AND DISCUSSION

Visual Examination

The appearance of the fuel element immediately after entry into the hot cell and before disassembly is shown in Fig. 2. The scale that formed on the surface of the fuel plates had undergone flaking primarily at the center and at the bottom (high flux zone) of the fuel element. The maximum thickness of the scale that spalled from the surface was 0.002 in. (0.05 mm). The condition and irregular appearance of the fuel-plate surface is shown in Fig. 3. The amount of scale that spalled from the surface was somewhat greater than what was observed in an earlier examination and has been identified as being composed of nickel, iron, and boehmite ($Al_2O_3 \cdot H_2O$).¹ The perforated Zircaloy-2 side plates were attached firmly except for a

106-7841

106-7840

Fig. 2. Appearance of EBWR Fuel Element ET-11 before Disassembly.
(The top of the element is at the right.)

EI-2460

7X

Fig. 3. Surface Scale on EBWR Fuel Plate

slight rippling between spot welds, and no preferential corrosion was observed to have occurred between the Type 304 stainless-steel rivets and the Zircaloy-2 end fittings (see Fig. 4).

106-7563A

Fig. 4. Scaling on Fuel-element Surface and Appearance of Stainless-steel Rivets and Zircaloy-2 Side Plates and End Fittings

Gamma Activity and Burnup Analyses

The gamma activity along the length of each plate was plotted to aid in the selection of burnup samples and metallography specimens. Burnup analyses were made at the area of highest gamma activity of each plate and at 6-in. (15-cm) intervals along the length of the plate having the highest gamma activity (plate 359). The results of the burnup analyses are shown in Table I. The highest burnup sample for plate 359 was lost during the analysis, and the burnup for that position was taken as the high value found in the other plates, or 0.61 a/o. A comparison of the plot of gamma activity for plate 359 versus burnup showed good correlation between the two curves (Figs. 5 and 6).

TABLE I. Burnup Analyses on EBWR Fuel Element ET-11 Fuel Plates

Plate Designation	Distance from Bottom of Fuel Plates, in.	Burnup, ^a a/o ^b	MWD/T U
E359	6	0.332	3320
E359	12	0.507	5070
E359	18	- ^c	-
E359	24	0.476	4760
E359	30	0.451	4510
E359	36	0.351	3510
E359	42	0.216	2160
E359	48	0.109	1090
E327	18	0.583	5830
E353	18	0.605	6050
E349	18	0.596	5960
E206	18	0.609	6090
E373	18	0.581	5810

^aBased on radiochemical analysis for Cs¹³⁵, accuracy of $\pm 5\%$.

^bBurnup (in a/o) is the ratio of the number of fissions to the total number of atoms present in the core, times 100.

^cSample lost during analysis.

Fig. 5. Gamma-activity Scan of EBWR Fuel Plate 359

Fig. 6. Burnup of EBWR Fuel Plate 359

Physical Dimensions

Channel Gap. The gap between the fuel-plate channels was measured to obtain information pertaining to the shutting off of the channels due to oxide formation. In addition, since it was estimated that scale buildup of the extent noted in previous examinations could raise the calculated centerline fuel temperature from 320°C (608°F) to more than 500°C (932°F), such measurements gave an indication of the location of the high-temperature regions in the fuel element.

The gaps were generally decreased by a maximum of 0.035 in. (0.89 mm). However, the gap between plates 373 and 349 was larger than the reference value of 0.438 in. (11.1 mm). This was probably due to a transposing of plate 349 in either direction during fabrication (see Table II). To obtain an indication of the relative amount of scale buildup along the length of plate 359, the sum of the half-values of the decrease in the gap on either side of the plate was determined as a function of distance. Values for initial channel-gap spacing other than that of the reference value were chosen to make all values negative, and the results therefore are an apparent rather than an actual indication of scale buildup. The results of the calculations (given in Fig. 7) show that the gap decreased; hence, the scale thickness and centerline fuel temperature increased near the top of the fuel element in regions of decreasing neutron flux.

TABLE II. Channel-gap Measurements on EBWR Fuel Element ET-11

Distance from Bottom of Fuel Plate, in.	Plate-gap Designations				
	206/359	359/327	327/373	373/349	349/353
	Channel Gap, in.				
$3\frac{1}{2}$	0.450	0.415	0.436	0.460	0.408
$6\frac{1}{2}$	0.452	0.407	0.426	0.459	0.400
$9\frac{1}{2}$	0.450	0.405	0.429	0.457	0.399
$12\frac{1}{2}$	0.443	0.402	0.432	0.460	0.400
$15\frac{1}{2}$	0.433	0.402	0.428	0.462	0.400
$18\frac{1}{2}$	0.429	0.403	0.432	0.461	0.404
$21\frac{1}{2}$	0.419	0.403	0.430	0.459	0.407
$24\frac{1}{2}$	0.413	0.407	0.434	0.460	0.410
$27\frac{1}{2}$	0.410	0.410	0.427	0.442	0.413
$30\frac{1}{2}$	0.406	0.404	0.415	0.447	0.407
$33\frac{1}{2}$	0.405	0.402	0.423	0.465	0.411
$36\frac{1}{2}$	0.413	0.407	0.430	0.468	0.413
$39\frac{1}{2}$	0.412	0.406	0.406	0.463	0.409
$42\frac{1}{2}$	0.416	0.404	0.428	0.471	0.406
$45\frac{1}{2}$	0.426	0.401	0.402	0.463	0.412
$48\frac{1}{2}$	0.441	0.422	0.427	0.447	0.449

Fig. 7. Apparent Scale Thickness on EBWR Fuel Plate 359 as Determined by Channel-gap Measurements

proximately 3-in. (7.7-cm) intervals, beginning at 6 in. (15.2 cm) from the bottom of each plate, and computing the increase in thickness with reference to nominal thickness of 0.212 in. (5.38 mm). The average increase in plate thickness before descaling varied from 0.007 to 0.013 in. (0.18 to 0.33 mm), compared to 0.003 to 0.009 in. (0.07 to 0.22 mm) found in EBWR fuel element ET-51 after 0.39 a/o burnup (see Tables IV and V).¹

Length. Length measurements were made at the center and at 1 in. (2.5 cm) from each edge of each plate. The values, shown in Table III, indicated that no significant change occurred in the length of the plates within the dimensional tolerances and the accuracy of the postirradiation measurements.

Thickness. The change in thickness of each plate was determined before descaling by measuring the thickness along the centerline at ap-

TABLE III. Length Measurements on EBWR ET-11 Fuel Plates

Location of Measurement	Plate Designation					
	206	359	327	373	349	353
	Length, in. ^a					
One inch from edge	53-31/32	53-31/32	54	53-15/16	53-15/16	53-15/16
Center	53-31/32	53-31/32	54	54	53-15/16	53-15/16
One inch from edge	53-31/32	53-31/32	53-31/32	53-15/16	53-15/16	53-15/16

^aReference length = $54 \pm 1/64$ in.; accuracy of measurements = $\pm 1/32$ in.

TABLE IV. Thickness of EBWR ET-11 Fuel Plates before Descaling

Distance from Bottom of Fuel Plate, in.	Plate Designation					
	206	359	327	373	349	353
	Plate Thickness, in.					
6	0.215	0.211	0.216	0.205	0.220	0.208
9	0.222	0.217	0.222	0.220	0.222	0.224
12	0.226	0.221	0.242	0.219	0.223	0.224
15	0.225	0.218	0.227	0.220	0.222	0.230
18	0.219	0.219	0.225	0.221	0.221	0.221
21	0.217	0.222	0.225	0.217	0.221	0.219
24	0.224	0.224	0.226	0.218	0.221	0.219
27	0.221	0.227	0.223	0.217	0.220	0.221
30	0.219	0.222	0.232	0.217	0.224	0.218
33	0.226	0.221	0.227	0.220	0.225	0.221
36	0.226	0.221	0.226	0.224	0.221	0.221
39	0.236	0.221	0.224	0.218	0.220	0.219
42	0.218	0.219	0.225	0.216	0.219	0.218
45	0.219	0.220	0.224	0.217	0.219	0.211
48	0.219	0.216	0.227	0.218	0.214	0.214
51	0.218	0.210	0.214	0.210	0.212	0.210

TABLE V. Increase in Thickness of EBWR ET-11 Fuel Plates before Descaling

Distance from Bottom of Fuel Plate, in.	Plate Designation					
	206	359	327	373	349	353
	Thickness Increase, in. ^a					
6	0.003	-	0.004	-	0.008	-
9	0.010	0.005	0.010	0.008	0.010	0.012
12	0.014	0.009	0.030	0.007	0.011	0.012
15	0.013	0.006	0.015	0.008	0.010	0.018
18	0.007	0.007	0.013	0.009	0.009	0.009
21	0.005	0.010	0.013	0.005	0.009	0.007
24	0.012	0.012	0.014	0.006	0.009	0.007
27	0.009	0.015	0.011	0.005	0.008	0.009
30	0.007	0.010	0.020	0.005	0.012	0.006
33	0.014	0.009	0.015	0.008	0.013	0.009
36	0.014	0.009	0.014	0.012	0.009	0.009
39	0.014	0.009	0.012	0.006	0.008	0.007
42	0.006	0.007	0.013	0.014	0.007	0.006
45	0.007	0.008	0.012	0.005	0.007	0.009
48	0.007	0.004	0.015	0.006	0.002	0.002
51	0.006	-	0.002	-	-	-

^aValues are based on nominal thickness of 0.212 in.; all negative values are neglected.

After descailing, the change in thickness was computed for the "hottest" plate, 359, as determined by gamma scanning (see Table VI). The maximum change in thickness was 0.010 in. (0.25 mm), and for a maximum burnup of 0.61 a/o the maximum rate of volume increase was 7.6% per a/o burnup. Calculation of the percent change in volume per a/o burnup, as a function of distance along the fuel plate, indicated that rates of volume increase as high as 13.3% occurred in regions of decreasing burnup (see Fig. 8). Comparison of this plot with that for scale buildup as determined by channel-gap measurements (see Fig. 7) showed that the maximum percent volume change occurred in an area of high centerline fuel temperature. The swelling of the fuel plate was therefore a function of burnup and of centerline fuel temperature.

TABLE VI. Thickness of EBWR ET-11 Fuel Plate 359 after Descaling

Distance from Bottom of Plate, in.	Thickness after Descaling, in.	Total Thickness Increase from Initial Thickness, in.	Distance from Bottom of Plate, in.	Thickness after Descaling, in.	Total Thickness Increase from Initial Thickness, in.
6	0.209	-	30	0.221	0.009
9	0.213	0.001	33	0.221	0.009
12	0.216	0.004	36	0.220	0.010
15	0.213	0.001	39	0.216	0.004
18	0.219	0.007	42	0.216	0.004
21	0.218	0.006	45	0.215	0.003
24	0.221	0.009	48	0.217	0.005
27	0.222	0.010	51	0.208	-

Fig. 8. Rate of Volume Increase across EBWR Fuel Plate 359

Residual Stress

One-sixteenth-in. (1.6-mm)-thick samples were cut from plate 359 to ascertain the relative residual stress in the fuel plate. In a previous examination, identical specimens warped and underwent severe cracking, but in this instance, no similar effect was noted. The samples were therefore mounted, ground, polished, and etched in a $\text{HNO}_3\text{-HF-H}_2\text{O}$ mixture to determine if microcracking had occurred. Only one sample showed microcracking, and this was in the

form of a single crack adjacent to the edge of the plate (see Fig. 9). A large void was also noted in this area, but none was found in any of the other specimens. The difference in residual stress in this element after 0.61 a/o burnup, and in the fuel elements after 0.39 a/o burnup, was probably the result of annealing due to the higher centerline fuel temperature.

EI-2456

7X

Fig. 9. Microcracking in Residual Stress Specimen. (Crack extends from right side of specimen to the top center of the photograph.)

Metallographic Examination

It has been noted previously that the fuel alloy is composed initially of the alpha phase and the metastable gamma phase, and that the grain structure becomes increasingly distorted with increasing burnup, until at approximately 0.30 a/o burnup the original grain structure is unresolvable.¹ The original grain structure and the structure as a function of burnup and distance along the fuel plate are shown in Fig. 10. The grain structure is

EI-2619

0.0 a/o

EI-5030

6 in. 0.33 a/o

EI-5031

30 in. 0.45 a/o

EI-5032

42 in. 0.22 a/o

Fig. 10. Variation in Microstructure of U-5w/oZr-1.5w/oNb Fuel Alloy as a Function of Distance and Burnup. (Unirradiated alloy at 500X, all other photomicrographs at 1500X.)

unresolvable and typical of that found in the element examined after 0.39 a/o burnup. At the upper regions of the plate, however, a portion of the original grain microstructure still remained and corresponded to burnups of less than 0.30 a/o. There was no apparent microstructural correlation between swelling and centerline fuel temperature.

During fabrication, the spot-welding of the Zircaloy-2 side plates had caused the fuel adjacent to these regions to become a transformed gamma and quenched structure, thereby resulting in a growth rate in those areas approximately 50 times that of the isothermally-transformed core alloy. These structures were observed during the earlier examinations and contributed to the severe cracking that occurred in those regions. The structures adjacent to the spot-weld areas were not, however, abnormally different from that in the center of the core and appeared again to be the result of the higher temperature of operation.

CONCLUSIONS

The EBWR fuel element was in satisfactory condition after a burnup of 0.61 a/o and had maximum rate of volume increase at the point of maximum burnup of 7.6% per a/o burnup. Increases in volume as high as 13.3% per a/o burnup in regions of lower burnup were attributed to scale accumulations in these areas, which resulted in centerline fuel temperatures calculated to be in excess of 500°C (932°F). The higher centerline fuel temperatures had a beneficial effect in that the fuel plates were in a relatively stress-free condition compared to elements operated at a lower temperature. Fuel elements of the EBWR type could probably be operated at high power levels and for extended burnup if the centerline fuel temperature was maintained below 500°C (932°F) near the reference value of 320°C (608°F) through the control of scale formation.

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