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EFFECTS OF IRRADIATION ON THE EBWR FUEL ALLOY
URANIUM-5 w/o ZIRCONIUM-1.5 w/o NIOBIUM

by

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EFFECTS OF IRRADIATION OF THE EBWR FUEL ALLOY URANIUM-5 w/o ZIRCONIUM-1.5 w/o NIOBIUM

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ABSTRACT

Irradiations were made on small specimens of U-5 w/o Zr-1.5 w/o Nb alloy with a wide variety of fabrication histories and heat treatments in order to determine the optimum heat treatment for the fuel plates for the EBWR (Experimental Boiling Water Reactor). In the time available, a heat treatment could not be found which simultaneously conferred dimensional stability and corrosion resistance to the alloy. The most effective heat treatment for dimensionally stabilizing swaged or round-rolled material was a 24-hour isothermal transformation from the gamma phase at 650°C. This heat treatment was subsequently used as a basis for the heat treatment specifications for the EBWR fuel plates. In later studies on specimens cut from plates it was learned that the alloy could be adequately stabilized against irradiation growth and also made corrosion resistant by first reducing the plate 12% in thickness by cold rolling, followed by a 24-hour isothermal transformation from the gamma phase at 665°C, and finally quenching from 800°C. Irradiation growth rates of plate specimens were effectively reduced by the presence of metallurgically bonded Zircaloy-2 cladding. Flat-rolled material under irradiation generally increased in length and width and decreased in thickness.

INTRODUCTION

The Experimental Boiling Water Reactor (EBWR), located at Argonne National Laboratory, is a metal-fueled direct-cycle boiling water reactor supplying saturated steam at 600 psi for generation of electricity.⁽¹⁾ Light water serves as a moderator and coolant and circulates through the core by natural convection.

The saturation temperature of water at 600 psi is 254°C. At this temperature unalloyed uranium would react rapidly with water if the cladding on the fuel were to fail in some manner. Therefore, in the fuel-development program which preceded the construction of EBWR, a resistance to aqueous corrosion was one of the primary requirements of the various fuels under

consideration. Other initial requirements were that the fuel alloy be dimensionally stable, contain a minimum of alloying elements, and that it be readily fabricable.

The alloy finally selected for the first core of EBWR has a composition of U-5 w/o Zr-1.5 w/o Nb. This alloy showed the most favorable combination of aqueous corrosion resistance⁽²⁾ and ease of fabrication.⁽³⁾ The alloy is most corrosion resistant when quenched from the gamma phase to form a martensitic alpha structure. Additional corrosion resistance can be obtained by a short aging treatment of the quenched material.

As soon as the U-5 w/o Zr-1.5 w/o Nb alloy was chosen as the reference fuel for the reactor, experiments were begun in order to evaluate the irradiation behavior of the alloy. Of particular interest were the dimensional stability of the alloy under irradiation and the manner in which its dimensional stability was affected by fabrication and heat treatment. Also of considerable interest, of course, was the ability of the alloy to retain its corrosion resistance when subjected to irradiation.

This report presents the results obtained in irradiation studies of the dimensional stability of the U-5 w/o Zr-1.5 w/o Nb alloy. The effects of irradiation on the corrosion resistance of the alloy have been previously reported,^(4,5) as have irradiation studies of other promising corrosion-resistant fuel alloys.⁽⁶⁾

SPECIMEN MATERIALS AND EXPERIMENTAL PROCEDURE

Seven different ingots were used to supply material for fabrication into irradiation specimens. Table I shows the analyzed compositions of the ingots. All were induction-melted and cast under vacuum.

TABLE I

Composition of Ingots Used for
Irradiation Specimens

Ingot No.	Zr, w/o	Nb, w/o	C, ppm	N, ppm
CNY-4	5.08	1.50	116	36
Y16F-100	5.01	1.59	17	47
L-24	5.27	1.59	35	73
L-85	5.25	1.77	44	64
L-125	5.00	1.79	107	114
L-128	5.07	1.67	32	9
L-215	5.40	1.67	21	17

The irradiation specimens were prepared by various fabrication techniques, including casting to size, swaging, and both flat and round rolling. A large variety of heat treatments was given to the specimens before irradiation. The fabrication methods and heat treatments used will be discussed in more detail in the following section with reference to their effects on the irradiation behavior of the specimens.

The specimens were irradiated in the MTR in loosely fitting capsules containing NaK for heat transfer. A typical capsule is shown in Figure 1. Each capsule contained an Al-Co alloy flux monitor.

Figure 1. Typical Fuel Irradiation Capsule Assembly for MTR. The Capsule is Approximately 3 in. High

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The activation of the cobalt provided data for calculations of fuel burnups and irradiation temperatures. Appropriate corrections were made for such factors as resonance activation in the cobalt, and flux depression and self-shielding caused by the fuel samples. Temperatures were calculated based on conventional thermal conduction and heat transfer relations or, where the geometrical arrangement was complex, use was made of an electrical geometrical analogue that was available in the Reactor Engineering Division.

The irradiation technique had been developed earlier for MTR conditions and has been described previously.⁽⁷⁾ The irradiations were made during the period 1954-1956. Where the condition of the specimen permitted, dimensional measurements by micrometers were made after irradiation. Dimensional determinations on distorted specimens were made by scaling photographs containing a length standard along with the specimen.

RESULTS AND DISCUSSION

The irradiation specimens can be conveniently classified into seven different groups depending upon their fabrication and heat treatment. As will be shown, the irradiation behavior of the alloy is very dependent upon its fabrication and thermal history. Each group of specimens thus showed a characteristic response to irradiation. The groups will therefore be discussed separately and in the approximate chronological order in which they were irradiated and examined.

As-fabricated Material (Group 1)

Results from as-fabricated specimens, which comprised the first group of irradiated specimens, are shown in Table II. Derivation of the growth coefficient, G_i , shown in the table, is given in reference 7. For small elongations,

$$G_i \approx \frac{\% \text{ length change}}{a/o \text{ burnup}}$$

A typical specimen before irradiation is shown in Figure 2.

TABLE II
Effects of Irradiation on As-fabricated Specimens(a) (Group 1)

Specimen No.	Fabrication	Burnup, a/o	Irradiation Temp, °C		Length Change, %	Growth Rate, $G_i^{(b)}$	Diameter Change, %	Remarks
			Surface	Center				
AH-1-6	Cast	0.046	120	130	1.16	25	0.44	
AH-2-6	Cast	0.048	120	130	-0.02	-0.4	1.31	
AB-36-1	Swaged at 800°C	0.071	140	160	11.5	150	-3.4	Slightly Warped

(a) All specimens were fabricated from ingot No. CNY-4.

(b) G_i = microin./in. per fission/ 10^6 total atoms.

Figure 2

Appearance of Typical Cast or Wrought Specimen before Irradiation

The two cast specimens, as expected, were much more stable than the highly oriented swaged specimen. The large scatter in the growth rates of the castings is unusual, although similar behavior has occasionally been noted in cast uranium-zirconium alloys.^(8,9) The appearance of the cast specimen shown in Figure 3 was not changed by irradiation.

17030

2X

Figure 3. Cast Specimen No. AH-1-6 after
0.046 a/o Burnup at a Center Tem-
perature of 130°C

The as-swaged specimen, No. AB-36-1, elongated under irradiation, with a growth coefficient of 150 microin./in. per fission/ 10^6 total atoms. As shown in Figure 4, although the as-swaged material did not develop surface roughening under irradiation, it exhibited a tendency to distort by warping.

16425

2X

Figure 4. Swaged Specimen AB-36-1 after
0.071 a/o Burnup at 160°C

Material Heat Treated for Corrosion Resistance (Group 2)

Of greatest interest, of course, was the dimensional stability under irradiation of the alloy when given a prior heat treatment for corrosion resistance. The second group of irradiation specimens was made from this type of material.

As noted earlier, the heat treatment consisted of quenching the alloy from the gamma phase, followed in some cases by an aging treatment. Table III summarizes irradiation results from quenched as well as quenched and aged specimens. The AF group of specimens was 10% enriched in order to accelerate the rate of burnup.

All specimens, with the exception of a group that was restrained during irradiation, showed growth rates that were even higher than those obtained with as-fabricated material. Values of G_i , the growth coefficient, were near 300 for the wrought specimens. Repeated gamma quenches steadily enhanced the growth rate, as shown in the results from specimens AB-26, AB-27, and AB-28. Thus, after four gamma quenches, specimen AB-28 was found to have a growth coefficient of 470. Aging the wrought specimens near 400°C diminished the growth rate to an average value of approximately 120.

All the quenched specimens were found to have distorted severely under irradiation. Figure 5 shows typical cast and gamma-quenched specimens after irradiation. The better surface smoothness shown by specimen AH-1-2 is attributed to the fact that prior to quenching it was annealed for only three minutes at 800°C, whereas the AF group of specimens was held for one hour at 1000°C before quenching. The latter heat treatment evidently resulted in gamma grain growth, which in turn caused surface roughening to develop under irradiation.

Postirradiation aqueous corrosion tests were made by S. Greenberg on cast and gamma-quenched specimens AF-1 and AF-10.⁽⁵⁾ It was found that both specimens disintegrated in water at 260°C, although before irradiation they were fairly corrosion resistant to water at 290°C, losing weight at an average rate of 39 mg/cm²-day.

Figure 6 shows gamma-quenched wrought material after irradiation, and illustrates the warping and elongation which was observed. The appearance of the specimen before irradiation was similar to the typical specimen shown in Figure 2. Irradiated specimen AB-37-2, which was aged for 72 hours at 375°C after gamma quenching, is shown in Figure 7. It appears that the marked warping tendency of the quenched material was reduced to some extent by the aging heat treatment.

TABLE III
Effects of Irradiation on Specimens Heat Treated for Corrosion Resistance (Group 2)

Specimen No.	Ingot No.	Fabrication	Heat Treatment	Burnup, a/o	Irradiation Temp, °C		Length Change,%	Growth Rate,G _i (a)	Diameter Change,%	Remarks
					Surface	Center				
Quenched from the Gamma Phase										
AH-1-2	CNY-4	Cast	800°C for 3 min, W.Q. ^(b)	0.046	120	130	-0.95	-21	6.0	Slightly Warped
AH-2-1	CNY-4	Cast	800°C for 3 min, W.Q.	0.048	120	130	2.9	60	4.9	Warped
AF-10	Y16F-100	Cast	1000°C for 1 hr, W.M.Q. ^(c)	0.15	150	200	11.0	70	0.0	Roughened Surface
AF-1	Y16F-100	Cast	1000°C for 1 hr, W.M.Q.	0.16	160	210	4.9	30	2.7	Roughened Surface
AF-2	Y16F-100	Cast	1000°C for 1 hr, W.M.Q.	0.30	250	360	6.0	19	(d)	Severely Roughened Surface, Swelled on One End
AF-3	Y16F-100	Cast	1000°C for 1 hr, W.M.Q.	0.42	330	480	32.0	66	-23 to +18	Severely Roughened Surface
AF-4	Y16F-100	Cast	1000°C for 1 hr, W.M.Q.	0.50	390	570	-	-	-	Disintegrated during Irradiation
AF-5	Y16F-100	Cast	1000°C for 1 hr, W.M.Q.	0.51	400	580	12.0	22	(d)	Severely Warped and Roughened
AB-36-2	CNY-4	Swaged at 800°C	800°C for 10 min, W.Q.	0.071	140	160	22.5	290	-6.1	Warped
AB-26	L-24	Rolled at 850°C	1000°C for 1 hr, W.M.Q.	0.036	120	220	12.0	320	(d)	Warped
AB-27	L-24	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; repeated 1 additional time	0.032	110	200	13.0	380	(d)	Warped
AB-28	L-24	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; repeated 3 additional times	0.024	100	160	12.0	470	(d)	Warped, Irregular Changes in Diameter
Quenched from the Gamma Phase and Aged										
AH-3-1	CNY-4	Swaged at 800°C	800°C for 3 min, W.Q.; 300°C for 24 hr, W.Q.	0.044	110	130	20.3	420	-5.8	Warped
AB-37-2	CNY-4	Swaged at 800°C	800°C for 10 min, W.Q.; 375°C for 72 hr, W.Q.	0.064	130	150	14.7	210	(d)	Warped, Irregular Changes in Diameter
AB-104	L-85	Rolled at 850°C	1000°C 1 hr, W.M.Q.; 400°C for 2 hr, A.C. ^(e)	0.053	90	120	6.7	120	0.8	Warped
AB-105	L-85	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; 400°C for 2 hr, A.C.	0.27	280	400	11.3	40	-2.8	Warped
AB-108	L-85	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; 400°C for 2 hr, A.C.	0.16	260	340	0.32	-	0.95	Restrained during Irradiation
AB-109	L-85	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; 400°C for 2 hr, A.C.	0.21	310	410	-0.39	-	1.2	Restrained during Irradiation
AB-107	L-85	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; 400°C for 2 hr, A.C.	0.24	330	440	-0.47	-	0.80	Restrained during Irradiation
AB-106	L-85	Rolled at 850°C	1000°C for 1 hr, W.M.Q.; 400°C for 2 hr, A.C.	0.28	370	500	0.0	-	0.91	Restrained during Irradiation

(a) G_1 = Microin./in. per fission/ 10^6 total atoms.

(c) W.M.Q. - Quenched in Wood's Metal at 100°C

(e) A.C. - Air cooled

(b) W.Q. - Quenched in water at room temperature.

(d) Too distorted for measurement

Negative No.	17020	16161	16163	16164

Specimen No.	AH-1-2	AF-1	AF-3	AF-5
Burnup, a/o	0.046	0.16	0.42	0.51
Irradiation Temp, °C	130	210	480	580

Figure 5. Typical Cast and Gamma-quenched Specimens after Irradiation

Figure 6. Specimen AB-36-2, Swaged and Gamma-quenched, after 0.071 a/o Burnup at 160°C

16429

2X

Figure 7. Specimen AB-37-2, Swaged,
Gamma-quenched, and Aged for
72 hours at 375°C, after 0.064 a/o
Burnup at 150°C

The last four specimens listed in Table III were irradiated in tightly fitting jackets in order to prevent mechanically any distortion under irradiation. The purpose of the experiment was to determine if the loss in corrosion resistance noted in the cast and gamma-quenched material was due to the extensive surface roughening which resulted under irradiation. Specimen AB-108 was selected for postirradiation corrosion tests in water at 260°C. Within 56 hours the irradiated specimen was reduced to a slurry,⁽⁵⁾ although preirradiation corrosion tests on the specimen for 88 hours at 290°C had shown a weight loss of only 9.5 mg/cm²-day.

The following conclusions can be drawn from the results on the Group 2 specimens:

1. The high irradiation growth rate of the wrought alloy was further increased by quenching from the gamma phase to impart corrosion resistance.
2. The loss in corrosion resistance resulting from irradiation was not due to surface changes.

Material Heat Treated for Dimensional Stability (Group 3)

After the first results became available on the specimens in Group 2 that had been gamma quenched for corrosion resistance, irradiations were begun on a third group of specimens in an attempt to find a suitable heat treatment for dimensionally stabilizing wrought U-5 w/o Zr-1.5 w/o Nb alloy under irradiation.

The selection of the various types of heat treatment for dimensional stabilization was largely based on earlier irradiation studies of uranium-zirconium alloys.⁽⁹⁾ In these experiments and in subsequent work it was found that the following types of heat treatment were effective in conferring a dimensionally stable condition to U-2 w/o Zr alloys: (1) cooling at an optimum rate from the gamma phase; (2) quenching from the gamma phase and tempering in the $\alpha + \gamma_1$ region; and (3) isothermally transforming from gamma in either the $\alpha + \gamma_1$ region or in the upper temperature range of $\alpha + \delta$. Since in some respects the U-5 w/o Zr-1.5 w/o Nb and U-2 w/o Zr alloys appeared to respond similarly to heat treatment, the same three types of heat treatment listed above were explored for their effectiveness in stabilizing the ternary alloy. Table IV summarizes irradiation results from swaged specimens with the heat treatments intended to impart dimensional stability to the alloy.

Under certain conditions, all three types of heat treatment were effective in reducing the irradiation growth rate of swaged material. The tendency for warping or bowing under irradiation was also almost completely eliminated.

The specimens cooled from the gamma phase were most effectively stabilized by very slow cooling rates. Thus, two specimens which were furnace cooled showed G_i values near 20. One of the specimens, No. AH-1-3, is shown in Figure 8 after irradiation. The appearance of the specimen was essentially unaffected by the irradiation it received.

The specimens which were quenched from the gamma phase and then tempered at alpha-phase temperatures of 550°C and 650°C showed lowest growth rates when tempered at the lower temperature. Specimen No. AH-4-2, which had been repeatedly quenched from 800°C and tempered for 24 hours at 550°C, showed the lowest growth coefficient, with a G_i value of 18. The irradiated specimen is shown in Figure 9.

A wider range of transformation temperatures was studied for those specimens isothermally transformed from the gamma phase. As shown in Table IV, specimen No. AH-2-3, which was transformed for 24 hours at 650°C, showed the lowest growth rate, with a G_i value of 5.4. In fact, no other heat treatment used in this investigation produced as low a growth coefficient. A photograph of specimen No. AH-2-3 after irradiation is shown in Figure 10.

The relationships between irradiation growth coefficients and microstructures resulting from various isothermal heat treatments have been discussed by Dwight and Mueller.⁽¹⁰⁾ It is postulated by Dwight and Mueller that by transforming the alloy in the range from 620 to 650°C, a microstructure is obtained, which consists of alpha particles in a gamma matrix, and that irradiation growth of the alpha particles is largely absorbed by the more plastic gamma phase.

TABLE IV

Effects of Irradiation on Specimens Swaged at 800°C and Heat Treated for Dimensional Stability^(a) (Group 3)

Specimen No	Heat Treatment	Burnup, a/o	Irradiation Temp, °C		Length Change, %	Growth Rate, G ₁ ^(b)	Diameter Change, %	Remarks	
			Surface	Center					
Cooled (But Not Water Quenched) from the Gamma Phase									
AH-1-1	800°C for 3 min, oil quenched	0.046	120	130	9.78	200	-2.66	Irregular Changes in Diameter	
AB-36-3	800°C for 10 min, air cooled	0.071	140	160	2.85	40	-0.53		
AH-1-3	800°C for 15 min, furnace cooled	0.046	120	130	0.98	21	0.0		
AB-37-1	800°C for 10 min, furnace cooled	0.064	130	150	1.08	17	-0.39		
Quenched from the Gamma Phase and Tempered									
AB-38-1	800°C for 10 min, W Q (c), 550°C for 30 min, W Q	0.054	110	130	3.07	56	-0.46		
AH-4-2	800°C for 3 min, W Q, 550°C for 24 hr, W Q, repeated 3 additional times	0.046	120	130	0.85	18	0.25		
AB-37-3	800°C for 10 min, W Q, 650°C for 30 min, W Q	0.064	130	150	6.3	95	-		
AH-4-4	800°C for 3 min, W Q, 650°C for 24 hr, W Q repeated 3 additional times	0.046	120	130	1.96	42	0.94		
Isothermally Transformed from the Gamma Phase									
AH-3-3	800°C for 3 min, to 475°C for 10 min, W Q	0.044	110	130	5.67	130	-1.53		
AH-3-2	800°C for 3 min, to 500°C for 3 min, W Q	0.044	110	130	6.82	150	-0.87		
AB-38-3	800°C for 10 min, to 550°C for 10 min, W Q	0.054	110	130	4.19	76	-1.45		
AB-38-2	800°C for 10 min, to 650°C for 30 min, W Q	0.054	110	130	1.25	33	-0.26		
AH-2-3	800°C for 15 min, to 650°C for 24 hr, W Q	0.048	120	130	0.26	5.4	0.0		
AH-2-4	800°C for 15 min, to 650°C for 24 hr, repeated 3 additional times, W Q	0.048	120	130	0.82	17	-0.07		
AH-4-6	800°C for 10 min, to 670°C for 24 hr, W Q	0.046	120	130	4.46	95	-2.81		
								Warped	

^(a)All specimens were fabricated from ingot No CNY-4^(b)G₁ = micron / in per fission, 10⁶ total atoms^(c)W Q - Quenched in water at room temperature

17021

2X

Figure 8. Specimen AH-1-3, Swaged and Furnace Cooled, after 0.046 a/o Burnup at 130°C

17038

2X

Figure 9. Specimen AH-4-2, Swaged, Gamma-quenched and Tempered for 24 Hours at 550°C Four Separate Times, after 0.046 a/o Burnup at 130°C

17027

2X

Figure 10 Specimen AH-2-3, Swaged and Isothermally Transformed for 24 Hours at 650°C, after 0.048 a/o Burnup at 130°C

Evidence is presented to show that under certain cooling conditions for U-5 w/o Zr-1.5 w/o Nb alloy, alpha particles can be produced in a metastable gamma matrix.

The following conclusions can be drawn from the Group 3 specimens:

1. U-5 w/o Zr-1.5 w/o Nb alloy can be stabilized against irradiation growth by several different heat treatments.
2. None of the dimensionally stabilizing heat treatments could be expected to confer a corrosion-resistant condition in the alloy.
3. The most effective stabilizing heat treatment consisted of heating the alloy into the gamma phase, followed by a 24-hour isothermal transformation to alpha at 650°C.

Material Heat Treated for Both Dimensional Stability and Corrosion Resistance (Group 4)

The successful attempts in stabilizing the U-Nb-Zr alloy, as described for the Group 3 specimens, led to preparation of a fourth group of specimens. Since the dimensionally stabilizing heat treatments were exactly opposite from those required for imparting the corrosion-resistant condition, the intent with this group was first to stabilize the wrought alloy against irradiation growth by suitable heat treatment and then to superimpose an additional heat treatment for conferring corrosion resistance in the material. The irradiation results are summarized in Table V.

As can be noted in the table, quenching the stabilized alloy resulted in irradiation growth rates as large as those obtained with quenching as-fabricated material which had been given no intermediate stabilizing heat treatment. Typical quenched specimens which were first furnace cooled, gamma quenched and tempered at 550°C, and isothermally transformed at 650°C are shown after irradiation in Figures 11, 12, and 13, respectively. The appearance of these specimens can be compared to their counterparts without the final gamma quench in Figures 8, 9, and 10. It is evident that quenching the stabilized material not only raised the growth rates to their formerly high levels in quenched as-fabricated material, but also caused severe irradiation-induced warping to reappear.

General Comments on Results from Groups 1 through 4

Figure 14 compares in the form of a bar graph the general status of knowledge of irradiation growth coefficients of U-5 w/o Zr-1.5 w/o Nb alloy as affected by typical heat treatments

TABLE V

Effects of Irradiation on Specimens Swaged at 800°C and Heat Treated for Both Dimensional Stability and Corrosion Resistance^(a) (Group 4)

Specimen No.	Heat Treatment	Burnup, a/o	Irradiation Temp, °C		Length Change,%	Growth Rate, G ₁ ^(b)	Diameter CChange,%	Remarks
			Surface	Center				
Furnace Cooled from the Gamma Phase, Followed by Quenching from the Gamma Phase								
AH-1-4	800°C for 15 min, furnace cooled; 800°C for 10 min, W.Q.(c)	0.046	120	130	15.5	310	-1.3	Warped Surface, Slightly Roughened
AH-1-5	800°C for 15 min, furnace cooled, repeated 3 additional times; 800°C for 10 min, W.Q.	0.046	120	130	18.5	370	-6.4	Warped Surface, Slightly Roughened
Quenched from the Gamma Phase and Tempered, Followed by Quenching from the Gamma Phase								
AH-4-3	800°C for 3 min, W Q., 550°C for 24 hr, W Q., repeated 3 additional times, 800°C for 10 min, W.Q.	0.046	120	130	15.3	310	-2.7	Slightly Warped
AH-4-5	800°C for 3 min, W.Q., 650°C for 24 hr, W Q , repeated 3 additional times; 800°C for 10 min, W Q.	0.046	120	130	15.5	310	-3.1	Warped
AH-2-2	800°C for 3 min, W.Q., 650°C for 24 hr, W.Q., repeated 3 additional times, 800°C for 10 min, W.Q , 375°C for 24 hr,W.Q	0.048	120	130	16.5	320	-5.9	Warped
Isothermally Transformed from the Gamma Phase, Followed by Quenching from the Gamma Phase								
AH-3-6	800°C for 3 min, 500°C for 3 min, repeated 3 additional times; 800°C for 3 min, W.Q.	0.044	110	130	14.8	310	-0.3	Warped
AH-3-5	800°C for 3 min, 550°C for 3 min, repeated 3 additional times; 800°C for 3 min, W.Q	0.044	110	130	18.7	390	-5.3	Warped
AH-4-1	800°C for 3 min, 550°C for 3 min, repeated 3 additional times; 800°C for 3 min, W Q., 375°C for 24 hr, W.Q	0.046	120	130	13.1	270	-2.7	Warped
AH-3-4	800°C for 3 min, 550°C for 3 min, W Q., repeated 3 additional times, 800°C for 3 min, W.Q	0.044	110	130	16.5	350	-5.2	Warped
AH-2-5	800°C for 15 min, 650°C for 24 hr, cycled 3 times between 65Q°C and 800°C, 800°C for 10 min, W Q.	0.048	120	130	14.5	280	0.5	Warped

(a) All specimens were fabricated from ingot No. CNY-4.

(b) G_1 = micron./in. per fission/ 10^6 total atoms.

(c) W.Q. - Quenched in water at room temperature.

17022

2X

Figure 11. Specimen AH-1-4, Swaged, Furnace Cooled, and Gamma Quenched, after 0.046 a/o Burnup at 130°C

17039

2X

Figure 12. Specimen AH-4-3, Swaged, Gamma-quenched and Tempered for 24 Hours at 550°C Four Separate Times, Followed by Gamma Quenching, after 0.046 a/o Burnup at 130°C

17029

2X

Figure 13. Specimen AH-2-5, Swaged, Isothermally Transformed for 24 Hours at 650°C Four Separate Times, Followed by Gamma Quenching, after 0.048 a/o Burnup at 130°C

106-1776

Figure 14. Comparison of Irradiation Growth Coefficients of Swaged U-5 w/o Zr-1.5 w/o Nb Alloy with Typical Heat Treatments

When irradiations were completed on the Group 4 specimens, a decision was required regarding the heat treatment specification for the EBWR fuel plates which were soon to be in production. Although the Group 4 specimens had indicated that simultaneous resistance to both irradiation growth and aqueous corrosion could not be imparted to the alloy, at least with any combination of heat treatments known at that time, it had been decided in any case to use the U-5 w/o Zr-1.5 w/o Nb alloy for the EBWR fuel loading because of the ease with which the fuel alloy could be roll bonded to Zircaloy-2 cladding.⁽¹¹⁾ Since either dimensional stability or corrosion resistance could be achieved in the fuel alloy, but not both, the choice of heat treatment was dictated by which condition was regarded as being the more essential to successful reactor operation.

On this basis it was decided to heat treat the fuel alloy for dimensional stability. The decision to remove corrosion resistance as an essential requirement for the fuel was based primarily on two factors:

1. Even when the fuel was in the corrosion-resistant condition, irradiation largely destroyed the corrosion resistance by the time 0.1 a/o burnup had been achieved.
2. Fabrication by roll cladding consistently produced defect-free closures, so that it appeared that entire reliance could be placed on the cladding for preventing catastrophic corrosion failures.

Accordingly, the stabilizing heat treatment used for specimen No. AH-2-3, a 24-hour isothermal transformation at 650°C, was selected as the best heat treatment. Since the 650°C transformation temperature

is only approximately 10°C below the upper limit of the alpha plus gamma region.⁽¹⁰⁾ it could be expected that dimensional stability of the alloy might be markedly affected if transformation were performed in a higher temperature region because of, for example, inadequate furnace temperature control. In order to provide for some latitude in furnace temperatures, as would be desirable for shop conditions, an isothermal transformation temperature of 640°C was specified for the EBWR fuel loading.^(3, 11) A temperature excursion by possibly as much as 20°C could thus be safely tolerated. The 24-hour transformation time used for specimen AH-2-3 was also specified for the fuel loading.

The decision to heat treat the fuel for dimensional stability and to rely on the cladding for corrosion protection was apparently wise. The EBWR fuel elements by mid-1959 had achieved 0.39 a/o burnup with negligible dimensional changes and no failures due to corrosion or any other cause.⁽¹²⁾

Miniature Roll-bonded Clad Plates (Group 5)

The specimens used in Groups 1 through 4 were either cast, round rolled, or swaged to form cylindrical irradiation specimens. This shape was simplest to produce and served as a convenient specimen shape for studies of the basic behavior of the U-Zr-Nb alloy under irradiation. During these experiments, however, it was recognized that the fuel for EBWR would be flat rolled and would have a texture considerably different from that produced in round-rolled or swaged material. The irradiation growth characteristics of flat-rolled material could therefore be expected to differ from those shown by the cylindrical specimens in Groups 1 through 4. An additional feature of the actual fuel plates, not represented by the cylindrical specimens, would be the presence of metallurgically bonded cladding. It could be assumed that the cladding would modify, in some fashion, the growth rate of unclad material. Irradiations were therefore also made on plate specimens during the period when the cylindrical specimens in Groups 1 through 4 were being investigated.

The plate specimens comprising Group 5 were the first attempt to determine the irradiation growth tendency of clad plates. The dimensions of each plate were approximately $1.25 \times 0.75 \times 0.19$ in. The plate size was necessarily this small in order to accommodate them in standard MTR-X-basket capsules. Each of these miniature plates was clad with 0.015 in. of Zircaloy-2 which was roll bonded to the fuel on the flat side. Of the six specimens irradiated in Group 5, three had open ends, so that only the edges and sides were clad. The remaining three specimens were also clad on the edges and sides, and in addition were closed at the ends with welded plugs. Before irradiation each specimen was heat treated for corrosion resistance by quenching from 850°C , followed by aging for 45 minutes at 425°C .

Table VI summarizes the irradiation results obtained. The 0.015-in. thickness of cladding was evidently highly effective in restraining the growth of the quenched fuel alloy, even when no end closures were present.

TABLE VI

Effect of Irradiation on Zircaloy-2 Clad Prototype Plate Specimens^(a) (Group 5)

Specimen No	Type of Assembly	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G_1 ^(b)	Thickness Change, %
AH-10-1	Core material exposed at ends	0 021	140	0 73	35	0 0
AH-12-1	Core material exposed at ends	0 079	260	1 43	18	1 4
AH-13-1	Core material exposed at ends	0 085	270	3 76	44	0 55
AH-10-2	With welded end closures	0 021	140	0 0	0 0	1 9
AH-12-2	With welded end closures	0 079	260	0 0	0 0	1 4
AH-13-2	With welded end closures	0 085	270	1 51	18	1 1

(a) All specimens were fabricated from ingot L-24, by rolling to 80% reduction in thickness at 775°C

(b) G_1 = microin/in per fission/ 10^6 total atoms

The specimens with open ends showed an average G_1 value of 32, which is less by a factor of 10 than that obtained on rolled and gamma-quenched unclad material in Group 2. Typical irradiated specimens are shown in Figures 15 and 16.

Figure 15. End View of Rolled and Gamma-quenched Miniature Plate No. AH-12-1, with Open Ends, after 0.079 a/o Burnup at 260°C

Figure 16

Side View of Rolled and Gamma-quenched Miniature Plate No. AH-13-2, With End Plugs, after 0.085 a/o Burnup at 270°C

17643

2X

Figure 17 shows the effect of irradiation on the microstructure of specimen No. AH-10-2. Enlargement of particle size of the precipitated phase was evidently induced by irradiation.

a. Before Irradiation

19591

250X

b. After Irradiation

19631

250X

Figure 17. Effect of 0.021 a/o Burnup at 140°C on the Microstructure of U-5 w/o Zr-1.5 w/o Nb Alloy (Specimen No. AH-10-2)

The effect of irradiation on the quenched alloy may therefore be similar to that produced by overaging, which numerous tests have shown to result in a marked loss in corrosion resistance. One might conclude, therefore, that it would be undesirable to age the quenched alloy prior to irradiation to obtain a minimum corrosion rate, as this would in effect hasten the onset of irradiation damage to corrosion resistance.

Postirradiation corrosion tests were performed on specimens AH-10-2 and AH-12-2 with 0.021 and 0.079 a/o burnup, respectively.⁽⁴⁾ The cladding on each specimen was defected before corrosion testing with a hole of 0.125-in. diameter. Specimen No. AH-10-2, which was tested for 58 hours at 260°C, showed no effects from the test. On the other hand, specimen No. AH-12-2, which was tested for 66 hours at 290°C, largely disintegrated during the test.

Clad Specimens Cut from Full-size EBWR Plates (Group 6)

The miniature plates described above were useful in first showing that a substantial degree of restraint could be expected from roll-bonded Zircaloy-2 cladding. It was not possible, however, to extrapolate accurately the results obtained to full-size EBWR plates. This was true because of the wide differences in fabrication history that necessarily existed between the miniature plates and the much larger 54-in. EBWR plates.

In order to obtain information on the behavior of material rolled under EBWR plate-fabrication conditions, a sixth group of specimens was prepared by cutting 1.00 x 0.75-in. coupons from full-size plates. A typical specimen is shown before irradiation in Figure 18. The heat treatments used are listed in Table VII, along with the dimensional changes resulting from irradiation. Quenched material was used for all specimens.

18093

2X

Figure 18. Typical Unirradiated Clad Specimen
Cut from Full-size EBWR Plate

TABLE VII

Effect of Irradiation on Clad Specimens Cut from Full-size EBWR Plates (Group 6)

Specimen No.	Ingot No.	Rolling Temp. °C	Cladding Thickness, in.	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G_i (a)	Width Change, %	Thickness Change, %
				<u>Uniform Cladding Thickness</u>						
AH-14	L-128	800	0.022	725°C for 3 min, 650°C for 1 hr, air cooled; 725°C for 3 min, W.Q., 400°C for 2 hr, A.C. (b)	0.034	170	1.11	33	1.21	-1.52
AH-16	L-128	800	0.022	725°C for 3 min, 650°C for 1 hr, air cooled; 725°C for 3 min, W.Q., 400°C for 2 hr, A.C. (b)	0.040	210	0.88	22	2.26	-2.80
AH-15	L-128	800	0.022	725°C for 3 min, 650°C for 1 hr, air cooled; 725°C for 3 min, W.Q., 400°C for 2 hr, A.C. (b)	0.071	410	0.73	10	3.16	-2.57
AH-19	L-128	800	0.022	850°C for 3 min, 650°C for 1 hr, air cooled; 850°C for 3 min, W.Q., 400°C for 2 hr, A.C.	0.025	130	1.11	45	3.32	-1.52
AH-17	L-128	800	0.022	850°C for 3 min, 650°C for 1 hr, air cooled; 850°C for 3 min, W.Q., 400°C for 2 hr, A.C.	0.050	270	1.43	29	2.92	-1.94
AH-18	L-128	800	0.022	850°C for 3 min, 650°C for 1 hr, air cooled; 850°C for 3 min, W.Q., 400°C for 2 hr, A.C.	0.079	430	0.48	6.1	2.40	-1.53
				<u>Varying Cladding Thickness</u>						
BF-8A	L-125	850	None	850°C for 15 min, water quenched	0.031	180	7.3	230	9.9	-10.5
BF-7A	L-125	850	None	850°C for 15 min, water quenched	0.062	340	7.7	120	11.0	-8.9
BF-5A	L-125	850	0.004	850°C for 15 min, water quenched	0.039	210	4.2	110	6.1	-5.9
BF-6A	L-125	850	0.004	850°C for 15 min, water quenched	0.082	460	3.7	45	4.3	0.9
BF-3A	L-125	850	0.034	850°C for 15 min, water quenched	0.020	120	3.0	150	4.1	-1.8
BF-4A	L-125	850	0.035	850°C for 15 min, water quenched	0.084	490	1.0	12	2.8	1.1
BF-2A	L-125	850	0.060	850°C for 15 min, water quenched	0.084	500	0.1	1.2	1.5	0.6

(a) G_i = microin./in. per fission/ 10^6 total atoms.

(b) A.C. - Air cooled.

As shown in Table VII, the first six specimens were given a double heat treatment intended to provide both dimensional stability and corrosion resistance. Three of the six specimens were given a final quench from 725°C, which is near the lower temperature limit of gamma equilibrium. The remaining three specimens were quenched from 850°C. Little difference is shown in the lengthwise growth coefficients that can be attributed to the difference in quenching temperatures. For each quenching temperature, a much greater dependence is shown on irradiation temperature (and possibly burnup). The lengthwise rate of growth diminished markedly with increasing irradiation temperature.

For both quenching temperatures the width of the specimens increased under irradiation at rates up to five times the rates of length increase. A difference in temperature dependence was noted, however. For the 725°C quenched material, the rate of width increase increased with irradiation temperature; for the 850°C quenched material the rate of width increase decreased with increasing irradiation temperature.

Both groups of specimens decreased in thickness under irradiation. Somewhat higher rates of thickness decrease were shown by specimens of the 725°C quenched material. For both groups the rate of thickness decrease seemed to be only randomly affected by irradiation temperature.

Figures 19 and 20 show typical end and edge views of irradiated specimens. The bulged appearance of the fuel indicates that the cladding was exerting restraint on irradiation growth of the fuel alloy.

Figure 19. End View of Specimen AH-17, Isothermally Transformed at 650°C and Gamma Quenched, after 0.050 a/o Burnup at 500°C

Figure 20. Edge View of Specimen AH-18, Isothermally Transformed at 650°C and Gamma Quenched, after 0.079 a/o Burnup at 760°C

In order to determine more quantitatively the effectiveness of the cladding in reducing irradiation growth, irradiations were made on an additional seven specimens cut from a full-size EBWR plate. The plate was quenched from 850°C prior to being sectioned for irradiation specimens. The plate was prepared with a 0.060-in. thick cladding instead of the customary 0.020-in. thickness. One of the specimens was left with the full 0.060 in. of cladding. The cladding was partially removed by grinding from two other pairs of specimens to give cladding thicknesses of 0.034 and 0.004 in. The cladding was completely removed from a third pair of specimens, to determine the growth tendencies of unrestrained gamma-quenched fuel alloy.

Figure 21. Effect of Zircaloy-2 Clad Thickness on the Lengthwise Growth Rate of Gamma-quenched U-5 w/o Zr-1.5 w/o Nb Alloy Plate

Results from these specimens are shown in Table VII. As can be noted, the 0.060-in. thick cladding almost completely restrained dimensional changes under irradiation. At the other extreme, unclad specimens elongated with an average G_i value of 180. Although the data show some scatter, it is evident that the intermediate cladding thicknesses reduced growth rates, depending on their thicknesses. Figure 21 shows the effect of the cladding on the specimens with the

higher burnups. As in the case of the other specimens described previously in Group 6, width increases occurred at higher rates than length increases, and the specimens decreased in thickness. Photographs of typical specimens after irradiation are shown in Figure 22, and illustrate the marked effect of the cladding on irradiation growth.

Several irradiated specimens from the group with variable cladding thickness were subjected to corrosion tests in water at 260, 290 and 315°C.⁽⁴⁾ It was found that specimens with less than 0.04 a/o burnup were corrosion resistant in water at the highest temperature, 315°C. Specimens with more than 0.06 a/o burnup disintegrated at the lowest test temperature, 260°C

The following conclusions can be drawn from the results on the Group 6 specimens cut from quenched full-size EBWR plates.

1. Both width and length increases occurred under irradiation, with the width increases occurring at higher rates.
2. The rates of width and length change depended on both quenching and irradiation temperatures.
3. The thickness of the plates decreased under irradiation, but the rate of decrease appeared to be only randomly affected by quenching and irradiation temperatures.
4. Zircaloy-2 cladding thicknesses as small as 0.004 in. reduced irradiation growth of the fuel alloy, so that it could be expected that the 0.020-in. thick cladding specifications for EBWR plates would aid materially in stabilizing the fuel elements against dimensional changes.
5. The corrosion resistance of the quenched alloy was destroyed by between 0.04 and 0.06 a/o burnup, with some indication that the loss in corrosion resistance might be the result of structural changes similar to overaging.

Unclad Specimens Cut from Full-size EBWR Plates (Group 7)

The results from the swaged Group 4 specimens and clad plate specimens from Group 6 showed that none of the heat treatments investigated were successful in producing a condition of both dimensional stability and corrosion resistance in the U-5 w/o Zr-1.5 w/o Nb alloy. As discussed earlier, these findings led to a final heat treatment specification for the EBWR fuel plates which did not include a gamma quench for corrosion resistance.

Later, it was decided to irradiate a relatively large final group of flat-rolled specimens in which additional heat treatments were evaluated for their effectiveness in achieving a simultaneous condition of both

Negative No.

18141

18137

18131

18125

Specimen No.

BF-7A

BF-6A

BF-4A

BF-2A

Burnup, a/o

0.031

0.082

0.084

0.084

Irradiation

Temp, °C

180

460

490

500

Cladding

Thickness, in.

None

0.004

0.035

0.060

Figure 22. Edge View of Irradiated Specimens With Various Cladding Thicknesses Cut from a Full-size EBWR Fuel Plate. Magnification 2X.

dimensional stability and corrosion resistance, even though production of EBWR plates with the stabilizing heat treatment was already in progress. The following variants were studied in this group of specimens:

1. Material prepared with the conventional rolling temperature of 850°C was compared to material given an additional 12% thickness reduction at room temperature prior to heat treatment.
2. Isothermal transformation temperatures of 655°C (alpha-plus-gamma region), 665°C (alpha-plus-beta-plus-gamma region), and 675°C (beta-plus-gamma region) were used. In addition, the effect of annealing the alloy at 685°C (gamma region) was investigated.
3. Transformation or annealing times of 2, 24, and 168 hours were investigated.
4. The effect of heating directly to the transformation or annealing temperature was compared to the effect of heating first into the gamma phase at 800°C and then cooling to the transformation temperature.
5. Material with each isothermal transformation or annealing heat treatment was compared with material having the same heat treatment plus a final quench from 800°C for corrosion resistance.

The specimens were 1.000 in. long and 0.137 in. square, with the lengthwise dimension in the rolling direction. The plate had been prepared by rolling at 850°C to a thickness of 0.258 in. Half of the specimens were cut from this material. The unused portion of the plate was then cold worked by being given a 12% thickness reduction at room temperature. This latter material was used for the remaining half of the specimens. The Zircaloy-2 cladding was removed by machining prior to heat treatment. Each specimen was transversely grooved on one of the originally clad surfaces in order to maintain orientation of the specimen for thickness and width measurements.

Table VIII shows the results of irradiation of as-rolled and of as-rolled and gamma-quenched specimens. As expected, the cold-worked material showed a much higher irradiation growth rate in the as-rolled condition. It is of interest to note that, whereas quenching swaged material resulted in increased growth rates (see Figure 14), quenching the cold-worked flat-rolled material resulted in a substantial reduction in growth rate. Almost a 10-fold decrease resulted from the final gamma quench. The growth rate of the hot-worked flat-rolled material was increased only slightly by gamma quenching. However, as shown in Figure 23, considerable warping occurred in the quenched specimens of both the cold-worked and hot-worked material.

TABLE VIII

Effect of Irradiation on Flat-rolled Specimens Not Isothermally Transformed or Annealed^(a) (Group 7)

Specimen No.	Final Rolling Temp, °C	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, $G_i^{(b)}$	Width Change, %	Thickness Change, %	Weight Change, mg.	Remarks
BH-25-1	25 ^(c)	None	0.045	59	39.0	730	14.4	-33.1	0.4	Warped
BH-25-2	25	800°C for 15 min, W.Q. ^(d)	0.045	59	4.0	87	(e)	(e)	0.5	
BH-25-4	850	None	0.045	59	7.1	150	17.0	-15.6	1.6	Severely warped
BH-25-5	850	800°C for 15 min, W.Q.	0.045	59	8.4	180	(e)	(e)	1.4	

^(a) All specimens were rolled from ingot L-215.^(b) G_i = microin./in. per fission/ 10^6 total atoms.^(c) Specimens were first rolled at 850°C, then reduced 12% in thickness by rolling at room temperature.^(d) W.Q. - Quenched in water at room temperature.^(e) Too distorted for measurement.

Negative No.	19772	19774	19773	19775

Specimen No.	BH-25-1	BH-25-2	BH-25-4	BH-25-5
Final Rolling Temp, °C	25	25	850	850
Heat Treatment	None	γ -quenched	None	γ -quenched

Figure 23 Effect of 0.045 a/o Burnup at 59°C on Flat-rolled U-5 w/o Zr-1.5 w/o Nb Alloy Not Isothermally Transformed or Annealed

The appearance of the irradiated specimens shown in Figure 23 is generally characteristic of all specimens from Group 7. Thus, the appearance of specimens BH-25-1 and BH-25-4 is typical of most irradiated specimens described in Tables VIII through XII which were not given a final quench for corrosion resistance. Similarly, the warped appearance of specimens BH-25-2 and BH-25-5 is generally characteristic of the irradiated specimens described in the above tables which were given a final quench for corrosion resistance.

Table IX shows the results from the specimens isothermally transformed at 655°C, in the alpha-plus-gamma region. Several conclusions can be drawn from results shown by the various groups of specimens in the table.

Considering, first, the specimens given isothermal heat treatments only, it is apparent that for cold-worked material, heating directly to the transformation temperature is much less effective in stabilizing the alloy than is heating first into the gamma phase followed by cooling to the transformation temperature. Under the latter conditions, a growth coefficient as low as 3.8 was obtained. This growth rate is approximately one-fourth that shown by the most stable specimen in the comparable hot-worked group. In general, the growth rates of the isothermally transformed groups decreased with increased transformation times.

Quenching the isothermally transformed materials for corrosion resistance produced growth rates that were more independent of prior rolling temperature. However, those specimens which were first heated into the gamma phase before isothermal transformation were generally more stable than those heated directly to the transformation temperature. With few exceptions the final gamma quench for corrosion resistance resulted in a marked increase in growth rate. The flat rolled specimens shown in Table IX, which were given heat treatments for both dimensional stability and corrosion resistance, were more resistant to anisotropic growth than similarly heat-treated swaged specimens described in Group 4. On the other hand, warping was much more severe in the flat rolled specimens

Table X summarizes results from specimens isothermally transformed at 665°C, in the alpha-plus-beta-plus gamma region of the equilibrium diagram. These results differ in some respects from those discussed above for the 655°C group. The specimens which were isothermally transformed at 665°C without subsequent gamma quenching were less stable than similar specimens isothermally transformed at 655°C. In contrast, lower growth rates and less distortion by warping were shown by the material transformed at 665°C and given a final gamma quench for corrosion resistance. This was particularly true for the cold-worked material. The best stability of the entire group of specimens described in Table X was shown by specimen BH-8-2, with a growth coefficient of 10. It is of interest that this specimen had been given a final gamma quench for corrosion resistance.

TABLE IX
Effect of Irradiation on Flat-rolled Specimens Isothermally Transformed at 655°C^(a) (Group 7)

Specimen No.	Final Rolling Temp, °C	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G_i ^(b)	Width Change, %	Thickness Change, %	Weight Change, mg	Remarks
Isothermally Transformed Only										
BH-1-4	25 ^(c)	655°C for 2 hr, A.C. ^(d)	0.042	55	13.6	300	8.9	-14.9	-1.2	
BH-2-4	25	655°C for 24 hr, A.C.	0.071	67	17.4	230	10.6	-17.3	-0.7	
BH-3-4	25	655°C for 168 hr, A.C.	0.083	66	17.0	190	10.9	-17.4	-0.7	
BH-1-1	25	800°C for 15 min, 655°C for 2 hr, A.C.	0.042	55	1.01	24	0.51	1.6	-1.2	
BH-2-1	25	800°C for 15 min, 655°C for 24 hr, A.C.	0.071	67	0.28	3.8	0.22	1.1	-0.9	
BH-3-1	25	800°C for 15 min, 655°C for 168 hr, A.C.	0.083	66	0.78	9.3	1.2	0.0	0.4	
BH-4-4	850	655°C for 2 hr, A.C.	0.031	49	4.7	150	1.9	-2.8	0.8	
BH-5-4	850	655°C for 24 hr, A.C.	0.048	54	3.5	72	2.5	-3.4	-0.8	
BH-6-4	850	655°C for 168 hr, A.C.	0.097	76	4.4	44	6.5	-10.0	1.2	
BH-4-1	850	800°C for 15 min, 655°C for 2 hr, A.C.	0.031	49	1.0	32	0.73	-0.74	0.8	
BH-5-1	850	800°C for 15 min, 655°C for 24 hr, A.C.	0.048	54	0.75	16	0.59	0.66	-0.7	
BH-6-1	850	800°C for 15 min, 655°C for 168 hr, A.C.	0.097	76	1.4	14	1.0	-1.3	0.1	
Isothermally Transformed and Quenched from the Gamma Phase										
BH-1-5	25	655°C for 2 hr, A.C.; 800°C for 15 min, W.Q. ^(e)	0.042	55	5	120	(f)	(f)	-1.3	Warped
BH-2-5	25	655°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.071	67	13	170	(f)	(f)	-1.4	Warped
BH-3-5	25	655°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.083	66	12	140	(f)	(f)	-0.9	Warped
BH-1-2	25	800°C for 15 min, 655°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.042	55	7	160	(f)	(f)	-1.2	Warped
BH-2-2	25	800°C for 15 min, 655°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.071	67	4	55	(f)	(f)	-0.4	Warped
BH-3-2	25	800°C for 15 min, 655°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.083	66	6	70	(f)	(f)	0.0	Warped
BH-4-5	850	655°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.031	49	4	130	(f)	(f)	-0.2	Warped
BH-5-5	850	655°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.048	54	12	240	(f)	(f)	-0.5	Warped
BH-6-5	850	655°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.097	76	7	70	(f)	(f)	-1.0	Warped
BH-4-2	850	800°C for 15 min, 655°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.031	49	2	64	(f)	(f)	-0.2	Warped
BH-5-2	850	800°C for 15 min, 655°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.048	54	4	82	(f)	(f)	-0.9	Warped
BH-6-2	850	800°C for 15 min, 655°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.097	76	5	50	(f)	(f)	0.7	Warped

(a) All specimens were rolled from ingot L-215.

(b) G_i = microin./in. per fission/ 10^6 total atoms.

(c) All specimens rolled at 25°C were given a 12% reduction in thickness at that temperature.

(d) A.C. - Air cooled.

(e) W.Q. - Quenched in water at room temperature.

(f) Specimen was too distorted for measurement.

TABLE X

Effect of Irradiation on Flat Rolled Specimens Isothermally Transformed at 665°C^(a) (Group 7)

Specimen No.	Final Rolling Temp, °C	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G _i ^(b)	Width Change, %	Thickness Change, %	Weight Change, mg	Remarks
Isothermally Transformed Only										
BH-7-4	25 ^(c)	665°C for 2 hr, A.C. ^(d)	0.102	81	41.7	340	29.3	-36.8	-0.9	Slightly Roughened
BH-8-4	25	665°C for 24 hr, A.C.	0.097	76	29.5	270	16.2	-25.2	0.0	
BH-9-4	25	665°C for 168 hr, A.C.	0.068	66	11.3	160	9.4	-13.5	0.8	
BH-7-1	25	800°C for 15 min, 665°C for 2 hr, A.C.	0.102	81	3.7	36	2.3	-4.2	-1.2	
BH-8-1	25	800°C for 15 min, 665°C for 24 hr, A.C.	0.097	76	2.0	20	2.2	-2.6	0.3	
BH-9-1	25	800°C for 15 min, 665°C for 168 hr, A.C.	0.068	66	1.7	25	2.8	-1.7	-0.3	
BH-10-4	850	665°C for 2 hr, A.C.	0.087	68	11.3	120	3.2	-10.4	-0.6	
BH-11-4	850	665°C for 24 hr, A.C.	0.069	62	7.4	100	4.2	-9.1	0.2	
BH-12-4	850	665°C for 168 hr, A.C.	0.051	56	3.9	75	2.7	-7.8	-0.3	
BH-10-1	850	800°C for 15 min, 665°C for 2 hr, A.C.	0.087	68	5.3	59	1.4	2.3	-0.3	
BH-11-1	850	800°C for 15 min, 665°C for 24 hr, A.C.	0.069	62	3.2	46	1.7	-1.1	1.1	
BH-12-1	850	800°C for 15 min, 665°C for 168 hr, A.C.	0.051	56	1.8	35	1.1	-1.7	0.3	
Isothermally Transformed and Quenched from the Gamma Phase										
BH-7-5	25	665°C for 2 hr, A.C.; 800°C for 15 min, W.Q. ^(e)	0.102	81	8	76	(f)	(f)	-0.1	Warped
BH-8-5	25	665°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.097	76	11	110	(f)	(f)	0.3	Warped
BH-9-5	25	665°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.068	66	5.6	80	18	-6.9	-29.7	
BH-7-2	25	800°C for 15 min, 665°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.102	81	5	48	(f)	(f)	-0.7	Warped
BH-8-2	25	800°C for 15 min, 665°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.097	76	1.1	10	13	-0.3	-0.3	Slightly Warped
BH-9-2	25	800°C for 15 min, 665°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.068	66	1	15	(f)	(f)	0.2	Warped
BH-10-5	850	665°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.087	68	8	89	(f)	(f)	0.6	Warped
BH-11-5	850	665°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.069	62	10	140	(f)	(f)	-1.3	Warped
BH-12-5	850	665°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.051	56	6	110	(f)	(f)	-0.6	Warped
BH-10-2	850	800°C for 15 min, 665°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.087	68	9.5	100	(f)	(f)	1.0	Warped
BH-11-2	850	800°C for 15 min, 665°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.069	62	2	29	(f)	(f)	-0.1	Warped
BH-12-2	850	800°C for 15 min, 665°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.051	56	2	39	(f)	(f)	-1.1	Warped

(a) All specimens were rolled from ingot L-215.

(b) G_i = microin./in. per fission/10⁶ total atoms.

(c) All specimens rolled at 25°C were given a 12% reduction in thickness at that temperature.

(d) A.C. - Air cooled

(e) W.Q. - Quenched in water at room temperature.

(f) Specimen was too distorted for measurement.

TABLE XI
Effect of Irradiation on Flat-rolled Specimens Isothermally Transformed at 675°C^(a) (Group 7)

Specimen No	Final Rolling Temp, °C	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G ₁ ^(b)	Width Change, %	Thickness Change, %	Weight Change, mg	Remarks
Isothermally Transformed Only										
BH-13-4	25 ^(c)	675°C for 2 hr, A C ^(d)	0 096	78	7 0	70	-3 5	-4 9	-0 8	
BH-14-4	25	675°C for 24 hr, A C	0 12	89	7 0	56	2 2	-4 2	-0 8	
BH-15-4	25	675°C for 168 hr, A C	0 15	100	7 1	46	2 4	-4 9	-1 1	
BH-13-1	25	800°C for 15 min, 675°C for 2 hr, A C	0 096	78	4 0	41	2 3	-5 1	-0 1	
BH-14-1	25	800°C for 15 min, 675°C for 24 hr, A C	0 12	89	3 6	29	1 8	-4 0	-0 8	
BH-15-1	25	800°C for 15 min, 675°C for 168 hr, A C	0 15	100	3 2	21	1 5	-3 4	-0 9	
BH-16-4	850	675°C for 2 hr, A C	0 066	61	3 1	46	2 1	-3 0	0 3	
BH-17-4	850	675°C for 24 hr, A C	0 085	67	3 4	39	1 8	-5 0	-0 1	
BH-18-4	850	675°C for 168 hr, A C	0 094	71	3 0	31	2 6	-3 1	0 1	
BH-16-1	850	800°C for 15 min, 675°C for 2 hr, A C	0 066	61	5 1	75	1 1	-3 3	-0 3	
BH-17-1	850	800°C for 15 min, 675°C for 24 hr, A C	0 085	67	4 4	51	0 073	-2 6	-1 0	
BH-18-1	850	800°C for 15 min, 675°C for 168 hr, A C	0 094	71	4 6	48	3 0	-3 1	-0 1	
Isothermally Transformed and Quenched from the Gamma Phase										
BH-13-5	25	675°C for 2 hr, A C , 800°C for 15 min, W Q ^(e)	0 096	78	8	80	(f)	(f)	-0 6	Warped
BH-14-5	25	675°C for 24 hr, A C , 800°C for 15 min, W Q	0 12	89	4	33	(f)	(f)	0 1	Warped
BH-15-5	25	675°C for 168 hr, A C , 800°C for 15 min, W Q	0 15	100	10	66	(f)	(f)	-0 8	Warped
BH-13-2	25	800°C for 15 min, 675°C for 2 hr, A C , 800°C for 15 min, W Q	0 096	78	3	31	(f)	(f)	-0 8	Warped
BH-14-2	25	800°C for 15 min, 675°C for 24 hr, A C , 800°C for 15 min, W Q	0 12	89	8	64	(f)	(f)	-1 1	Warped
BH-15-2	25	800°C for 15 min, 675°C for 168 hr, A C , 800°C for 15 min, W Q	0 15	100	7	47	(f)	(f)	0 1	Warped
BH-16-5	850	675°C for 2 hr, A C , 800°C for 15 min, W Q	0 066	61	12	170	(f)	(f)	-0 5	Warped
BH-17-5	850	675°C for 24 hr, A C , 800°C for 15 min, W Q	0 085	67	14	150	(f)	(f)	-0 9	Warped
BH-18-5	850	675°C for 168 hr, A C , 800°C for 15 min, W Q	0 094	71	13	130	(f)	(f)	-0 2	Warped
BH-16-2	850	800°C for 15 min, 675°C for 2 hr, A C , 800°C for 15 min, W Q	0 066	61	8	120	(f)	(f)	1 0	Warped
BH-17-2	850	800°C for 15 min, 675°C for 24 hr, A C , 800°C for 15 min, W Q	0 085	67	10	110	(f)	(f)	0 3	Warped
BH-18-2	850	800°C for 15 min, 675°C for 168 hr, A C , 800°C for 15 min, W Q	0 094	71	10	100	(f)	(f)	0 6	Warped

(a) All specimens were rolled from ingot L-215

(b) G₁ = microin / in per fission / 10⁶ total atoms

(c) All specimens rolled at 25°C were given a 12% reduction in thickness at that temperature

(d) A C - Air cooled

(e) W Q - Quenched in water at room temperature

(f) Specimen was too distorted for measurement

TABLE XII

Effect of Irradiation on Flat-rolled Specimens Annealed at 685°C^(a) (Group 7)

Specimen No.	Final Rolling Temp, °C	Heat Treatment	Burnup, a/o	Center Irradiation Temp, °C	Length Change, %	Growth Rate, G _i ^(b)	Width Change, %	Thickness Change, %	Weight Change, mg	Remarks
<u>Annealed Only</u>										
BH-19-4	25 ^(c)	685°C for 2 hr, A.C. ^(d)	0.16	102	3.8	23	2.5	-5.5	0.5	
BH-20-4	25	685°C for 24 hr, A.C.	0.15	100	4.5	29	1.9	-4.7	0.1	
BH-21-4	25	685°C for 168 hr, A.C.	0.12	90	5.3	43	-2.1	-4.1	0.8	
BH-19-1	25	800°C for 15 min, 685°C for 2 hr, A.C.	0.16	102	4.3	26	-1.8	-5.5	0.1	
BH-20-1	25	800°C for 15 min, 685°C for 24 hr, A.C.	0.15	100	3.6	24	1.9	-4.0	0.2	
BH-21-1	25	800°C for 15 min, 685°C for 168 hr, A.C.	0.12	90	3.0	25	1.3	-3.4	1.4	
BH-22-4	850	685°C for 2 hr, A.C.	0.10	73	4.8	47	1.9	-4.6	-0.2	
BH-23-4	850	685°C for 24 hr, A.C.	0.11	74	4.6	41	1.5	-4.3	0.1	
BH-24-4	850	685°C for 168 hr, A.C.	0.096	71	4.3	44	1.3	-3.7	-0.5	
BH-22-1	850	800°C for 15 min, 685°C for 2 hr, A.C.	0.10	73	5.0	49	1.3	-3.9	0.9	
BH-23-1	850	800°C for 15 min, 685°C for 24 hr, A.C.	0.11	74	5.1	45	0.45	-1.8	0.2	
BH-24-1	850	800°C for 15 min, 685°C for 168 hr, A.C.	0.096	71	3.7	38	0.59	-2.9	1.5	
<u>Annealed and Quenched from the Gamma Phase</u>										
BH-19-5	25	685°C for 2 hr, A.C.; 800°C for 15 min, W.Q. ^(e)	0.16	102	8.5	51	(f)	(f)	0.6	Warped
BH-20-5	25	685°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.15	100	5	32	(f)	(f)	0.8	Warped
BH-21-5	25	685°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.12	90	6	49	(f)	(f)	0.5	Warped
BH-19-2	25	800°C for 15 min, 685°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.16	102	8	46	(f)	(f)	1.1	Warped
BH-20-2	25	800°C for 15 min, 685°C for 24 hr, 800°C for 15 min, W.Q.	0.15	100	6	39	(f)	(f)	2.6	Warped
BH-21-2	25	800°C for 15 min, 685°C for 168 hr, A.C. 800°C for 15 min; W.Q.	0.12	90	3	25	(f)	(f)	-0.2	Warped
BH-22-5	850	685°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.10	73	12	110	(f)	(f)	-0.4	Warped
BH-23-5	850	685°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.11	74	13	110	(f)	(f)	0.0	Warped
BH-24-5	850	685°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.096	71	10	100	(f)	(f)	0.5	Warped
BH-22-2	850	800°C for 15 min, 685°C for 2 hr, A.C.; 800°C for 15 min, W.Q.	0.10	73	14	130	(f)	(f)	0.6	Warped
BH-23-2	850	800°C for 15 min, 685°C for 24 hr, A.C.; 800°C for 15 min, W.Q.	0.11	74	12	100	(f)	(f)	-0.4	Warped
BH-24-2	850	800°C for 15 min, 685°C for 168 hr, A.C.; 800°C for 15 min, W.Q.	0.096	71	9	90	(f)	(f)	1.4	Warped

(a) All specimens were rolled from ingot L-215.

(b) G_i = microin./in. per fission 10⁶ total atoms.

(c) All specimens rolled at 25°C were given a 12% reduction in thickness at that temperature.

(d) A.C. - Air cooled.

(e) W.Q. - Quenched in water at room temperature.

(f) Specimen was too distorted for measurement.

Results from the specimens isothermally transformed at 675°C, in the beta-plus-gamma region, are shown in Table XI. As can be seen from the results shown in the upper half of the table, growth rates of the specimens isothermally transformed without a subsequent gamma quench were generally insensitive to rolling temperature, transformation time, and whether or not the material was first heated into the gamma phase before being taken to the transformation temperature.

The lower half of the table, in which are given the results on the specimens with a final gamma quench for corrosion resistance, shows that final rolling temperature had a significant effect. The growth rates of the cold-worked specimens were only about half those shown by the hot-worked material. None of the specimens in the 675°C isothermally transformed group was of particular interest for its dimensional stability.

Table XII summarizes the results from the specimens annealed at 685°C, in the lower temperature region of the gamma phase. These specimens were given annealing heat treatments that paralleled those given to the specimens isothermally transformed at 655°C, 665°C, and 675°C. However, in the 685°C group, no transformation could occur since the specimens were not cooled below 677°C, the lower temperature limit of the gamma phase.⁽¹⁰⁾ One would not expect, therefore, to see any marked effect resulting from varying annealing times. This was generally the case. As a matter of fact, most specimens described in Table XII showed similar growth rates, regardless of heat treatment. An exception was the hot-worked material with a final gamma quench, which grew at about double the rate of the other specimens. In this respect the 685°C annealed specimens were similar to those isothermally transformed at 675°C. No surface roughening occurred with the specimens in this group, as would be expected if grain growth had occurred during the long anneals in the gamma phase. As in the case of the specimens isothermally transformed at 675°C, none of the specimens annealed at 685°C showed particularly good dimensional stability.

The following conclusions can be drawn from the results on the Group 7 flat rolled specimens:

1. The lowest growth coefficient, 3.8 microin./in. per fission/ 10^6 total atoms, for dimensionally stabilized material occurred in a cold-worked specimen that was isothermally transformed at 655°C for 24 hours.
2. The least warping and lowest growth coefficient, 10 microin./in. per fission/ 10^6 total atoms, for dimensionally stabilized and corrosion-resistant material occurred in a cold-worked specimen that had been isothermally transformed at 665°C for 24 hours prior to a final quench from 800°C.

3. For those specimens isothermally transformed at 655°C and 665°C, better dimensional stability was obtained by heating the material into the gamma phase and cooling to the isothermal transformation temperature, rather than by heating the specimen directly to the transformation temperature.
4. Material isothermally transformed at 675°C and 685°C was generally insensitive to prior rolling temperature, transformation or annealing times, and whether the material was heated directly to the transformation or annealing temperature or first heated into the gamma phase and cooled to the transformation or annealing temperature.
5. For each transformation or annealing temperature, a final quench of isothermally transformed or annealed material from the gamma phase resulted in the development of marked warping distortion under subsequent irradiation.
6. For each transformation or annealing temperature, specimens under irradiation generally increased in length and width and decreased in thickness.

CONCLUSIONS

1. The most effective heat treatment for dimensionally stabilizing swaged or round-rolled U-5 w/o Zr-1.5 w/o Nb alloy consisted of a 24-hour isothermal transformation from the gamma phase at 650°C. This heat treatment was subsequently used as a basis for specifying the heat treatment to be given to the EBWR fuel plates.
2. The most effective heat treatment for dimensionally stabilizing flat-rolled material consisted of a 12% reduction in thickness by cold rolling, followed by a 24-hour isothermal transformation from the gamma phase at 655°C.
3. Swaged alloy could not be successfully heat treated to be both dimensionally stable and corrosion resistant.
4. Flat-rolled material could be made both dimensionally stable and corrosion resistant by first reducing the material in thickness 12% by cold rolling, then isothermally transforming the alloy from the gamma phase for 24 hours at 665°C, and finally quenching from 800°C.
5. Zircaloy-2 cladding in thicknesses as small as 0.004 in. and metallurgically bonded to the fuel alloy restrained at least partially the irradiation growth of the fuel alloy.
6. Flat-rolled fuel alloy under irradiation generally increased in length and width and decreased in thickness.

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REFERENCES

1. The EBWR Boiling Water Reactor, ANL-5607 (1957).
2. J. E. Draley, S. Greenberg and W. E. Ruther, The High-temperature Aqueous Corrosion of Uranium Alloys Containing Minor Amounts of Niobium and Zirconium, ANL-5530 (1957).
3. C. H. Bean, R. E. Macherey and J. R. Lindgren, Roll Cladding Uranium-Zirconium and Uranium-Zirconium-Niobium Alloys with Zircaloy-2 for Plate-type Fuel Elements, ANL-5628 (1958).
4. J. H. Kittel, S. Greenberg, S. H. Paine and J. E. Draley, Effects of Irradiation on Some Corrosion-resistant Alloys, Nuclear Science and Engineering, 2, 431-449 (1957).
5. S. Greenberg and J. E. Draley, Effects of Irradiation on Corrosion Resistance of Some High Uranium Alloys, Nuclear Science and Engineering, 3, 19-28 (1957).
6. J. H. Kittel and K. F. Smith, Effects of Irradiation on Some Corrosion-resistant Fuel Alloys, ANL-5640 (1960).
7. J. H. Kittel and S. H. Paine, Effects of High Burnup on Natural Uranium, ANL-5539 (1957).
8. J. H. Kittel and S. H. Paine, Effects of High Burnup at Elevated Temperatures on Uranium-0.52 and 1.62 w/o Zirconium Alloys, ANL-5406 (1959).
9. J. H. Kittel, S. H. Paine and H. H. Chiswik, Influence of Heat Treatment on Irradiation-induced Dimensional Changes in Some Uranium-Zirconium Alloys, Symposium on Radiation Effects on Materials, 1, 87-99, ASTM Special Tech. Pub. No. 208 (1957).

10. A. E. Dwight and M. H. Mueller, Constitution of the Uranium-rich U-Nb and U-Nb-Zr Systems, ANL-5581 (1957).
11. R. E. Macherey, C. H. Bean, J. R. Lindgren and N. J. Carson, Jr., Manufacture of Fuel Plates for the Experimental Boiling Water Reactor, ANL-5629 (1957).
12. C. F. Reinke and R. Carlander, Examination of Irradiated EBWR Core-1 Fuel Subassemblies, ANL-6091 (1960).