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**ZIRCALOY-CLAD UO_2 FUEL ROD
EVALUATION PROGRAM
QUARTERLY PROGRESS REPORT No. 4
AUGUST 1968-OCTOBER 1968**

COMPILED BY
F. H. MEGERTH

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
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NUCLEAR FUELS DEPARTMENT
GENERAL ELECTRIC
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Contract AT(04-3)-189
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SECTION I

INTRODUCTION

At the time of the final shutdown of the Vallecitos Boiling Water Reactor (VBWR) and the termination of the AEC Fuel Cycle Program [Contract AT(04-3)-189, Project Agreement 11] the leading Zircaloy-2-clad, UO_2 fuel rods of the program's Type J basic assemblies had attained rod-average exposures as high as 3×10^{20} fissions/cc (10,000 MWd/tU). To demonstrate at the earliest possible time the capability of Zircaloy-clad fuel to achieve average burnups of at least 6×10^{20} fissions/cc (20,000 MWd/tU) and to take advantage of the available lead time in achieving these burnup targets, 98 of the higher exposure Fuel Cycle Program rods were incorporated in a special assembly, designated SA-1, and inserted in the Dresden reactor for additional irradiation. The assembly consists of two 7-by-7 subassemblies stacked one on top of the other in a channel of standard dimensions for the Dresden reactor.

Assembly SA-1 has been operated continuously from June 1964 to the present time with the exception of reactor shutdowns for refueling and maintenance.

To investigate in detail the performance of the SA-1 fuel rods and to determine the isotopic composition of the highly exposed fuel, a two-phase program of destructive examination and analysis was drawn up. For the initial phase of the program, 10 rods were removed from the assembly in January 1967 and were shipped to the Vallecitos Nuclear Center. The examination of these 10 rods is now in progress.

Prior reports to the Atomic Energy Commission under Project Agreement 41 comprise the following:

1. "Quarterly Progress Report No. 1, November 1967 - January 1968," GEAP-5598.
2. "Quarterly Progress Report No. 2, February 1968 - April 1968," GEAP-5624.
3. "Quarterly Progress Report No. 3, May 1968 - July 1968," GEAP-5667.

SECTION II

SUMMARY

Assembly SA-1 continued to operate in the Dresden reactor during the report period.

Additional metallographic examinations were performed on sections of some of the ten fuel rods that were removed from the assembly in January 1967. It was noted that

some increase in corrosion, but apparently no appreciable mechanical wear, occurred at or near SA-1 spacer spring contact points. One such point showed a layer of ZrO_2 0.14 cm (0.055 inch) across and 70 to 100 microns (~ 0.003 to 0.004 inch) thick. Elsewhere the external oxide consisted of a 10-micron film with intermittent patches 40 to 50 microns (0.0015 to 0.002 inch) thick.

Increased corrosion was noted in and around a 0.005- to 0.008-cm (0.002- to 0.003-inch) -deep groove that had been worn in the cladding of a rod by a spacer wire during VBWR operation. Within the groove and for a distance of about 0.3 cm (1/8 inch) on either side, the ZrO_2 was essentially a continuous layer 50 to 100 microns (0.002 to 0.004 inch) thick. There also was some indication that, to a lesser degree, a rather general enhancement of ZrO_2 formation had taken place around the rod at the VBWR spacer location. During an earlier visual examination, it was noted the surface of the rod had an unusually rough appearance in this region.

Blister-like protrusions that were grouped in the form of circumferential rings on a rod surface appeared in sectional view as areas of greater than normal corrosion. Patches of ZrO_2 which were considerably more extensive and thicker (83 microns or 0.0035 inch average) than normal were noted where these "rough rings" were pronounced. The cause of the rings is unknown. One conjecture is that they may have resulted from surface scratches that were possibly acquired prior to Dresden exposure.

The ZrO_2 films on the internal cladding surfaces averaged from less than 1 to a maximum of 5 microns among the two transverse and three longitudinal metallography specimens. Cladding hydrogen content was visually estimated to be no greater than 100 ppm.

The UO_2 in three specimens was examined. The grain size in two of these was quite uniform; the third showed a slight amount of central grain growth. Intragranular precipitates of the types noted in earlier examinations and reported in the preceding quarterly progress report were seen in the currently examined specimens. Clusters of white metallic particles also were observed throughout the fuel.

Gas samples collected from two fuel rods were analyzed for carbon dioxide by chromatography. The CO_2 content in each case was 0.11 volume percent.

Work on determining isotopic distribution as a function of radial distance from the pellet center was started. By using a grinding technique, ten samples were obtained from each of two fuel rods. The samples were dissolved, and analyses are in progress.

SECTION III

ASSEMBLY OPERATION

The Dresden reactor operated throughout August, September, and October at an average thermal power of approximately 600 MW and at a maximum power of 700 MW. Estimated thermal performance and exposure data on Assembly SA-1 are given in Table 1. As mentioned previously, some of these es-

timates may have to be revised in view of the chemical burnup data being obtained on the removed rods. These burnup and isotopic composition analyses are scheduled for completion early in November 1968, and any adjustments to the data on SA-1 operation will be made at that time.

TABLE 1
THERMAL PERFORMANCE AND EXPOSURE OF SA-1
 (Unrevised)
August - October 1968

Reactor Power (MWt)	<u>600 (Average)</u>		<u>700 (Maximum)</u>	
	<u>Average</u>	<u>Peak</u>	<u>Average</u>	<u>Peak</u>
SA-1 Thermal Performance				
Heat Flux, W/cm ² (Btu/h-ft ²)	32(101,000)	56(179,000)	37(118,000)	66(209,000)
Specific Power, kW/kg U	16.6	29.4	19.5	34.5
Power Density, kW/liter	29.3	51.9	34.4	60.9
Assembly Average Exposure,	<u>July 31, 1968</u>		<u>October 31, 1968</u>	
fissions/cc × 10 ⁻²⁰ (MWd/tU)	7.7(28,000)		8.0(29,300)	

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Reactor water chemistry data, presented in Table 2, were extracted from the June, July, and August monthly reports of

the Commonwealth Edison Company on Dresden operation, and are the most recent that are presently available.

TABLE 2

DRESDEN REACTOR WATER CHEMISTRY

	June 1968			July 1968			August 1968		
	<u>Min.</u>	<u>Avg.</u>	<u>Max.</u>	<u>Min.</u>	<u>Avg.</u>	<u>Max.</u>	<u>Min.</u>	<u>Avg.</u>	<u>Max.</u>
pH	6.3	7.2	8.7	6.00	6.80	7.90	6.5	7.2	8.2
Conductivity (μ mhos)	0.31	0.44	1.0	0.32	0.52	0.86	0.32	0.42	0.75
Turbidity (APHA)	2.2	5.4	26.0	2.00	4.30	10.00	1.6	3.5	6.0
Chloride (ppm)	0.001	0.03	0.06	0	0.027	0.057	0.010	0.042	0.076

SECTION IV

EXAMINATION AND ANALYSES OF FUEL RODS

During this period, the following work was carried out on the ten fuel rods that were permanently removed from assembly SA-1 in January 1967.

4.1 FUEL ROD PERFORMANCE EVALUATION

4.1.1 Metallographic Examinations

The examination of five transverse fuel rod sections was taken up in the preceding

quarterly progress report ⁽¹⁾. Two more transverse metallography specimens and three specimens which were prepared over longitudinally oriented planes through the fuel rods were examined during the current period. The objectives of these later examination were to investigate unusual, localized areas of rod surface roughness, spacer—fuel rod contact areas, and regions that showed peaks in rod diameter profile traces, as well as to acquire additional general information on cladding corrosion and on UO₂ and cladding microstructures.

4.1.1.1 Cladding

a. Corrosion — Crud Deposition

During the visual examinations of the external fuel rod surfaces, marks located in those areas where the SA-1 subassembly spacer springs had contacted the cladding surface were apparent on most of the rods from which the crud had been chemically removed (2). The more prominent marks of this type were observed on rod B70 at 36 cm (14 inches) from the short end plug and can be seen in Figure 1.* B70 was located in an outside non-corner position in Assembly SA-1; it was in contact at each spacer with three springs and the peripheral spacer band at 90-degree intervals. The band contacted the rod near the top and bottom edges of the 2.5-cm (1-inch)-high spacer; spring contact was at the midpoint.

The rod was sectioned transversely and ground so that the plane through the center of the spacer spring marks could be examined. These marks can be seen on the macrograph of Figure 2 as regions of increased cladding corrosion. One of these regions showed a layer of ZrO_2 0.14 cm (0.055 inch) across and 70 to 100 microns (~ 0.003 to 0.004 inch) thick (Figure 3). In general, as Table 3 indicates, the external ZrO_2 around the circumference of specimen No. 9960 took the form of a 10-micron film, with intermittent patches 40 to 50 microns (0.0015 to 0.002 inch) thick.

No evidence of mechanical wear of the cladding was detected in the spring contact regions.

Rod B70, like most of the ten rods removed from SA-1 for examination, did show evidence of cladding wear near mid-length, which was caused during VBWR operation by

contact with the wire-type spacers used on the AEC Fuel Cycle Program assemblies (Figure 4). All of these rods exhibited local diameter peaking at the VBWR spacer locations. In the case of B70, this increase in diameter was 0.009 cm (0.0035 inch). As Figure 4 shows, a pronounced localized increase in surface roughness occurred in the vicinity of the VBWR spacer location.

A longitudinal section that passed through a wear groove in the cladding of rod B70 was examined metallographically. The 0.005- to 0.008-cm (0.002- to 0.003-inch)-deep groove is shown in Figure 5 (where it is barely discernible) and in Figure 6. A buildup of ZrO_2 50 to 100 microns (0.002 to 0.004 inch) thick was observed within the groove and for a distance of about 0.3 cm (1/8 inch) on either side of it ("a" in Figure 5). Elsewhere on the "groove side" of specimen No. 9961, the external oxide consisted of an even ~ 9 -micron film with a few intermittent patches 14 to 75 microns (0.0006 to 0.003 inch) thick. On the opposite (270-degree) side of the specimen, the external ZrO_2 generally consisted of an ~ 10 -micron film with intermittent patches 28 to 103 microns (~ 0.001 to 0.004 inch) thick distributed over the entire length. Over that portion designated "d" in Figure 5, however, a fairly continuous layer of oxide that built up to a maximum thickness of 75 microns (0.003 inch) was noted. A part of region "d" is shown at a higher magnification in Figure 7. This particular region may have been close to another spacer wire contact point, although no evidence of wear was observed in the plane examined.

The gap between the two pellets of specimen No. 9961 probably did not exist during the irradiation of rod B70, but was formed during specimen preparation. The neutron radiograph taken of the rod did not show such a gap at this location.

* All illustrations referenced here are shown in Section V.

Rings of blister-like protrusions were noted on the surfaces of three rods. Such rings on rod A13 at 45 cm (17-5/8 inches) from the short end plug are shown in Figure 8.

A longitudinal specimen (No. 9955) from rod A13 was prepared so that the most pronounced portion of the rings could be examined in sectional view. Over much of this portion, which is designated as the 90-degree side in Figure 9, the external ZrO_2 took the form of patches of oxide that had an average thickness of 83 microns (~ 0.0035 inch) and a maximum thickness of 105 microns (0.004 inch). Part of this region is shown at a higher magnification in Figure 10. At a location 180 degrees away, the rings were less well defined and the rod surface was generally smoother. Patches of ZrO_2 appeared here also in sectional view, but there were relatively fewer of them, and their average thickness was only 35 microns (~ 0.0015 inch). The ZrO_2 took the form of a fairly even 9- or 10-micron film between the thick patches on both sides of the specimen (Table 4).

The profiles of most of the fuel rods showed, to some degree, local increases in diameter at pellet-length intervals. The maximum difference in diameter between any of these apices and the corresponding troughs was about 0.0025 cm (0.001 inch).

In an attempt to learn more about the mechanism(s) responsible for diameter increases of this type, a longitudinal specimen was taken from rod A41 at the location indicated in Figure 11. A macrograph of the specimen is shown in Figure 12. The distribution of the external ZrO_2 along the two sides of the specimen is shown.

It will be noted that the degree of corrosion is significantly different at different locations on the specimen. The patch-type oxide and, to a lesser degree, the even film-type are thicker on one side (270-degree) than on the other. On both sides, the patch-

type ZrO_2 is thicker over the whole pellet portion of the specimen than over the ends. In fact, essentially no pitting corrosion took place over the ends of the 90-degree side. The variations in diameter along the specimen that one might expect from differences in ZrO_2 thickness are of about the same magnitude as the variations over the corresponding portion of the profile scan, but the relationship in regard to distribution is not well defined. It is difficult to say whether or not cladding deformation has occurred at locations of local diameter increase.

A transverse section through the fuel column near the plenum of fuel rod A46 showed, over three octants of the circumference, a rather continuous external layer of ZrO_2 that ranged from 31 to 64 microns (~ 0.001 to 0.0025 inch) in thickness (specimen No. 9959, Table 3). Part of the layer is shown in Figure 13. The cause of this unusually high corrosion is unknown. The section was located, of course, in relatively low flux regions during both VBWR and Dresden operation. The maximum thickness of crud around the periphery was only approximately 3 microns.

The average thicknesses of the internal corrosion films ranged from 0.7 micron to 5 microns among the five specimens. In general, this internal film did not vary markedly from one side to the other of the longitudinal specimens nor about the circumference of the transverse specimens. However, specimen No. 9961 from rod B70, which contained the spacer wire groove, had a 4-micron average ZrO_2 film on the groove side and a ~ 1.5 -micron average film on the opposite side. The internal ZrO_2 film on specimen No. 9959 from rod A46 was unusually thin (0.7 micron), yet it was comparable to that on another specimen (No. 9958) from the same rod, which was one of the initial five specimens prepared.

TABLE 3
THICKNESS OF CRUD AND ZrO_2 ON THE CLADDING
OF TRANSVERSE METALLOGRAPHIC SPECIMENS

Rod Designation Specimen Number, and Location [Approximate cm (in.) up from Bottom of Bottom Subassembly]	Octant	Crud Average Thickness (microns)	ZrO ₂ on Outside Surface					ZrO ₂ on Inside Surface Average Thickness (microns)
			Patches		Even Film	Overall		
			Relative Amount	Average Thickness (microns)	Average Thickness (microns)	Average Thickness (microns)	Weight Gain 2O ₂)*	
Rod A46 No. 9959 11.59 cm (4-9/16 in.)	1	3		46	9			0.5 - 0.9 ↓
	2	3		36	8			
	3	3		26	8			
	4	3		53	31			
	5	3		72	64			
	6	2		59	41			
	7	2		42	8			
	8	3		33	7			
	1 through 8	3	0.7	46	22	39	610	0.7
Rod B70 No. 9960 140.35 cm (55-3/8 in.)	1	Crud Chemically Removed		50	10			4
	2			34	9			3
	3			49	10			5
	4			40	10			3
	5			46	10			3
	6			45	10			4
	7			46	9			3
	8			55	9			3
	1 through 8		0.1	46	10	14	220	4

* Weight gain in $mg \text{ per } dm^2$ of rod surface = $15.6 \times ZrO_2$ thickness in microns.

TABLE 4
THICKNESS OF ZrO₂ ON THE CLADDING
OF LONGITUDINAL METALLOGRAPHIC SPECIMENS

Rod Designation, Specimen Number, and Location [Approximate cm (in.) up from Bottom of Bottom Subassembly]	Orientation (degrees)	ZrO ₂ on Outside Surface			ZrO ₂ on
		Patches	Even Film	Estimated Overall Weight Gain (mg/dm ² O ₂) *	Inside Surface Average Thickness (microns)
		Average Thickness (microns)			
Rod A13 No. 9955 57.31 to 59.21 cm (22-9/16 to 23-5/16 in.)	90	83	9		4
	270	35	10		4
				550	
Rod A41 No. 9956 78.26 to 81.76 cm (30-13/16 to 32-3/16 in.)	90	17	10		4
	270	43	11		6
				210	
B70 No. 9961 155.58 to 159.07 cm (61-1/4 to 62-5/8 in.)	90	65	21		4
	270	57	15		~1.5
				330	

* Weight gain in mg per dm² of rod surface = 15.6 × ZrO₂ thickness in microns.

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As noted on the earlier specimens, particles or layers of fuel were bonded to the cladding or internal ZrO_2 film in some regions of the current specimens.

b. Microstructure

Typical examples of the cladding microstructure in transverse and longitudinal specimens are shown in Figures 14 and 15. There was no marked difference between the two orientations with respect to the distribution and concentration of hydride platelets. The longitudinal specimens had relatively fewer of the unidentified small, round spots which are dark under normal lighting and optically active under polarized lighting.

With all five specimens, the hydrogen content was visually estimated to be no greater than 100 ppm, and the grain size was estimated to be about ASTM No. 6.

4.1.1.2 Fuel

The UO_2 of specimens Nos. 9956, 9959, and 9960 was examined in the as-polished and etched conditions. The grain size was quite uniform in the latter two specimens, but specimen No. 9956 from the peak power location of rod A41 showed a slight amount of central grain growth. A radial composite from near the mid-length of this last specimen is shown in Figure 16. Precipitates were observed within the grains of this specimen, both near the outside surface of the pellet and at interior locations. The highest concentration of interior precipitates, which had the appearance of higher oxide structures, occurred in two approximately parallel bands each at a distance from the center approximately equal to 0.4 of the pellet radius (Figures 12 and 16). A similarly located concentration of intragranular precipitates was observed previously in the form of a ring in transverse specimen No.

9954 from rod A13. Intragranular precipitates were noted near the outside surface of the pellets in specimens Nos. 9959 and 9960, but the concentration in the former specimen was very low (Figure 17). Neither specimen contained any precipitates of the type seen in specimen No. 9956 within the more centrally located grains.

In specimens Nos. 9956 and 9960, etchant attack at the UO_2 grain boundaries was severe enough near the outer surface of the pellets to allow a significant fraction of the grains to fall out (Figures 16 and 17).

Clusters of white metallic particles were observed throughout the fuel of all specimens. Frequently they were located in the vicinity of voids, as shown in Figure 18. It will be noted that in some places a secondary gray-colored phase is associated with the white particles. Figure 19 shows an area near the center of specimen No. 9960 where the gray phase is prevalent. Fine white particles are dispersed throughout.

4.1.2 Gas Analysis

Mass spectrometric analyses which were carried out in the preceding quarter had indicated the presence of CO_2 in four of five gas samples collected from the fuel rods. During the current period, two of the four samples were analyzed for CO_2 (as well as for ethane, ethylene, and acetylene) by gas chromatography with a silica gel column. A CO_2 concentration of 0.11 volume percent was measured on both samples: one from rod A13 and the other from rod A46. None of the above hydrocarbons was detected. An earlier analysis failed to show the presence of CO or CH_4 in any of the five rods.

The amounts of CO_2 collected from the open void volumes of rods A13 and A46 are equivalent to approximately 0.01 microliters

CO₂ per gram of UO₂, or only ~5 ppb C in the UO₂. These concentrations are compatible with the contents of carbonaceous residuals one would expect to find in the UO₂ pellets.

It may be recalled that vacuum hot extraction analysis of irradiated Zircaloy-2 cladding samples from the AEC Fuel Cycle Program showed appreciable CO and CO₂ contents, and it was postulated that the fuel was the source of these gases.⁽³⁾ Similar analyses of SA-1 cladding samples are in progress.

4.2 FUEL BURNUP AND ISOTOPIC COMPOSITION ANALYSES

(C. P. Ruiz, Technical Director)

Work on determining isotopic distribution as a function of radial distance

from the pellet center was started. Samples were taken from the ~26.0-cm (10-1/4-inch) location of high exposure rod A13 and the ~25.7-cm (10-1/8-inch) location of a relatively low exposure rod, B70. (The locations refer to distances from the short end plug shoulder.) The samples were removed from different radial locations of a pellet by grinding one end of a 4.5-cm (2-inch) rod length toward the center in steps as the piece was rotated. Figure 20 shows the end of a rod length at the completion of sampling. Ten samples were taken from each rod at the locations indicated in Table 5.

The samples were dissolved, and analyses are in progress.

TABLE 5

LOCATION OF SAMPLES FOR RADIAL ISOTOPIC DISTRIBUTION ANALYSES

<u>No.</u>	<u>Distance from Pellet Surface - cm (inch)</u>	<u>Sample Width - cm (inch)</u>
1	0 - 0.005 (0 - 0.002)	0.635 (0.25)
2	0.005 - 0.010 (0.002 - 0.004)	0.60 (0.235)
3	0.010 - 0.018 (0.004 - 0.007)	0.56 (0.22)
4	0.018 - 0.025 (0.007 - 0.010)	0.52 (0.205)
5	0.025 - 0.038 (0.010 - 0.015)	0.485 (0.19)
6	0.038 - 0.051 (0.015 - 0.020)	0.445 (0.175)
7	0.051 - 0.076 (0.020 - 0.030)	0.405 (0.16)
8	0.076 - 0.127 (0.030 - 0.050)	0.37 (0.145)
9	0.127 - 0.254 (0.050 - 0.100)	0.33 (0.13)
10	0.254 - center (0.100 - center)	0.29 (0.115)

SECTION V

ILLUSTRATIONS

This section contains the following illustrations.

<u>Figure</u>	<u>Title</u>
1	Subassembly Spacer Markings at 36-cm (14-in.) Location of Fuel Rod B70
2	Macrograph of Specimen No. 9960 (as-ground-10 × Magnification)
3	Thick ZrO ₂ Layer on Cladding in Spacer Spring Contact Area (Rod B70, Specimen No. 9960)
4	VBWR Spacer Region on Fuel Rod B70
5	Macrograph of Specimen No. 9961 (as-ground—5 × magnification). External ZrO ₂ Thickness in Various Locations is Shown.
6	Highly Corroded Groove Worn into Cladding of Rod B70 by VBWR Spacer Wire (Specimen No. 9961)
7	Thick External ZrO ₂ Layer in Region d of Specimen No. 9961 (see Figure 5)
8	Rings of "Blisters" at 45-cm (17-5/8-in.) Location of Fuel Rod A13. View b. is approximately 180 degrees from View a.
9	Macrograph of Specimen No. 9955 (as-ground-5 × magnification). Thickness of Patch-Type and Even Film-Type ZrO ₂ on External Cladding Surface is shown in microns.
10	Thick ZrO ₂ Patches Where Rings of "Blisters" Were Observed on the Surface of Rod A13 (Specimen No. 9955)
11	Diameter Profile Traces over Part of Rod A41 at 0-180 Degree and 90-270 Degree Orientations. The Location of Metallography Specimen No. 9956 is Indicated.
12	Macrograph of Specimen No. 9956 (as-ground-5 × magnification). Thickness of Patch-Type and Even Film-Type ZrO ₂ on External Cladding Surface is shown in microns.
13	Thick ZrO ₂ Layer on External Cladding Surface of Specimen No. 9959 from Fuel Rod A46
14	Cladding Microstructure Typical of Transverse Specimens (Specimen No. 9959)
15	Cladding Microstructure Typical of Longitudinal Specimens (Specimen No. 9956)
16	UO ₂ Microstructure of Specimen No. 9956 (Fuel etched 60 seconds)
17	UO ₂ Microstructures Near Pellet Peripheries in (a) Specimen No. 9959 and (b) Specimen No. 9960 (Fuel etched 60 seconds)
18	Clusters of Metallic Particles Around Voids in Fuel of Specimen No. 9960 (Fuel etched 30 seconds)
19	Dark Gray-Colored Phase with Fine White Particles Near Center of Pellet in Specimen No. 9960
20	Appearance of Portion of Fuel Rod B70 After Samples Had Been Removed From Different Radial Locations

FIGURE 1. SUBASSEMBLY SPACER MARKINGS AT 36-cm (14-inch) LOCATION OF FUEL ROD B70

- a. HIGH CORROSION REGIONS ARE INDICATED BY ARROWS.
- b. LOCATIONS OF OCTANTS LISTED IN TABLE 3 ARE INDICATED BY NUMBERS ABOUT CIRCUMFERENCE.

FIGURE 2. MACROGRAPH OF SPECIMEN NO. 9960 (AS-GROUND - 10X MAGNIFICATION)

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**FIGURE 3. THICK ZrO_2 LAYER ON CLADDING IN SPACER SPRING CONTACT AREA
(ROD B70, SPECIMEN NO. 9960)**

FIGURE 4. VBWR SPACER REGION ON FUEL ROD B70

REGIONS	EXTERNAL ZrO ₂ THICKNESS IN MICRONS	
	CONTINUOUS FILM AVERAGE (RANGE)	INTERMITTENT PATCHES AVERAGE (RANGE)
a	60 (56-66)	84 (75-94)
b	} 9 (4-11)	50 (14-75)
c		NONE
d	46 (19-75)	—
e	10 (8-14) *	57 (28-103)

* DOES NOT INCLUDE REGION d

FIGURE 5. MACROGRAPH OF SPECIMEN NO. 9961 (AS-GROUND - 5X MAGNIFICATION).
EXTERNAL ZrO₂ THICKNESS IN VARIOUS LOCATIONS IS SHOWN.
(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

FIGURE 6. HIGHLY CORRODED GROOVE WORN INTO CLADDING OF ROD B70 BY VBWR SPACER WIRE (SPECIMEN NO. 9961)(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

FIGURE 7. THICK EXTERNAL ZrO₂ LAYER IN REGION d OF SPECIMEN NO. 9961. (SEE FIGURE 5)(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

a.

b.

FIGURE 8. RINGS OF "BLISTERS" AT 45-cm (17-5/8-in.) LOCATION OF FUEL ROD A13. VIEW b IS APPROXIMATELY 180 DEGREES FROM VIEW a.

FIGURE 9. MACROGRAPH OF SPECIMEN NO. 9955 (AS-GROUND - 5X MAGNIFICATION). THICKNESS OF PATCH-TYPE AND EVEN FILM-TYPE ZrO₂ ON EXTERNAL CLADDING SURFACE IS SHOWN IN MICRONS.

FIGURE 10. THICK ZrO₂ PATCHES WHERE RINGS OF "BLISTERS" WERE OBSERVED ON THE SURFACE OF ROD A13 (SPECIMEN NO. 9955) (REDUCED TO 55% FOR REPRODUCTION PURPOSES)

FIGURE 11. DIAMETER PROFILE TRACES OVER PART OF ROD A41 AT 0-180 DEGREE AND 90-270 DEGREE ORIENTATIONS. THE LOCATION OF METALLOGRAPHY SPECIMEN NO. 9956 IS INDICATED.

FIGURE 12. MACROGRAPH OF SPECIMEN NO. 9956 (AS-GROUND - 5X MAGNIFICATION). THICKNESS OF PATCH-TYPE AND EVEN FILM-TYPE ZrO₂ ON EXTERNAL CLADDING SURFACE IS SHOWN IN MICRONS.

FIGURE 13. THICK ZrO_2 LAYER ON EXTERNAL CLADDING SURFACE OF SPECIMEN NO. 9959 FROM FUEL ROD A46

CLADDING ETCHED

250 X

PHOTOGRAPHED UNDER POLARIZED LIGHT

CLADDING ETCHED

250 X

PHOTOGRAPHED UNDER NORMAL LIGHT

FIGURE 14. CLADDING MICROSTRUCTURE TYPICAL OF TRANSVERSE SPECIMENS
(SPECIMEN NO. 9959)(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

CLADDING ETCHED

250 X

PHOTOGRAPHED UNDER POLARIZED LIGHT

CLADDING ETCHED

250 X

PHOTOGRAPHED UNDER NORMAL LIGHT

FIGURE 15. CLADDING MICROSTRUCTURE TYPICAL OF LONGITUDINAL SPECIMENS
(SPECIMEN NO. 9956)(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

FIGURE 16. UO₂ MICROSTRUCTURE OF SPECIMEN NO. 9956 (FUEL ETCHED 60 SECONDS) (REDUCED TO 46% FOR REPRODUCTION PURPOSES)

FIGURE 17. UO_2 MICROSTRUCTURES NEAR PELLET PERIPHERIES IN (a) SPECIMEN NO. 9959 AND (b) SPECIMEN NO. 9960 (FUEL ETCHED 60 SECONDS)(REDUCED TO 75% FOR REPRODUCTION PURPOSES)

(a)

500 X

(b)

500 X

**FIGURE 18. CLUSTERS OF METALLIC PARTICLES AROUND VOIDS
IN FUEL OF SPECIMEN NO. 9960 (FUEL ETCHED 30 SECONDS)**

AS-POLISHED

500 X

FIGURE 19. DARK GRAY-COLORED PHASE WITH FINE WHITE PARTICLES
NEAR CENTER OF PELLET IN SPECIMEN NO. 9960

FIGURE 20. APPEARANCE OF PORTION OF FUEL ROD B70 AFTER SAMPLES
HAD BEEN REMOVED FROM DIFFERENT RADIAL LOCATIONS

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